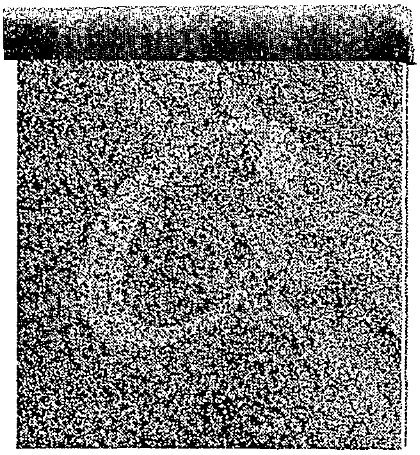

PETROLOGICAL AND GEOCHEMICAL CLASSIFICATION OF LATERITES

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Abstract

In this classification of lateritic covers four major types are distinguished: ferricretes, latosols, conakrytes and bauxites.

In ferricretes, hematite is associated with kaolinite, forming mottles, nodules and metanodules. When, at the top of profiles, goethite and sometimes gibbsite develop at the expense of hematite and kaolinite, protopisolitic and pisolitic dismantling facies are formed. Ferricretes, in which hematite and kaolinite form concretions, are widespread and are the most common iron accumulations.

Latosols are soft lateritic covers with a microglaebular structure. Red latosols, like ferricretes, are essentially formed by an association of hematite and kaolinite, but with larger proportions of goethite and with the presence of gibbsite.

Lateritic bauxites are concentrations of aluminium with which iron is very often associated. Four major types of lateritic bauxites: protobauxites, orthobauxites, metabauxites and cryptobauxites are defined as a function of the nature of iron and aluminium minerals as well as their relative distributions in profiles.

Protobauxites are lateritic soils where gibbsite and goethite form together under very humid climates. Orthobauxites are allites or alferrites, rich in gibbsite and red in colour, which do not exhibit a concretionary structure. Iron may be concentrated in hard caps called conakrytes and located close to the top of the bauxitic profiles. Conakrytes are reticular and non nodular ferrites or ferrallites in which hematite and goethite dominate and where gibbsite could be present in small proportions. The presence of kaolinite at the bottom of the profiles is not necessary. Metabauxites are boehmitic and show a concretionary or pisolitic structure; iron is dissociated from aluminium and is frequently concentrated as hematite in a kaolinitic ferricrete located at the bottom of the bauxitic profile. Kaolinite always appears at the bottom of metabauxite profiles and less frequently at the base of orthobauxites. In cryptobauxites, kaolinite is abundant at the top and at the bottom of the profiles so that the gibbsitic layer is embedded between two kaolinitic horizons.

This petrological and geochemical classification of laterites is based on reactions of hydration–dehydration and of silication–desilication regulated by temperature, water activity and chemical composition of the parent material. Lateritic bauxites, ferricretes and latosols are witnesses of the succession of paleoclimates throughout the last 150 million years, since the Atlantic opening.

Keywords: laterites, ferricretes, latosols, conakrytes, bauxites, hematite, goethite, kaolinite, gibbsite, boehmite

INTRODUCTION

Bauxites (massive or pisolitic, and often indurated), conakrytes (massive or reticulated and often indurated), latosols (soft and microglaebular) and ferricretes (nodular and always indurated) are lateritic covers, widely distributed in North and South America, in West, Central and East Africa, as well as in Australia, India and South East Asia. These laterites form under tropical climates depending on rainfall, temperature, length of the dry season and on the nature of the parent material. Their geographic distribution is larger than the latitudinal zones of climates under which they normally form or develop. Almost all of them are very old: some are fossil, others are still active, but most of them are polygenic.

Some bauxites formed under humid conditions and later evolving under a drier climate, may generate ferricretes localised at the bottom of profiles, while ferricretes formed under seasonally contrasted climate, later evolving under wetter conditions may generate a new bauxitic horizon within a soft kaolinic latosol (Tardy *et al.*, 1991; Tardy and Roquin, 1992; Tardy, 1993).

CLASSIFICATION OF IRON-RICH LATERITES

Tardy (1993) distinguishes two mechanisms of iron accumulation: concretion and excretion as well as four kinds of iron-rich lateritic formations: (i) mottled horizon and nodular ferricretes, (ii) microglaebular latosol, (iii) conakrytes of massive structures and (iv) plinthites and petroplinthites.

Ferricretes: nodular iron-rich accumulations

Ferricretes or 'cuirasses ferrugineuses' *stricto sensu* are indurated iron concentrations, showing generally a noticeable nodulation. The words ferricrete, calcrete and silcrete are formed like concretion with 'the formant crete' which etymologically comes from Latin *con-crescere* signifying to cement or to grow together. Although these features may exhibit a concentric structure (Pettijohn, 1957) the definition of concretions does not include that they are concentric as proposed by Brewer (1964) but are only indurated or cemented accumulations. Concretion also designates the mechanism of cementation and induration, by centripetal accumulation of material, in pores of small size (Tardy, 1993). In ferricretes, the mechanism of concretion leads to the formation of indurated nodules by accumulation of hematite in the very fine porosity developed by kaolinite crystal assemblages.

In a sequence of ferricrete development from mottles (diffuse accumulations) to subnodules (nodules with diffuse edges), nodules (with distinct edges), and to metanodules (anastomosed), iron content increases, quartz content decreases drastically, while kaolinite content decreases slowly or even increases moderately. In mottles goethite dominates hematite, but in well developed nodules the contrary is observed. The ratio hematite/ (hematite + goethite) increases from the mottled zone to the ferricrete zone.

Concretion and nodulation, the fundamental process of ferricrete formation, is based on the association of hematite and finely crystallised kaolinite.

Compared to hematite (Fe_2O_3), goethite is hydrated ($Fe_2O_3.H_2O$). Gibbsite ($Al_2O_3.3H_2O$) is more hydrated than kaolinite ($SiO_2.Al_2O_3.2H_2O$). The stability of hematite–kaolinite nodules is ensured as long as hematite and kaolinite are stable, i.e. they are not rehydrated or desilicated.

Tardy (1993) has shown that this association of dehydrated or poorly hydrated minerals is very stable and develops under tropical climates with a long dry season. This paragenesis hematite–kaolinite, when previously formed under contrasted tropical climates, is even stabilised in more arid conditions. In contrast, nodules of hematite and kaolinite are destabilised in humid tropical conditions, particularly under the great equatorial forest (Beauvais and Tardy, 1991).

Latosol: a microglaebular iron-rich laterite

Beauvais (1991) and Beauvais and Tardy (1991) have shown that, under a humid climate, the transformation of a ferricrete into a microglaebular latosol corresponds to the transformation of a part of kaolinite into gibbsite by desilication and hydration, and to the transformation of hematite into goethite by hydration. During this process, the size of nodules is reduced and they are transformed into microglaebules.

Tardy and Roquin (1992) and Tardy (1993) have delineated the climatic limits of formation of latosols and ferricrete by taking into account their distribution in both Brazil and Africa.

Finally, ferricretes form under tropical climates which are warm, humid and seasonally contrasted ($T \simeq 25°C$; $1100 < P < 1700$ mm y^{-1}).

An increase in humidity to above 1700 mm y^{-1} or a decrease of temperature to below 25°C act in favour of the dismantling of ferricretes and their transformation into latosols (Tardy and Roquin, 1992).

Conakrytes: massive and non-nodular iron accumulations

There are non aluminous iron accumulations which develop from non aluminous parent rocks, such as dunites, similar to those described by Bonifas (1959), in Conakry (Guinea). They are widely distributed lateritic products formed by weathering of ultramafic rocks and are characterised by massive or crystalliplasmic structures and the absence of concretions or nodules. Consequently they cannot be called ferricretes even if indurated. They were called *conakrytes* (Tardy, 1993)

Orthobauxitic profiles (discussed later) are very often capped by ferruginous hardcaps (Grubb, 1971) which were improperly named laterites by Balasubramanian *et al.* (1987). As in Mali (Tardy, 1993), these ferruginous horizons are often gibbsitic and of massive structure and, consequently, do not exhibit concretions. The absence of concretion is due to the fact that under very humid climates gibbsite forms instead of kaolinite. Hardcaps are not ferricretes in the sense of Nahon (1976) but aluminous conakrytes associated with ferruginous bauxites.

Plinthite: a cutanic and reticular iron-rich laterite?

Camargo *et al.* (1988), in the Brazilian soil classification, referring to the FAO soil classification (FAO-UNESCO, 1975), and numerous other researchers describe a plinthite as an iron accumulation showing laminar, reticular or polygonal organisation. An iron accumulation principally characterised by mottles or nodules, which result from concretion, must be classified as a mottled horizon (soft material) or a ferricrete (hardened material).

Consequently, if the reading of the term reticular is correct, an iron accumulation characterised by iron-rich reticular cutans more abundant than nodules may be classified as a plinthite (soft material) or petroplinthite (hardened material). The first should correspond to a gley, the second should correspond to a pseudo-gley.

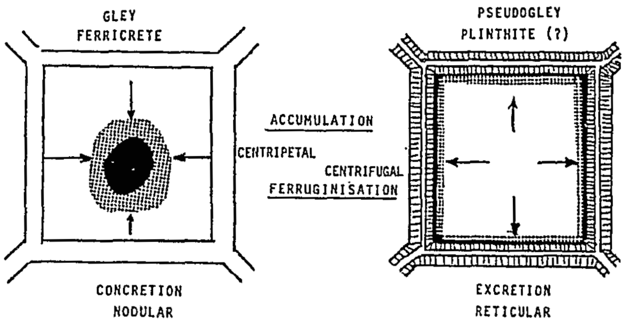

Fig. 1 Concretion (mottle and nodule formation) versus excretion (cutan formation): two processes of iron accumulation which may allow, if acceptable, the distinction of ferricretes from plinthites. (from Tardy, 1993).

Tardy (1993) has shown that what he called *excretion* and *incrustation,* which appear as cutanic accumulations, have to be clearly distinguished and separated from *concretions.* A cutan of excretion results from a centrifugal transfer of the argillaceous matrix with a porosity of small size towards the voids and the porosity of large size. A cutan of incrustation results in a transfer of matter which goes from voids and the porosity of large size towards the soil matrix. *Excretion* and *concretion* are opposite with respect to features (cutan versus nodule) and to processes (centrifugal versus centripetal). *Excretion* and *incrustation* are similar with respect to features (cutans in both cases) but are of opposite polarity (centrifugal versus centripetal). *Incrustation* and *concretion* are opposite with respect to feature (cutan versus nodule) but similar with respect to the polarity of processes (centripetal towards the porosity of fine size). The process of excretion corresponds to the leaching of iron from kaolinitic domains and to the cutanic accumulation of hematite in the voids. Excretion is clearly distinguished from concretion which corresponds to a leaching in domains close to the voids and an accumulation of hematite in domains rich in kaolinite.

Obviously this distinction was not taken into consideration so that plinthite and ferricrete are both indistinctly used to designate all kinds of iron accumulations. It is suggested here that plinthites and petroplinthites, defined as iron cutanic and reticular accumulations resulting from a process of excretion, have to be clearly separated from mottled horizons and ferricretes which are iron accumulations resulting from a process of concretion (Fig. 1). Climates of development are distinct. Mechanisms of formation are different.

CLASSIFICATION OF LATERITIC BAUXITES

The bauxitisation of very thick lateritic profiles is slow, requiring millions to tens of millions of years to form. This is the reason why bauxitic profiles have been evolving under different types of climatic and morphological situations which do not necessarily correspond to their conditions of formation.

Protobauxites

Protobauxite is the name of a gibbsitic soil that could be considered as the precursor of a lateritic bauxite. It is rather difficult to determine with precision the time required for transformation and what is the type of soil which could be the precursor of thick bauxitic profiles. Tardy (1993) admitted that among the different types of oxisols (sols ferrallitiques, in the French classification) the most sensitive to bauxitisation are the red or the yellow oxisols in which gibbsite, goethite and hematite dominate and where kaolinite and quartz are, at least originally, subsidiary (Sieffermann, 1973).

Orthobauxites

The prefix *ortho* in Greek means normal. Orthobauxites are products of evolution of gibbsitic protobauxites, developed under an annual rainfall greater than 1700 mm y^{-1} (Tardy, 1993).

A typical orthobauxitic profile is made of three major horizons (Valeton, 1972, 1981; Aleva, 1979, 1981, 1982, 1989; Bardossy, 1989; Bardossy and Aleva, 1990). From the top to the bottom one finds:

- a ferruginous, hematitic and gibbsitic horizon, red in colour, located close to the surface;
- a bauxitic horizon, less coloured, less ferruginous and more aluminous, with gibbsite and hematite;
- an argillaceous horizon, rich in kaolinite, poorly ferruginous and red-yellow in colour.

Typical orthobauxitic profiles are those of Mounts Bakhuis, Surinam (Aleva, 1981), Jarrahdale in the Darling Range, Australia (Grubb, 1971), Mount Tato at Lakota in the Ivory Coast, Africa (Boulangé, 1983, 1984) and some profiles of Famansa in Mali, Africa (Tardy, 1993), which are of Cretaceous age (Michel, 1973).

There are two types of bauxites in Famansa: orthobauxites and metabauxites. The orthobauxites are homogeneously red, and do not exhibit nodules, concretions or pisolites. Over thicknesses of about 10 m they are constituted of gibbsite, hematite and goethite. From the bottom to the top of profiles, typical orthobauxites show an increase in iron (goethite and hematite) versus aluminium (gibbsite) content, an increase in the hematite/goethite ratio and a decrease in the content of quartz and kaolinite (Tardy, 1993).

An orthobauxite is dominantly gibbsitic in the thick intermediate horizon and does not show boehmite, pisolites or concretions. It is normally capped by a conakryte when developed from a ferruginous parent rock.

There are several orthobauxitic profiles which do not exhibit a kaolinitic layer at the base and where bauxite develops down to the contact with the unaltered parent rock. The volume and the architecture of the parent rock are preserved and that is the reason why Boulangé *et al.* (1973, 1975) and Boulangé (1984) call these formations isalteritic bauxites.

Cryptobauxites

In Amazonia, bauxites are widespread. Lucas *et al.* (1986) and Lucas (1989) have presented an interesting synthesis concerning the ore deposits of Juriti and Trombetas. The parent rocks are sandstones and argillites of Alter-do-Chão from the later Cretaceous or the early Tertiary (Daemon, 1975). All bauxitic profiles are capped by an argillaceous horizon, very rich in kaolinite and poor in quartz, called Clays of Belterra and considered by Sombroek (1966) and Tricart (1978) as a Quaternary sedimentary lacustrine formation; by Grubb (1979), Kotschoubey and Truckenbrodt (1981) as a Pliocene lacustrine or desertic deposit; and finally by Aleva (1981, 1989) as a sedimentary cover. Chauvel *et al.* (1982) and Lucas *et al.* (1984) first called attention to a pedogenetic origin, while Tardy (1993) proposed that the pedogenetic phase takes place in a biogenic formation. The peculiarity of this type of bauxite comes from the fact that a gibbsitic horizon is interbedded between two kaolinite-rich horizons.

It is also interesting to remark that hematite is associated with gibbsite in the bauxitic horizon while goethite is the iron mineral dominant in the superficial layer. We agree with Lucas (1989) that bauxites of Amazonia are polygenic. They are similar to gibbsitic soils of Cameroon such as those described by Muller (1987). Both were considered by Tardy (1993) to be ancient ferricretes, formed under seasonally contrasted tropical climates and later dismantled under a more humid tropical climate. Gibbsite forms in place of the ancient ferricrete, and continues to develop in situ, close to the water table (Lucas, 1989) but below a thick kaolinic soft horizon, so that the bauxite layer is called cryptobauxite. This peculiar distribution implies a strong necessity of supplying silica from the lower to the upper part of the profile. Several biological processes can be responsible for that: termites (Truckenbrodt *et al.*, 1991) or phytolites (Lucas *et al.*, 1993). Cryptobauxites are common in equatorial forests and, if really polygenic, characterise a paleoclimatic succession which has been moving from arid to humid. The opposite is observed for the metabauxite evolution.

Metabauxites

Metabauxites are orthobauxites, initially formed under a tropical humid climate and later transformed under warmer and drier climates. *Meta* in Greek means which comes later. Metabauxites are diagenetised bauxites (Tardy, 1993).

Typical metabauxite profiles

Some of the most typical profiles that we can classify as metabauxites, are those of Weipa and Pera Head, in the Cape York Peninsula, N.E. Australia. They were described by Loughnan and Bayliss (1961) and Loughnan (1969). Over a thickness of 10 m, a quartz–argillaceous sandstone is transformed into an aluminium-rich bauxite. From the bottom to the top of the profile, quartz and kaolinite, always present, diminish while gibbsite and boehmite increase. In the lower part, goethite dominates while in the higher part, hematite becomes the dominant iron mineral.

The metabauxite profile of Famansa in South Mali was described by Tardy (1993). This so-called white bauxite profile exhibits, over 10 m of thickness, an increase in aluminium, gibbsite and boehmite and a decrease in silicon towards the profile surface. The three ratios boehmite/(boehmite + gibbsite), hematite/(hematite + goethite) and gibbsite/(gibbsite + kaolinite) rise constantly from the bottom to the top of the profile. In this profile, iron does not accumulate in the superficial horizon but at depth, between 6 and 8 m, forming a typical kaolinite–hematite rich nodular ferricrete.

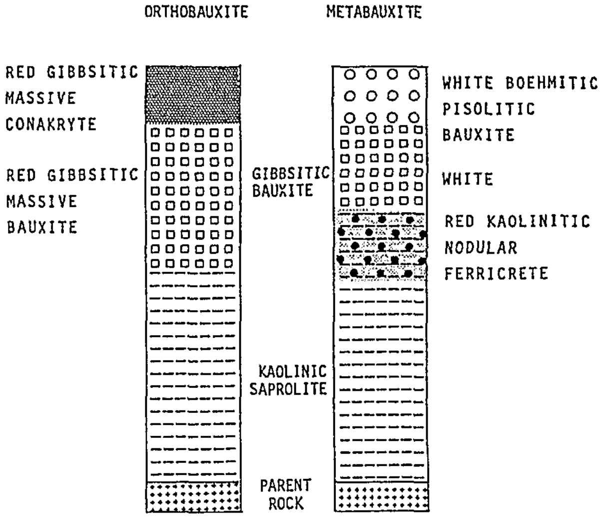

Fig. 2 Schematic distribution of boehmite, gibbsite, kaolinite and hematite in conakrytes associated with orthobauxites on one hand and in ferricretes associated with metabauxites on the other hand (from Tardy and Roquin, 1992; Tardy, 1993).

Metabauxites are deferruginised at the top but ferruginised at the bottom of profiles. The massive gibbsitic structure is replaced by a boehmitic, pisolitic structure. In orthobauxites, iron in hematite and aluminium in gibbsite are associated at the top of the profile forming conakrytes of massive structure. In metabauxites, at the surface of profiles, iron and aluminium in boehmitic pisolites separate, while in the ferricrete located at the bottom, iron in fine grained hematite and aluminium in kaolinite are again associated.

Regional metabauxitisation

Balkay and Bardossy (1967) first pointed out that the amounts of boehmite in bauxites of Western Africa, increase from the south to the north.

Seven regions were distinguished by Bourdeau (1991), who studied 3750 analyses of samples collected by Pechiney-Sarepa

Table 1 Elements of classification of iron and aluminium laterites

Name	Structure	Al	Fe	Hematite	Goethite	Gibbsite	Boehmite	Kaolinite
		(contents)		(size)		(contents)		
Conakryte	crystalliplasmic	poor	abundant	large	present	present	absent	absent
Ferricrete	nodular	moderate	abundant	very small	present	possible	absent	abundant
Orthobauxite	massive	abundant	moderate	large	present	abundant	absent	absent
Metabauxite	pisolitic	very rich	poor	very small	absent	present	abundant	present
Latosols	microglaebular	medium	medium	small	moderate	frequent	absent	abundant

Note that hematite is always present but in different sizes and gibbsite is always present but in different proportions

Table 2 Geochemical and mineralogical classification of laterites

Name	Geochemical process	Mineral constituents	Geochemical composition
Conakryte[1]	hydro-ferrallite	goethite, hematite, gibbsite	$Fe_2O_3.H_2O.Al_2O_3$
Conakryte[2]	ferrite	hematite, goethite	$Fe_2O_3.H_2O$
Ferricrete	xero-fersiallite	hematite, kaolinite	$Fe_2O_3.SiO_2.Al_2O_3.H_2O$
Orthobauxite	hydro-alferrite	gibbsite, goethite, hematite	$H_2O.Al_2O_3.Fe_2O_3$
Metabauxite	xero-allite	boehmite, hematite	$Al_2O_3.Fe_2O_3$
Red latosol	xero-sialferrite	kaolinite, hematite, goethite	$SiO_2.Al_2O_3.H_2O.Fe_2O_3$
Yellow latosol	hydro-sialferrite	goethite, kaolinite, gibbsite	$H_2O.Al_2O_3.SiO_2.Fe_2O_3$
Podzol	sillite	quartz	SiO_2

[1] conakrytes on aluminous rocks, [2] conakrytes on ultramafic rocks

in bauxites of Guinea and Mali: (I) Fouta Djalon in Guinea, (II) Balea, North of Guinea, (III) Bamako-West in South Mali, (IV) Falea, (V) Kenieba in South-West Mali, (VI) Koulikoro, West Mali and (VII) Bafoulabe North-West Mali. In each region, the upper or superficial and the lower horizon of the profile, were distinguished.

It is clear that from the south (humid) to the north (dry and hot) i.e. from the humid Guinea to the Sahara

water content diminishes;

- iron content decreases in the superficial horizon;
- in the deep horizon, iron content increases and aluminium decreases;
- gibbsite and goethite contents diminish, while hematite and boehmite increase;
- kaolinite content increases;
- the contrast between ratios: Al_2O_3/Fe_2O_3 in the upper horizon versus Al_2O_3/Fe_2O_3 in the lower horizon increases significantly.

From the south to the north, bauxites dehydrate, more so in the upper than in the lower horizon. Accompanying the dehydration process, a migration of iron proceeds from the top (conakryte) to the bottom of the profile (ferricrete) (Tardy, 1993) (Fig. 2).

CONCLUSION

Tables 1–3 summarise the elements of classification of iron-rich and aluminium-rich lateritic formations. They are conakrytes, ferricretes, orthobauxites, metabauxites and latosols. As well as the nature of the parent rock, climatic and paleoclimatic influences are major factors controlling the nature of laterites.

Aluminous conakrytes and orthobauxites are associated in humid conditions. Ferricretes form under seasonally contrasted climates. Ferricretes and metabauxites can be associated in semi-arid or arid conditions because metabauxites are ancient orthobauxites formed under humid climates and further dehydrated and deferruginised.

Hematite is less hydrated than goethite:

$$Fe_2O_3 + H_2O \rightarrow 2FeO(OH) \qquad (1)$$

Boehmite is less hydrated than gibbsite:

$$AlO(OH) + H_2O \rightarrow Al(OH)_3 \qquad (2)$$

and finally, kaolinite contains more Si but is less hydrated than gibbsite:

$$Al_2Si_2O_5(OH)_4 + 5H_2O \rightarrow 2Al(OH)_3 + 2H_4SiO_4 \qquad (3)$$

Reactions of hydration–dehydration and silication–desilication are the processes of laterite climatic formation and paleoclimatic evolution. Dehydration favours concretion and formation of nodules while hydration favours excretion and development of crystalliplasmic structures. In ferricretes hydration of hematite into goethite favours the dismantling of previously formed nodules. In contrast, hydration of bauxites, favours the induration of crystalliplasmas of gibbsite. Dehydration works in the

Table 3 Climatic conditions (H: humidity; T: temperature) and paleoclimatic evolution (H_1–H_2; T_1 –T_2) for controlling the laterite evolution

		Parameter		Paleoclimatic	Parameters			
	Tropical climate	H	T	evolution	H_1	H_2	T_1	T_2
Conakryte(1)	humid	medium	high	constantly humid tropical	>		>	
Conakryte(2)	undifferent.	—	—	undifferent.	—		—	
Ferricrete	tropical contrasted	high	medium	constantly contrasted	—		—	
Latosol	cool humid	high	medium	from contrasted to humid		/	\	
Orthobauxite	humid	high	medium	constantly humid	>		>	
Metabauxite	arid	low	very high	from humid to arid		\	/	
Cryptobauxite	humid	high	medium	from arid to humid		/	\	

[1] from ferrialuminous rocks; [2] from ultramafic rocks.
H_1, H_2: humidity stage 1 or 2; T_1, T_2: temperature stage 1 or 2.

direction of aggradation and induration. Hydration works in the direction of degradation and dismantling (Tardy, 1993).

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