Mineralogical norm calculations applied to tropical weathering profiles

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Abstract

In contrast with igneous and metamorphic rocks, classical petrochemical calculation methods cannot be used for tropical weathering components (saprolite, bauxitic, ferruginous, siliceous and calcareous laterite) in converting whole-rock chemical analyses into normative mineralogical weight percentages. Weathering profiles are characterized by a mixture of primary and secondary minerals, which are not considered in the classical methods of mineralogical norm calculation. A new petrochemical calculation algorithm is proposed for the conversion of whole-rock chemical analyses into weathering norm (WN) for several components of the tropical weathering profiles. The normative minerals are represented by three primary minerals, six secondary minerals, four primary/secondary mineral pairs, and five minerals which can have both primary and secondary origin. This algorithm has been used in MINNOR, a WINDOWS application written in Visual Basic, which calculates the mineralogical norm. In order to test the program, several types of different chemical weathering profiles from South America and Africa have been selected. Special attention is paid to the weathering profile from Omai, Guyana, South America.

KEYWORDS: mineralogical norm, whole-rock analyses, tropical weathering profile, computer program.

Introduction

THE special climatic and geomorphologic conditions prevailing in tropical regions have a direct influence on the supergene alteration processes. The mineralogical composition of the tropical weathering products is very different from that of the initial unaltered rock or from the equivalent weathering products in the temperate and cold climatic regions. The various methods proposed for the calculation of the normative mineralogy of the igneous and metamorphic fresh rocks are based only on primary minerals, without considering the mineral phases resulting from the alteration processes. For tropical profiles, characterized by various degree of mineral weathering leading to the formation of mixtures of relict primary and neoformed secondary phases, these methods can not be applied. A calculation method formulated for bauxitic laterites, but which is not useful for determining the mineralogical norm of other types of saprolite and laterite profiles, has been proposed by Nyobe (1991).

The purpose of the present paper is to present a new algorithm leading to the conversion of the whole-rock chemical analyses into normative mineralogical percentages, which can be used for various tropical weathering components. The algorithm gives good results and the normative minerals are closer to the real mineralogy of the weathered profile when the rocks are intensively altered, with the chemical index of alteration (CIA; Nesbitt and Young, 1982; Fedo et al., 1995) greater than 80. This value corresponds to a mineralogical index of alteration (MIA, proposed in this paper) greater than 60. Geologic systems,

however, are not simple and a single calculated value may not adequately reflect their complexities. Due to the highly variable mineralogy and, sometimes, to the poor crystallinity of the neoformed mineral phases, the present norm calculations only illustrate trends in the weathering profile composition. The algorithm used for norm calculations is based on a number of simplifications and assumptions. The main simplification is that the minerals used in the norm have their stoichiometrically ideal compositions, excluding any substitutions (except Al-goethite). The ubiquitous occurrence of pure and mixed amorphous phases of Al, Si, Mn, and Fe, which cannot be reported by X-ray diffraction and are rarely considered, yet abundant in some saprolite profiles, are integrated in the calculations of their crystallized equivalents (kaolinite, gibbsite, pyrolusite, etc.) and as amorphous silica. The main assumption is that the mineralogical index of alteration of a sample is the same for all its mineralogical pairs used for the partition of a chemical element between a primary and its equivalent secondary mineral. The norm computations may give interesting indications of the changes in mineralogy with depth in the composition of a weathering profile, may help to determine local zones depleted/enriched in certain chemical elements, or may give a warning of unusual compositions, which should be followed up by detailed mineralogical analysis. In this paper, the examples used for the application of the mineralogical norm calculations are constrained by semi-quantitative/qualitative XRD analyses. The similarity between the two sets of results provides additional credence to the normative calculations.

The algorithm has been used in MINNOR, a WINDOWS application which performs mineralogical norm calculations and plots frequency histograms of the normative minerals.

Weathering profile

The terminology used for tropical regolith represents the subject of many recent studies (Lecomte, 1988; Butt and Zeegers, 1989, 1992; Bàrdossy and Aleva, 1990; Tardy, 1992; Lawrance, 1994). The multitude of terms used to describe each horizon makes it difficult to apply a uniform scheme for the description and terminology of the lateritic profiles. For the purposes of this paper, we have used the terminology of Butt and Zeegers (1992) and Bàrdossy and Aleva (1990).

Although the supergene processes are integrated and complex, specific supergene alteration horizons are produced within the regolith. Some of these horizons are characterized by secondary mineral formation, associated with important isovolumetric changes, but with preservation of primary rock

fabric by weathering products (Lawrance, 1994). These horizons define the saprolith, which generally comprises at least 2/3 of the whole weathering profile. It can be subdivided into two zones: at the base, the saprock, which represents slightly weathered rock with an arbitrary upper limit of 20% weatherable minerals altered (Trescases, 1992). The upper part of the saprolith is defined as saprolite, which can be subdivided into coarse (containing remnants of unweathered bedrock) and fine (without remnants of unalterd bedrock) saprolite. The algorithm for the norm calculation proposed in this paper cannot be used for saprock and coarse saprolite.

The upper part of the regolith, affected by surface oxidation associated with volumetric changes, and characterized by total extinction of the parent rock fabric and the development of new fabric, is defined as pedolith or laterite *sensu stricto*. At the lower part, the pedolith consists of a mottled clay zone, characterized by localized spots, patches, and streaks of Fe oxides and oxy-hydroxides in an argillaceous matrix. The middle part is defined as duricrust, which represents a highly indurated zone, composed of ferruginous, aluminous, siliceous or calcareous material, with a pisolitic, botryoidal or massive fabric. The ferruginous duricrust is a highly weathered material consisting mainly of Fe oxides and oxy-hydroxides, with variable amounts of Al hydroxides, silica and phyllosilicates. It is normally referred to as ironstone or ferricrete. The aluminous duricrust is characterized by a major enrichment of free Al hydroxide minerals and it is referred to as bauxitic laterite. This term may include also an aluminous mottled clay zone and even alumina-rich saprolite. The siliceous (or silcrete) and calcareous (or calcrete) duricrust represent strongly silicified/carbonatized indurated material formed by *in situ* cementation/replacement of pre-existing regolith. The upper part of the pedolith is affected by surface physical and chemical reworking of the duricrust, which may separate pisoliths from their matrix, resulting in a lateritic gravel. Thin residual soils can also develop at the surface, containing secondary and resistent primary minerals.

Normative minerals

The minerals used in the weathering norm are represented by three primary minerals, six secondary minerals, four primary/secondary mineral pairs, and five minerals which can have both primary and secondary origin. These minerals have been selected on the basis of their frequency in the published mineralogical data for supergene alteration profiles and of chemical and mineralogical data obtained for the weathering profile of Omai, Guyana. Most of the

abbreviations for these minerals are from Cross *et al.* (1903) and Kretz (1983). The complete list of the minerals used in normative calculations and their symbols is presented in Table 1.

Primary minerals

Ilmenite (FeO·TiO₂) occurs as an inherited heavy mineral in weathering profiles derived from igneous and metamorphic rocks, especially from the more mafic types (Allen and Hajek, 1989). Its average content is less than 1%, exceptionally 5%. In supergene environments, ilmenite frequently transforms first to pseudorutile and then to anatase within porous leucoxene grains.

Magnetite (FeO·Fe₂O₃). All magnetite reported from the weathering profiles is a relict mineral, inherited from the parent rock. It generally represents less than 2% in bauxitic laterite and saprolith, and up to 8% in the ferruginous horizons and over BIFs. Partial or complete oxidation of the magnetite leads to the formation of its isostructural form, maghemite (γ-Fe₂O₃), frequently described in the superficial horizons. The normative magnetite calculated in this paper represents the total amount of magnetite + maghemite.

Apatite (CaO·P₂O₅). Phosphate minerals make up only a very small percentage of the weathering profiles. Their direct determination is difficult because P₂O₅ is only a minor constituent, ranging from 0.02 to 0.5%. A large fraction of it is organic (Lindsay *et al.*, 1989). Apatite is the most commonly listed inorganic soil phosphate, but it usually represents less than 0.5%. The P₂O₅ content remaining unused in some samples after the normative apatite calculation may be considered as representing organic phosphorus.

TABLE 1. Symbols for the weathering profile-forming minerals

Minerals	Symbols	Minerals	Symbols
Albite	Ab	Ilmenite	Ilm
Anatase	Ant	Kaolinite	Kln
Anorthite	An	Magnetite	Mag
Apatite	Ap	Montmorillonite	Mnt
Boehmite	Bhm	Orthoclase	Or
Calcite	Cal	Pyrolusite	Pyt
Chlorite	Chl	Quartz	Qtz
Corundum	Crn	Sericite	Ser
Gibbsite	Gbs	Amorphous silica	Sil
Al-Goethite	Al-Gt	Epidote	Ep
Hematite	Hem	Pyroxene	Px

Secondary minerals

Pyrolusite (MnO₂) is used as a general mineralogical term for the Mn oxide and hydroxide minerals described in supergene environments. The mineralogy of Mn is complicated by the large number of chemical substitutions, resulting in the formation of continuous series of compositions from MnO to MnO₂, within which a number of stable and metastable arrangements of atoms form a variety of minerals. As Mn is generally leached in weathering profiles, the amount of the Mn-bearing minerals is usually less than 0.5%. However, the Mn oxides can be enriched (up to 5%, Séa *et al.*, 1994) in profiles developed on Mn-rich parent rocks or on certain ultramafic rocks.

Al-goethite [(Fe₁.₆₀Al₀.₄₀)$_{\Sigma 2.0}$O₃·H₂O] is considered the most widespread Fe mineral in ferruginous (up to 50–60%) and bauxitic (between 1 to 30%) laterites. The amount of Al substitution for Fe in the goethite structure is often considerable, varying between 4 to 30% (Allen and Hajek, 1989). Higher Al substitution has been observed in goethite from extremely weathered profiles, in comparison with goethite formed in reductomorphic environments. A synthesis of the published data for Al substitution in goethite in various weathered profiles (Allen and Hajek, 1989; Bàrdossy and Aleva, 1990; Oliveira and Campos, 1991) indicates a mean value of 20%, which has been used for the Al-goethite normative calculations.

Kaolinite (2SiO₂·Al₂O₃·2H₂O) is the most frequent silicate mineral formed in all types of weathering profiles. It has been commonly described as a weathering product of almost all primary silicate minerals, including mainly feldspar, muscovite and biotite. Minor isomorphous substitution of Fe³⁺ in the octahedra of kaolinite has been sometimes reported in poorly crystallized kaolinites, but the substitution ratio do not justify the Fe consideration in the chemical formula. Halloysite, another 1:1 phyllosilicate, and its dehydrated form, metahalloysite, are also frequently reported in the weathering profiles, but not as common as kaolinite. The halloysite stability under weathering conditions has been subdivided (Allen and Hajek, 1989) into an initial stage of hydrated halloysite followed by a more stable metahalloysite stage. As metahalloysite and kaolinite have the same stoichiometric formula, the normative kaolinite calculated in this paper may be interpreted as representing the total amount of these two minerals.

Gibbsite (Al₂O₃·3H₂O) is a product of extremely advanced weathering, formed by the desilication of kaolinite or by direct weathering of feldspar and biotite. It is the main alumina mineral in the lateritic bauxites (Bàrdossy and Aleva, 1990), where the

amount of gibbsite generally ranges from 40 to 70%, but values up to 90% are not uncommon. Gibbsite may also be present in minor amount in coarse saprolite, close to the contact with the bedrock, or in the upper saprolite, interlayered with kaolinite-rich horizons (Tardy, 1992).

Boehmite $(Al_2O_3 \cdot H_2O)$ forms in some bauxitic profiles, particulary those located close to the edge of a plateau and in a horizon close to the soil surface (Tardy, 1992). When this occurs, goethite disappears and hematite becomes the single iron mineral present. Boehmite has been not described in saprolite or ferruginous laterites.

Amorphous silica $(SiO_2 \cdot H_2O)$. Amorphous phases represent a major problem of the weathering profiles and are not entirely confined to silica. Amorphous Al oxy-hydroxides may comprise over 30% of some bauxitic laterites, and amorphous Al silicates, with variable Al/Si ratios, are abundant in some saprolites and soils, especially over the felsic rocks. They 'crystallize' to a mixture of poorly ordered kaolinite and amorphous silica. The amorphous silica (opal) can also have an organic origin, especially in soils and in the upper parts of the weathering profiles. The few published data on the amorphous silica in the supergene environments do not give much information about its occurrence in different weathering horizons.

Primary/secondary mineral pairs

Chemical weathering strongly affects the mineralogy and major-element geochemistry of the unaltered bedrock. The degree of weathering, which must yield distinct values for different weathered materials, can be evaluated by quantitative measures, using whole-rock chemical analyses. These values, representing the average weathering index for each analysed system (sample), can also be applied for the determination of the weathering index of each separate mineralogical component of the system. Several primary/secondary mineral pairs can be considered as reflecting the degree of weathering of the entire system. The principal condition is to consider the system as closed, without mass transfer (loss or gain). This mineralogical index of weathering can be further used in normative calculations for the partitioning of the chemical elements between several pairs of primary and their equivalent altered minerals. The first step is represented by the calculation of the chemical index of alteration (CIA; Nesbitt and Young, 1982; Fedo *et al.*, 1995) for each analysed sample, using the following equation:

$$CIA = [Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)] \times 100 \quad (1)$$

The equation yields values between 50 and 60 for incipient weathering, between 60 and 80 for intermediate weathering, and more than 80 for intense to extreme weathering. Usually, the lower part of the weathering profile has CIA values between 60 and 90, and the upper part more than 80, frequently between 95 and 100.

Because CIA values range between 50 and 100 and cannot be directly applied for the normative calculations, the second step is represented by the calculation of the mineralogical index of alteration (MIA), using the following equation:

$$MIA = 2 \times (CIA - 50) \quad (2)$$

The mineralogical index of alteration evaluates the degree of mineralogical weathering, i.e. the transformation ratio of a primary mineral into its equivalent alteration mineral. MIA yields values between 0 and 100, and reflects incipient (MIA<20), intermediate (MIA = 20−60), and intense to extreme (MIA>60) mineralogical transformation. The value of 100 means complete transformation of a primary mineral into its equivalent alteration product. The calculated MIA values are further used for partitioning the major oxides between the pairs of primary/secondary minerals. As an example, an MIA value of 60 means that for the albite/montmorillonite pair, 60% of the Na_2O content is used for the normative montmorillonite calculation (secondary mineral) and 40% for the normative albite calculation (primary mineral).

Anorthite $(CaO \cdot 2SiO_2 \cdot Al_2O_3)/epidote$ $(4CaO \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot H_2O)$ pair represents minor Ca-bearing mineral phases reported only in saprolite. Their total amount does not exceed 1%. Anorthite in supergene environments is greatly dependent on the presence or absence of plagioclases in the parent rock. It weathers out rapidly even in temperate regions. Epidote is considered as a secondary mineral formed by weathering of calcic plagioclase. Its stability in supergene conditions is comparable to that of quartz, ilmenite and titanite (Allen and Hajek, 1989).

Orthoclase $(K_2O \cdot 6SiO_2 \cdot Al_2O_3)/sericite$ $(K_2O \cdot 6SiO_2 \cdot 3Al_2O_3 \cdot 2H_2O)$ pair represents the main K-bearing minerals in the weathering profile, especially in the saprolite. Locally, the saprolite formed over K-rich parent rocks, may contain up to 25% sericite. For the purposes of the present paper, the sericite represents the mixture of more or less altered muscovite, phlogopite and biotite. In the bauxitic laterite, further potassium leaching results in partial or total transformation of these minerals first into illite and then into kaolinite.

Pyroxene $(2MgO \cdot 2SiO_2)/chlorite$ $(5MgO \cdot 3SiO_2 \cdot Al_2O_3 \cdot 4H_2O)$ pair represents an important indicator of the intensity of weathering. In

normative calculation, Mg-bearing orthopyroxene (enstatite) is used. For the saprolite formed over the olivine-rich ultrabasic rocks, enstatite can be replaced by forsterite, which have the same stoichiometric formula. If the primary minerals are represented by amphiboles instead of pyroxenes, the normative enstatite represents in fact an anthophyllite-cummingtonite mixture, but the calculated content must be considered as semi-quantitative/qualitative. Chlorite is considered as an alteration product of pyroxenes/amphiboles and it is calculated as its Mg-bearing form (clinochlore). Even if chlorite is the main Mg-mineral phase in the saprolite, other Mg-bearing alteration minerals (serpentine, talc) can form, especially over ultramafic rocks. In this situation, the calculated amount of normative chlorite represents in fact a mixture of serpentine/talc. Because there are differences between their stoichiometric formulae, the normative serpentine/talc content must be considered as a semi-quantitative/qualitative value. Mg-bearing minerals are almost completely leached from the upper part of the saprolite and overlying horizons. Only small amounts of chorite have been reported from the mottled clay zone and the ferruginous/bauxitic laterites. The amount of Mg increases in the saprolite towards the parent rock.

Albite $(Na_2O \cdot 6SiO_2 \cdot Al_2O_3)$/montmorillonite $(Na_2O \cdot Al_2O_3 \cdot 5SiO_2 \cdot H_2O)$ pair. Because only few soil smectites have the ideal stoichiometric composition and most are not completely dioctahedral or trioctahedral, montmorillonite is used for the normative calculation purposes as a generic term for the smectite group, including beidellite and nontronite. These Na-bearing minerals are confined to the lower part of the saprolite. Albite content increases and montmorillonite content decreases with depth in weathering profiles, presumably due to a diminution in alteration intensity. Rare and insignificant quantities of these minerals have been described in feruginous and bauxitic laterite.

Primary and secondary minerals

Calcite $(CaCO_3)$ represents a primary mineral in the lower part of the saprolite and a secondary one in the upper part of the lateritic profile and bauxite deposits. Usually it is less than 1%. The amount of calcite drastically increases in the calcareous laterite (up to 80%). The calcite resulted by using MINNOR is greatly dependant on the accuracy of the CO_2 analytical determination.

Anatase (TiO_2). Most of the titanium oxide is present as neoformed anatase, with average content between 1–4%, but primary rutile is also reported, usually less than 1%. Brookite, the third titanium oxide polymorph, is a very rare inherited mineral in bauxitic laterite. Because in the mineralogical norm calculations it is impossible to make the distinction between the three polymorphs, the anatase calculated using MINNOR represents in fact the total quantity of the three titanium oxides.

Hematite (Fe_2O_3) represents a common iron oxide in the mottled clay zone, duricrust and bauxitic laterite (Boeglin and Mazaltarim, 1989; Bàrdossy and Aleva, 1990; Zang and Fyfe, 1993). It is a rare mineralogical phase in saprolite, where generally goethite/hematite ratio is greater than 5. Most of the hematite has a secondary origin, but it has been also reported as an inherited primary mineral. Aluminium can replace iron in the hematite structure, but to a lesser extent than in goethite. The degree of substitution ranges from 1 to 10 mol.% Al_2O_3 , most frequently from 2 to 5 mol.%. Because Al substitution in the hematite structure is missing in many weathering profiles, we have preferred for the normative calculations to use the stoichiometric formula of hematite.

Corundum (Al_2O_3) has been reported as associated with magnetite and maghemite from the upper part of the bauxitic laterite deposits. In the saprolite and mottled clay zone it represents a relict mineral inherited from the parent rock. In duricrust, corundum may reach up to 10% and it is associated with iron oxy-hydroxides. A decrease in water activity at a constant temperature or an increase in temperature at a constant water activity may induce gibbsite and/or boehmite dehydration, resulting in the formation of secondary corundum (Nahon and Tardy, 1992).

Quartz (SiO_2) is very common in most lateritic regoliths. In bauxitic laterite, the quartz represents a relict mineral inherited from silicic sedimentary and igneous parent rocks. It can also be abundant as a secondary mineral in lateritic regoliths formed over ultramafic rocks in most climatic environments, and over most lithologies, especially felsic, in arid environments.

Calculation procedures of the weathering norm (WN) and comments

The calculation procedures of the WN include several steps as follows:

(1) Form the molecular proportions by dividing the weight percent of each analysed oxide by its molecular weight.

(2) Calculate the chemical index of alteration (CIA).

(3) Calculate the mineralogical index of alteration (MIA).

(4) If CaO>0, go to (5). If CaO = 0, go to (9).

(5) If CO_2>0, form calcite and then go to (6). Remaining CaO becomes CaO^1. If CO_2 = 0, go to (6).

The amount of calcite is greatly dependent on the accuracy of the CO_2 analytical determination. Missing data for CO_2 do not affect the program running, but calcite is not calculated, influencing the norms of other Ca-bearing minerals (anorthite, apatite, epidote). However, the error in this case is less than 0.5%. If the samples are from a calcrete horizon, the CO_2 content must be absolutely analysed.

(6) If $P_2O_5 > 0$, form apatite and go to (7). Remaining CaO^1 becomes CaO^2. If $P_2O_5 = 0$, go to (8).

(7) If $CaO^2 > 0$, go to (8). If $CaO^2 = 0$, go to (9).

(8) Form the anorthite/epidote pair using for partitioning the MIA values, and then go to (9). Remaining SiO_2, Al_2O_3, and H_2O become SiO_2^1, $Al_2O_3^1$, and H_2O^1, respectively.

(9) If $FeO > 0$, form ilmenite and then go to (10). Remaining FeO and TiO_2 become FeO^1 and TiO_2^1, respectively. If $FeO = 0$, go to (11).

Certain analytical techniques do not distinguish between the ferric and ferrous iron content. Because their proportions have an important effect on the norm calculations, the program provides two different ways of allocating the iron:

(a) If the FeO and Fe_2O_3 values are reported in the chemical analyses, the program uses these values as entered.

(b) The second procedure can be used only if the weathering profile is considered as a closed system. FeO and Fe_2O_3 are initially recalculated following the method used for unaltered rocks suggested by Irvine and Baragar (1971):

$$FeO^* = (0.863 \times Fe_2O_3T) - 0.0065 \qquad (3)$$

$$Fe_2O_3^* = (0.152 \times Fe_2O_3T) - 0.0073 \qquad (4)$$

where FeO^* and $Fe_2O_3^*$ represent the iron content in the hypothetical unaltered protolith. Further, the following equations are used in order to allocate the iron:

$$FeO = FeO^* \times (100 - MIA)/100 \qquad (5)$$

$$Fe_2O_3 = (FeO^* - FeO) + Fe_2O_3^* \qquad (6)$$

These equations have been tested on hundreds of published chemical analyses of the weathering profiles, with both FeO and Fe_2O_3 reported. The differences between calculated and reported contents do not exceed 2%.

(10) Form magnetite from FeO^1 and Fe_2O_3 and go to (11). Remaining Fe_2O_3 becomes $Fe_2O_3^1$.

(11) Form anatase from TiO_2^1 and go to (12).

(12) Form the orthoclase/sericite pair from K_2O, SiO_2^1, $Al_2O_3^1$, and H_2O^1 using the MIA values and go to (13). Remaining oxides become SiO_2^2, $Al_2O_3^2$, and H_2O^2.

(13) Form the pyroxene/chlorite pair from MgO, SiO_2^2, $Al_2O_3^2$, and H_2O^2 using the MIA values and go to (14). Remaining oxides become SiO_2^3, $Al_2O_3^3$, and H_2O^3.

(14) Form the albite/montmorillonite pair from Na_2O, SiO_2^3, $Al_2O_3^3$, and H_2O^3, using the MIA values and go to (15). Remaining oxides become SiO_2^4, $Al_2O_3^4$, and H_2O^4.

(15) Form pyrolusite and go to (16).

(16) Form Al-goethite from $Fe_2O_3^1$, $Al_2O_3^4$ and H_2O^4, and go to (17). Remaining oxides become $Fe_2O_3^2$, $Al_2O_3^5$, and H_2O^5.

(17) Form hematite from $Fe_2O_3^2$ and go to (18).

Hematite forms only when $Fe_2O_3^2$ is in excess relative to H_2O^5 after the Al-goethite formation. It is usually the case of the ferruginous laterite profiles, where the iron content is relatively high in relation to the water content.

(18) Form kaolinite from SiO_2^4, $Al_2O_3^5$, and H_2O^5 and go to (19). Remaining oxides become SiO_2^5, $Al_2O_3^6$, and H_2O^6.

Kaolinite forms until one of the three oxides is entirely consumed. For the bauxitic laterite, characterized by weak silica content, SiO_2 is the first entirely consumed oxide. For the ferruginous laterite, the water is first consumed due to the important quantity used in the Al-goethite calculation. For the saprolite and the siliceous/calcareous laterite, any of these oxides may be first totally used.

(19) If $Al_2O_3^6 \leqslant H_2O^6$, form boehmite and return to (16). Cancel the normative goethite and kaolinite and go to (17). Form hematite and go to (19). Recalculate the normative boehmite and go to (21). Remaining H_2O becomes $H_2O^7_{(Bhm)}$. If $Al_2O_3^6 > H_2O^6$, go to (20).

As mentioned earlier, boehmitic profiles of the bauxitic laterites are characterized by the lack of kaolinite and the exclusive presence of hematite, instead of the Al-goethite-hematite association described in the gibbsitic profiles. The procedure used in (19) allocates all available iron to hematite when the alumina/water ratio allows boehmite formation.

(20) Form gibbsite and go to (21). Remaining oxides become $Al_2O_3^7$ and $H_2O^7_{(Gbs)}$.

(21) Form amorphous silica from SiO_2^5 and $H_2O^7_{(Bhm)}$ or from SiO_2^5 and $H_2O^7_{(Gbs)}$ and go to (22). Remaining silica becomes SiO_2^6.

(22) Form corundum from $Al_2O_3^7$ and go to (23).

(23) Form quartz from SiO_2^6.

(24) Calculate the normative weight percents by multiplying the molecular proportions of each mineral by its molecular weight.

The MINNOR program description

MINNOR is a WINDOWS application written in Visual Basic for IBM-compatible computers. The

TABLE 2. Comparison between the normative mineral calculations for bauxitic laterite from Fongo Tongo deposit, Cameroon, using the method of Nyobe (1991) and MINNOR

Minerals	Ab	Ant	An	Ap	Bhm	Cal	Chl	Crn	Gbs	Al-Gt[†]	Hem	Ilm	Kln	Mag	Mnt	Or	Pyt	Qtz	Ser	Sil	Ep	Px
Sample																						
1*	0.00	1.76	0.00	nc	nc	nc	0.00	1.94	78.31	12.71	nc	nc	4.39	nc	nc	nc	0.00	0.00	nc	nc	nc	nc
1**	0.00	1.72	0.00	0.15	0.00	0.00	0.43	0.49	78.40	11.88	2.28	0.06	3.53	0.00	0.15	0.00	0.04	0.00	0.25	0.00	0.13	0.00
2*	0.00	1.82	0.00	nc	nc	nc	0.56	0.00	78.31	10.02	nc	nc	8.78	nc	nc	nc	0.00	0.00	nc	nc	nc	nc
2**	0.00	1.80	0.00	0.10	0.00	0.00	0.68	0.00	76.62	9.49	1.82	0.02	8.23	0.00	0.07	0.00	0.05	0.00	0.25	0.00	0.08	0.00
3*	0.52	1.19	0.00	nc	nc	nc	0.00	4.79	80.65	5.52	nc	nc	7.22	nc	nc	nc	0.00	0.00	nc	nc	nc	nc
3**	0.00	1.17	0.00	0.06	0.00	0.00	0.32	4.13	80.65	5.15	0.98	0.02	6.78	0.00	0.38	0.00	0.02	0.00	0.33	0.00	0.08	0.00
4*	0.00	1.84	0.00	nc	nc	nc	0.00	4.08	80.96	7.35	nc	nc	4.90	nc	nc	nc	0.00	0.00	nc	nc	nc	nc
4**	0.00	1.84	0.00	0.03	0.00	0.00	0.46	3.27	81.02	7.24	1.39	0.00	4.28	0.00	0.15	0.00	0.02	0.00	0.08	0.00	0.02	0.00
5*	0.00	1.84	0.00	nc	nc	nc	0.00	0.92	80.65	9.13	nc	nc	6.97	nc	nc	nc	0.09	0.00	nc	nc	nc	nc
5**	0.00	1.82	0.00	0.03	0.00	0.00	0.49	0.00	80.51	8.56	1.64	0.02	6.25	0.00	0.15	0.00	0.10	0.00	0.25	0.00	0.02	0.00
6*	0.00	1.61	0.00	nc	nc	nc	0.00	3.06	81.74	8.01	nc	nc	4.90	nc	nc	nc	0.00	0.00	nc	nc	nc	nc
6**	0.00	1.59	0.00	0.03	0.00	0.00	0.33	2.20	81.82	7.59	1.45	0.02	4.25	0.00	0.15	0.00	0.04	0.00	0.16	0.00	0.02	0.00
7*	0.00	1.26	0.00	nc	nc	nc	0.00	4.08	73.94	14.95	nc	nc	5.93	nc	nc	nc	0.18	0.00	nc	nc	nc	nc
7**	0.00	1.23	0.00	0.03	0.00	0.00	0.27	2.43	74.07	13.57	2.60	0.04	5.26	0.00	0.07	0.00	0.14	0.00	0.25	0.00	0.02	0.00
8*	0.00	1.13	0.00	nc	nc	nc	0.00	6.12	56.16	12.64	nc	nc	22.70	nc	nc	nc	0.18	0.00	nc	nc	nc	nc
8**	0.00	1.11	0.00	0.03	0.00	0.00	0.33	4.66	56.31	11.90	2.28	0.02	21.93	0.00	0.07	0.00	0.17	0.00	0.25	0.00	0.02	0.00

nc = not considered
† = Al-goethite has been calculated by Nyobe (1991) as goethite
* = normative minerals using the method of Nyobe (1991)
** = normative minerals using MINNOR

program requires Microsoft WINDOWS 3.1x and runs from the hard-disk. It can be installed using Setup.exe command. The program allows a user to create a file by clicking the 'Create File' button. The user must give a file name (which automatically registers with the .TRS suffix) and the number of analysed samples. The program opens a table with a number of rows equal to the number of samples. The table contains sample name and twelve major oxides. For the calculation of calcite, CO_2 values are requested. If both FeO and Fe_2O_3 are analysed, and FeO=0, the user must enter 0.01 in order to avoid the allocating of iron. Missing analytical data for one or more oxides do not affect the program running but, given the interdependence of variables in normative calculations, the results obtained are erroneous. The file can be saved using the 'Save File' button. The 'Close' button closes the file without saving it.

In order to see or to add more analysed samples in an already existing file, the user must click the 'Open File' button.

The 'Run using...' button allows the user to perform mineralogical norm calculations. The user must choose the file (from hard-disk or floppy-disk) and, after clicking the 'Open File' button, the program plots the percentages of the normative minerals from the first sample. By clicking 'Forwards' and 'Backwards' buttons, the user can see the mineralogical norm for each sample of the file. By clicking the downpage buttons, the program plots histograms for each normative mineral from all samples of the file.

Applications

In order to test the program, three different types of tropically weathered profiles have been choosen: a bauxitic laterite deposit from Cameroon (Nyobe, 1991), a ferruginous laterite profile from Burkina Faso (Boeglin and Mazaltarim, 1989) and a complete weathered profile from Omai, Guyana (Voicu and Bardoux, 1995).

Bauxitic laterite deposit. The chemical analyses of eight bauxitic laterite samples (data from Nyobe, 1991) are stored in the Cameroon.trs file. Because the iron is reported as Fe_2O_3 total, the program has automatically allocated the iron content between Fe_2O_3 and FeO. CO_2 has not been analysed. The comparison between the results obtained for the normative minerals using MINNOR and chemical calculations of Nyobe (1991) are presented in Table 2. The two methods give similar results, but the calculations using MINNOR are developed for a wider range of normative mineral phases. The normative mineral assemblages are constrained by qualitative modal estimates obtained by X-ray powder diffraction.

Ferruginous lateritic profile. The mean values of 224 chemical analyses (Boeglin and Mazaltarim, 1989) of ironstones of the Gaoua area in Burkina Faso are stored in the Burkina.trs file. Because the iron content is reported as Fe_2O_3 total, the program has allocated the iron using the equations (3)–(6). The mineralogical composition of each sample has been determined by X-ray powder diffraction. The

TABLE 3. Comparison between the mineralogical compositions of ironstones of the Gaoua area in Burkina Faso determined by semi-quantitative XRD method and normative mineralogical compositions using MINNOR

Samples Minerals (in wt.%)	20–25% (n = 1)	25–30% (n = 5)	30–35% (n = 19)	35–40% (n = 25)	40–45% (n = 48)	45–50% (n = 76)	50–55% (n = 43)	55–60% (n = 7)
Qtz*	51	42	37	25	17	11	6	3
Qtz+Sil**	52.05	41.96	37.93	26.26	19.27	13.39	7.45	4.02
Kln*	22	26	26	30	32	33	34	31
Kln**	18.42	20.21	20.78	26.14	27.53	28.78	28.37	27.03
Gt+Hem*	27	32	38	43	49	55	59	66
Al-Gt+Hem+Mag**	27.23	31.82	46.26	42.47	47.96	53.03	57.44	61.27
Gbs*	0	0	0	2	1	1	0	0
Gbs**	0	0	0	0	0	0	0	0

Sample names represent their iron content

n = number of analysed samples

* = mineralogical composition determined by semi-quantitative XRD method (data from Boeglin and Mazaltarim, 1989, Table III). Only the principal mineralogical phases are determined

** = normative mineralogical composition using MINNOR. Only the same minerals determined by XRD method are shown.

TABLE 4. Whole-rock chemical analyses for the weathering profile from Omai, Guyana

Sample Oxides	S2 Saprolite	S6 Saprolite	702 Saprolite	738 Saprolite	1423 Mottled clay zone	3432 Mottled clay zone	1cw Mottled clay zone	1dw Siliceous duricrust	1aw Pisolith
SiO_2	70.21	51.36	45.70	69.30	48.86	56.67	56.20	61.34	65.88
TiO_2	1.28	1.27	2.32	0.62	1.89	1.16	1.72	0.86	1.38
Al_2O_3	19.85	19.71	33.88	19.92	33.12	18.59	27.92	10.71	20.63
Fe_2O_3	0.65	17.98	4.52	1.44	2.78	11.09	2.01	22.29	4.51
FeO	0.17	0.35	0.01	0.42	0.05	2.40	0.06	0.21	0.01
MgO	0.13	0.13	0.07	0.14	0.07	1.45	0.10	0.00	0.01
CaO	0.21	0.15	0.01	0.01	0.00	0.13	0.00	0.00	0.02
Na_2O	2.35	0.07	0.05	0.25	0.05	1.42	0.02	0.00	0.02
K_2O	0.30	0.01	0.02	2.81	0.34	0.63	0.51	0.06	0.24
MnO	0.01	0.06	0.01	0.01	0.01	0.02	0.01	0.01	0.01
P_2O_5	0.02	0.03	0.07	0.02	0.05	0.08	0.06	0.09	0.05
H_2O	4.25	9.80	13.91	5.25	13.03	6.53	11.25	5.22	7.80
CO_2	na	na	na	na	na	na	na	na	na
Total	99.55	100.79	100.65	100.27	100.33	100.15	100.77	100.82	100.77
MIA	74.81	97.69	99.58	73.29	97.61	79.00	96.27	98.88	97.32

na = not analysed
MIA = mineralogical index of alteration, calculated using equation (2) (see text)
FeO calculated using the equations (3)−(6) (see text).

TABLE 5. Mineralogical norm for the weathering profile from Omai, Guyana

Sample Minerals	S2 Saprolite	S6 Saprolite	702 Saprolite	738 Saprolite	1423 Mottled clay zone	3432 Mottled clay zone	1cw Mottled clay zone	1dw Siliceous duricrust	1aw Pisolith
Ab	5.00	0.01	0.00	0.56	0.01	2.52	0.00	0.00	0.00
Ant	1.09	0.88	2.30	0.14	1.83	0.00	1.65	0.62	1.26
An	0.26	0.01	0.00	0.01	0.00	0.13	0.00	0.00	0.00
Ap	0.02	0.04	0.00	0.02	0.03	0.11	0.00	0.00	0.06
Bhm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chl	0.26	0.34	0.19	0.28	0.18	3.15	0.26	0.00	0.02
Crn	4.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gbs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al-Gt	0.67	18.71	4.70	1.49	2.89	8.40	2.09	17.12	4.69
Hem	0.12	3.59	0.90	0.28	0.55	1.61	0.40	9.12	0.90
Ilm	0.35	0.73	0.02	0.88	0.01	2.20	0.12	0.44	0.21
Kln	25.33	43.01	83.83	29.75	79.85	32.12	65.72	21.29	48.65
Mag	0.00	0.00	0.00	0.00	0.00	4.37	0.00	0.00	0.00
Mnt	13.68	0.53	0.38	1.42	0.37	8.73	0.14	0.00	0.15
Or	0.44	0.00	0.00	4.43	0.04	0.78	0.11	0.00	0.03
Pyt	0.01	0.05	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Qtz	44.79	24.93	0.73	43.04	5.33	29.73	18.01	49.95	40.81
Ser	1.89	0.08	0.16	17.42	2.80	4.20	4.15	0.50	1.97
Sil	0.00	7.34	7.21	0.26	6.14	0.89	7.07	1.61	1.76
Ep	0.42	0.39	0.00	0.01	0.02	0.27	0.00	0.00	0.05
Px	0.08	0.00	0.00	0.09	0.00	0.75	0.00	0.00	0.00
Total	99.21	100.72	100.48	100.16	100.22	100.05	99.79	100.69	100.63

peak characteristics have allowed a quantitative estimation of the principal ironstone-forming minerals. Accessory minerals have not been considered. The comparison between the quantitative composition determined by XRD of the principal minerals and the same minerals using the normative calculations is presented in Table 3. The results obtained by these two different approaches are similar. It should be noted that the composition of all normative minerals is within the standard deviation limits reported by Boeglin and Mazaltarim (1989).

Complete weathered profile. Nine selected whole-rock chemical analyses of all distinctive horizons of the weathering profile from Omai, Guyana, South America (Voicu and Bardoux, 1995; Voicu et al., 1996) are shown in Table 4. They are stored in the Guyana.trs file. The iron, reported as Fe_2O_3 total, has been partitioned between the two iron oxides. CO_2 content has not been determined. The weathering norm (WN) for each sample is presented in Table 5. Mineralogical norm values are concordant with the semi-quantitative XRD determinations. Normative mineral histograms plotted with MINNOR for goethite, kaolinite, sericite and quartz are shown in Fig. 1. The variation of the normative mineralogy observed in the same horizon or between the different horizons of the weathering profile suggests that the supergene alteration processes have been greatly influenced by the protolith composition and by locally enhanced permeability created by structural discontinuities including faults joints and lithologic contacts. These discrete structures, frequently ob-
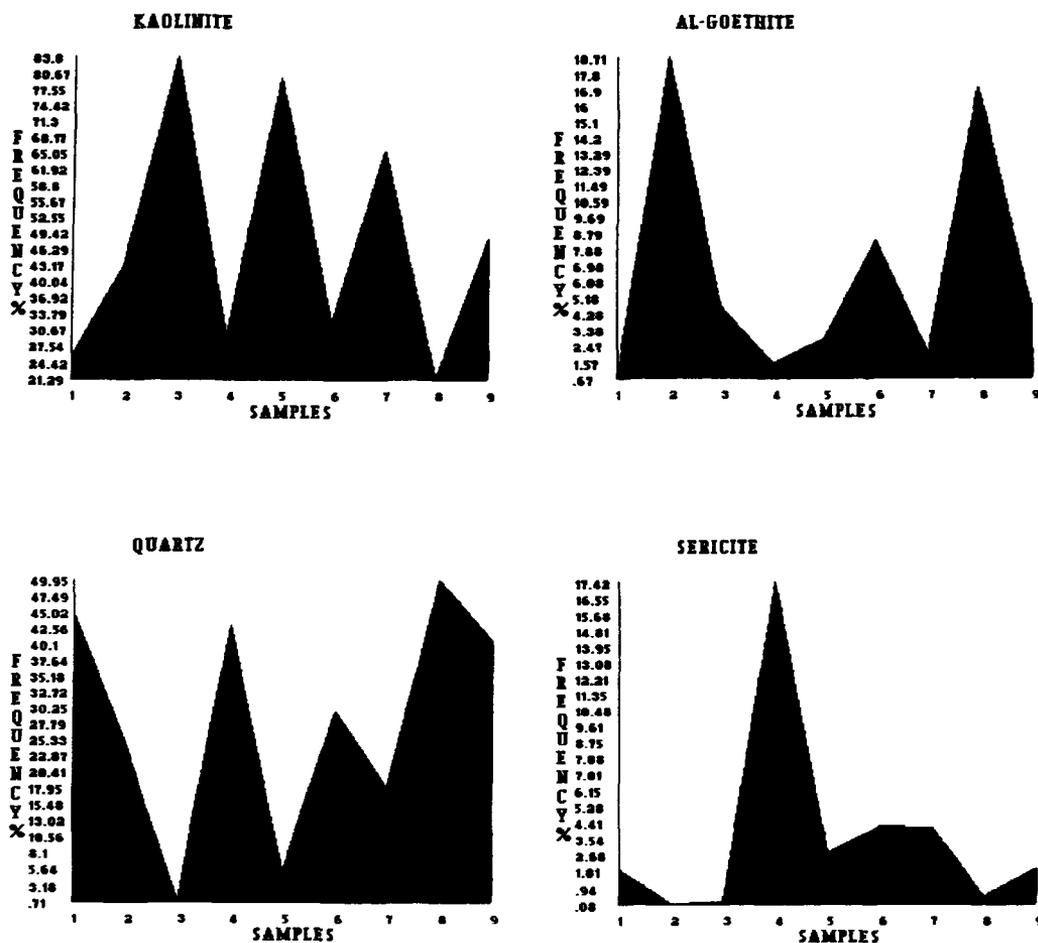
FIG. 1. Frequency histograms for the Omai samples of kaolinite, Al-goethite, quartz and sericite. Data are plotted using the MINNOR program. The sample order is the same as in Tables 4 and 5.

servable at Omai, may initially weather and erode rapidly, creating favourable conditions to focus meteoric waters and to become zones of sesquioxide accumulation and induration. Sample S6 is such an example. On the other hand, some local zones are depleted in Fe oxy-hydroxides but enriched in other chemical elements (samples S2, 702, 738). For the mottled clay zone, the normative mineralogical composition reflects the variations of the argillaceous matrix/ ferrugineous spot ratio and the presence of weathered quartz veins. The result is a wide range in the mineralogical composition of this horizon. The mineralogical composition of the analysed pisolith (sample 1aw) may help to define its formation. Low normative Al-goethite/hematite and high normative quartz and kaolinite content means that only a thin cortex is formed by Fe oxy-hydroxides which have precipitated from aqueous solutions around a central nucleus represented by a probably residual quartz grain and Al—Si-rich material.

Conclusions

A new petrochemical calculation algorithm is proposed for the conversion of the whole-rock chemical analyses into specific minerals of the tropically weathered terrains. The algorithm can be used on several types of lateritic profiles. The minerals used in calculations have been selected on the basis of published mineralogical data from the weathering profiles of the intertropical belt (South America, Africa, Australia, and Southern Asia). This algorithm has been used in MINNOR, a user-friendly application for WINDOWS, which performs the weathering norm (WN) calculations and plots histograms for each normative mineral from the analysed samples. The MINNOR program is available for distribution free to interested users; those desiring copies are asked to send one formatted 3.5" disk to the first author.

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