SELECTED THOUGHTS ON 'LATERITE'

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Abstract: 'laterite' is a word that has come to mean almost anything the user decides. Its application ranges from strict conformity to Buchanan's original definition, to any outcrop of ferruginous rock. We first consider the meanings of the word and conclude its use be discontinued. We consider the ways that deeply weathered profiles with an iron-rich upper crust develop, using examples from Weipa, the Darling Ranges and Charters Towers. From this it is evident that while some ferruginous crusts are genetically related to their underlying weathering profiles others are not and thus the concept of a lateritic profile is flawed. The implications of three genetic models:

- seasonal tropical weathering profiles;
- lateral migration; and,
- valley bottom

for the development of ferruginous crusts ('laterite', ferricrete or bauxite) are discussed and the implications of each for landscape evolution and the age of ferruginisation considered. We conclude with, not a universal law of 'laterite', but rather better 'laterite' lore

This paper represents an opening salvo of what we hope will be an on-going discussion and clearing of the air regarding 'laterite' and other ferruginous materials.

Preamble

We hand you a piece of rock containing visible crystals of feldspar, quartz and biotite and ask, "What is it?" You reply, "granite", and we can all agree that it is indeed granite. We are using a common language and thus we can have meaningful communication.

We now hand you a piece of rock containing red-brown rounded bits cemented in a red-brown rusty looking stuff. "What is it?" we ask. One answers, "laterite", another answers 'ferricrete'.

We now hand you a rock composed of quartz grains and a few rounded red-brown lumps also cemented by red-brown rusty looking stuff. "What is this then?" "Ferricrete" one replies; 'laterite' says another. Next we are in the field together and come to a weathering profile consisting of rounded loose Fe-rich gravels over Fe-cemented Fe-rich gravels which lie on red and white mottled clays and sands that grade down into white clays and sands and eventually into fresh granite. The question arises, "What are we looking at here?" Many might answer "A laterite"

We are now confused. The rocks we showed you were cemented by Fe-rich material and yet some called it 'laterite' and others ferricrete, and when we examined the weathering profile some called this a 'laterite' also. Although we have been in the field together and looked at lots of rocks and outcrops we are obviously not communicating otherwise we would not be confused about what you mean when you use the word 'laterite'. Nor do we understand how 'laterite' and 'ferricrete' differ because they look similar

The difference between the materials lies not in them but in us. How we use these words depends on who taught us, where we study, our experience, and our beliefs. If we are to advance our science we must speak the same language. And that language must evoke the same or similar images of how these features may have come to be the way they are. For example, if we mention schist, you will immediately have a mental picture of a rock with metamorphic minerals and a well-developed schisosity. Not only that but your mind will also conjure images of regional metamorphism, pressures, temperatures and mineral growth by solid state diffusion. So the use of a word to describe a rock also carries genetic links, which we as geoscientists use to communicate whole sets of information and ideas

'Laterite' and 'lateritic profile' are words. But they convey different meanings and connotations to different professionals. Are they then useful words?

INTRODUCTION

This paper is the beginning of what we hope to be a series of articles raising issues with respect to the nature and origin of ferruginous regolith materials It is also designed to provide some insights to lessons learned by the authors as they have tussled with ferruginous problems

The confusion over whether 'laterite' refers to a material or a group of materials organised in a particular way derives from the misuse of a word originally coined to describe a material by extending its use to describe a profile in which this material commonly occurs in its type area, Kerala in southwestern India. In Australia many of these problems originate with the very good early work done in a geological environment very different from today's For example the, then modern, geomorphic ideas of Davis (1889) held sway for a long time and strongly influenced the work of Australian geologists like David, Jutson and Woolnough, who in turn influenced subsequent generations until about the late 1960's, and some still hold to those paradigms.

Additionally, because various authors have attributed particular genetic connotations to the occurrence of 'laterite profiles', further confusion has resulted regarding the geological meaning of 'laterite profiles'. This in turn has lead to confusion over the age and environments of formation of the profiles

In this paper we attempt to:

- throw some light on the use of the word 'laterite' to describe a material;
- comment on whether a 'lateritic profile' is the result of in situ weathering or otherwise;
- look briefly at ferruginous weathering materials at some localities; and,
- summarise the examples to evaluate some models for the genesis of ferruginous accumulations associated with weathering profiles in Australia.

The word 'laterite'

Buchanan (1807), to whom the term 'laterite' is attributed, described it as follows (from Ollier & Pain 1996):

> *"It is a diffused in great masses, without any appearance of stratification, and is placed over the granite that forms the basis of Malayala. It is full of cavities and pores, and contains a very large quantity of iron in the form of red and yellow ochres In the mass, while excluded from air, it is so soft that any iron instrument readily cuts it, and it is cut into square masses with a pick axe and immediately cut into the shape wanted with a trowel or large knife It soon becomes as hard as brick, and resists the air and water much better than any bricks. I have seen it in India."*

There is no doubt that if we accept the precedence of Buchanan the material called 'laterite' is a massive softish material containing diffuse hematite and goethite. There is little doubt that the idea of any ferruginised regolith material being called 'laterite' is not in keeping with precedent This does not however, make the term redundant, but simply restricts its use to soft materials containing diffuse Fe-oxides

Despite matters of precedent, the word 'laterite is used to describe almost any materials rich in Fe-oxides, particularly hard materials. There is however little consistency in its use For example, Anand (1997) uses 'laterite' to describe residual ferruginous materials and 'ferricrete' to indicate 'secondary' ferruginous materials The distinction being that the former is ferruginised in situ material while the latter is ferruginised transported material Pain et al. (1991) do not use the term at all, but rather use ferricrete to describe any Fe-oxide cemented regolith materials Hunt et al (1977) saw 'laterites' as pedological modifications of earlier Fe-rich zones of the underlying Mesozoic rocks. Hunt (1980) recommended the term 'laterite' no longer be used. Bourman (1995a, 1995b) is firmly of the opinion that 'laterite' is a term which has become redundant and he refers to all regolithic Fe-oxide cemented materials as ferricrete

The idea of 'laterite profiles' and laterisation

Buchanan (1807) described 'laterite' as being part of a weathering profile containing dispersed Fe-oxides overlying granite. We begin by using the expression 'lateritic profile' as a preliminary indication of the phenomenon of laterisation

'Lateritic profiles' have been described in Australia from many parts of the country. The aspects of these, which we include for the purposes of this discussion, are:

- with or without an uppermost, varyingly hard, Fe-oxide- and/or alumina-rich regolith which commonly has a pisolitic part;
- beneath this a region which has a patchy distribution of Fe-oxyhydroxides, commonly referred to as a mottled zone or mottled horizon;
- beneath this a region which is largely devoid of Fe-oxyhydroxides, and which commonly is clay-rich, referred to by some as a pallid zone or a bleached zone, and by others as a plasmic horizon;
- beneath this saprolite; and,
- beneath this rock

There is no presumption in this description of a regolith profile that the upper regions are alteration products of the lower region. Some (e.g. Milnes et al. 1985, Bourman et al. 1987, Ollier & Galloway 1990, Ollier & Pain 1996) suggest that rarely, if ever, is the ferruginous upper part conformable over the lower parts. Others (from Jutson 1914 and Walther 1915, 1916 to Anand et al. 1997) consider the upper regions to represent the deeply weathered equivalent of the underlying rocks.

THE OLD MASTERS

In 1914, Jutson defined 'laterite' as: A rock which usually forms in dry climates as a cap on the surface of other rocks generally containing iron. An essential constituent of laterites is an iron compound, but silica and other substances may be present.

Walther (1915, 1916) gives extensive descriptions and interpretations of 'laterite', including the Western Australian 'laterites'. His (1916) definition includes his recognition that:

> *"the primary laterite is not a rock but rather a weathering blanket."*

In his 1915 paper "Laterite in Western Australia" he wrote:

> *"The question arises first of all, what should be called "laterite"? Which rock was given the name by Buchanan in his time as the original rock can not be ascertained today - in any case Buchanan described it as "red clay used for brick production", and compared it to the "terra lapidea" of previous authors. Certainly he did not mean the hard iron crust of the overlying unit of the described profile. Considering the facts that white, yellow, violet-red mottled, red and brown-red plastic clays lie one upon another without sharp boundary in the laterite profiles I have investigated, it appears to me expedient to designate the whole phenomenon as laterisation (lateritisation is linguistically incorrect).*
>
> *The geological mappers of east India over the past 50 years have laid the emphasis on the surficial iron crust, and describe only this as laterite; later observers have repeatedly followed this interpretation - alone, I hold this diagnosis to be incorrect. It contradicts first of all the rule of priority, also it selects an admittedly frequent but by no means universal aspect of the laterite profile, and puts this so to the fore that numerous just as important and just as wide-spread elements of the fully described profile are not included in the definition."*

"The geological age and formation of laterite" followed this paper in (1916). In this he declares:

> *"Then the issue is: the primary laterite is not a rock but rather a weathering blanket."*

According to Walther:

> *"Foote [working in India] defined lateritic rocks in two groups. The high plain laterite ... is a primary weathering product and always occurs in its original position ... A hard iron crust from 1-2 metres thick, which is resistant to denudation, overlies red and red-mottled clays under which the coloured iron salts disappear and give way to a white body.*
> *The iron crust mostly forms an overhanging top layer, deep caverns open occasionally beneath it and gigantic blocks have slid down the hill slope.*
> *The pale clay under the iron crust has a thickness of about 30-50 metres. The variegated upper part I will call the mottled zone, the de-coloured lower part the pallid (pale) zone.*
> *After all, there can be no doubt, that the whole pallid zone with the overlying mottled zone besides the iron crust arises from the weathering of the underlying rocks."*

Walther absolutely considered that 'laterite' encompasses a variety of materials, generally involving three distinct aspects (crust, mottled zone, and pallid zone), but not necessarily involving all three. He argues that one cannot go on the iron crust alone:

> *"The iron crust is not always developed as it is described as a continuous sheet. Following Jutson (sadly I have not seen such occurrences myself), the iron-enriched greenstones have an especially hard and thick iron crust, over granites (there is) a silcrete blanket. Also their (the crusts over granites) structure often appears not to be so cohesive that it can withstand erosion. If it becomes eroded, then depending on the depth of denudation comes to light the red upper zone, the coloured mottled zone or the white pallid zone. If one should follow such outcrops from one to another, then one will be irresolute as to which one should be called "laterite"."*

Furthermore, he describes 'laterite' where no iron crust is present. For example, in the 1916 paper he observes:

> *"In Ceylon ... by Mount Lavinia I saw one metre brown loam, 2 m brick red mottled laterite, 2 m light red to grey decomposed gneiss, 3 m of fresh grey gneiss."*

Here there is no mention of an iron crust, either hard or soft. And later he writes:

> *"An especially interesting outcrop at the rapids of the Kalu Ganga offered me the opportunity to observe the first true veins of graphite. Here one sees in a 12 m deep open cast mine, the mottled zone of a laterised gneiss, and contrasting effectively with the variegated mottled clay wall, the branching coal black altered graphite. Here there can be no doubt that the thick clay body weathered (= laterised) cumulatively in situ."*

The development of mottled clay is, to Walther, the development of 'laterite'. We reiterate that Walther saw 'laterite' encompasses the whole profile, not simply the hard Fe-rich crust.

THE NEW MASTERS

The most recent 'authority' would appear to be the compilation by Aleva (1994). It draws heavily on Schellmann (1983) for its definition of 'laterite':

> *"... laterites are mineral assemblages which have formed as a result of intensive subaerial weathering of rocks."*
> *"... laterites are primarily to be regarded as rocks"*
> *"They belong to the group of residual rocks ..."*
> *"... they should be defined according to the same criteria as other rocks, i.e. on the basis of their genesis and of their mineral content"*
> *"all the severely weathered varieties should be included in the laterite group"*
> *"They consist predominantly of mineral assemblages of goethite, hematite, aluminium hydroxides, kaolinite minerals and quartz. The SiO2: (Al2O3+Fe2O3) ratio of a laterite must be lower than that of the kaolinised parent rock in which all the alumina of the parent rock is present in the form of kaolinite, all the iron in the form of iron oxides, and which contains no more silica than is fixed in the kaolinite plus the primary quartz."*

It is quite clear from this that Schellmann treats 'laterite' as a material, not a profile. It is also clear that the definition embraces anything more weathered than saprolite.

Both Walther (1915, 1916) and Schellmann (1983), while clearly recognising the common development of a triad of crust, mottled zone and pallid zone, do not consider this triad to be essential to the definition: 'laterite' is defined by what it is:

(Schellmann) *"all the severely weathered varieties"*; and, (Walther) *"laterite is not a rock but rather a weathering blanket."*

However, just as clearly, they are in complete opposition about the way to define 'laterite'. Walther (1915, 1916) says it is NOT a rock, Schellmann (1983) says it certainly is. The International Soil Reference and Information Centre in Aleva's (1994) compilation adopted Schellmann's view of 'laterite'. Yet that recent work is quite contradictory within itself. Having completely opted for the Schellmann (1983) definition (p. 14), several of the examples given contradict that definition.

Schellmann's definition is consistent with that of Millot (1964), who grouped those parts of the profile between saprolite and soil as 'laterite' (Aleva Fig 3A). But this is contrary to Aleva's own examples of 'laterite' profiles (Aleva Fig 3B), which include only the upper part of the profile above saprolite as 'laterite', having a mottled zone and a plasmic zone between 'laterite' and saprolite. The same view is presented in Aleva (his Figure 9A), attributed to Anand et al (1991): 'laterite' is only a small part of the profile, below the soil and above the mottled zone It appears that in Aleva's compilation, 'laterite' is being used in three ways. "The typical laterite profile" comprises (from the top) soil, 'laterite', mottled zone, plasmic zone, saprolite, saprock and bedrock Of these components, according to the Schellmann definition accepted by Aleva, the plasmic zone, the mottled zone and the 'laterite' are themselves all 'laterite' Thus:

- the plasmic zone is 'laterite';
- the mottled zone is 'laterite';
- the 'laterite' is 'laterite'; and,
- a profile may be 'laterite'

One may be forgiven for concluding that Aleva's compilation falls somewhat short of helpful clarity (ie completely confuses the issue)

Ollier and co-workers have provided a useful approach to using the word 'laterite' Their main recommendation seems to be not to use the word at all, and if you must then to confine its use to the kinds of materials reported by Buchanan (1807) Ollier's definition is generally in agreement with Buchanan (1807) and Walther (1915, 1916) who emphasised again and again the importance of the red colouration For example, Walther in his 1915 publication:

> *Following the procedure by Buchanan, who put the main emphasis on the red colour, it is therefore appropriate in the narrow sense to characterise red weathering masses as laterite "*

Ollier's definition only includes a part of the material Schellmann calls 'laterite', and it excludes the ferruginous (or aluminous) crust, which is just the part that almost every geologist in Australia describes as 'laterite' Ollier recommends in several publications the use of **ferricrete** for any iron-cemented regolith Pain & Ollier (1992) use lateritic profile in the same way as other workers, except they do not use the word 'laterite' to describe any part of the profile The ferruginous crust, should there be one, they describe as ferricrete

Ferricrete is a word introduced by Lamplugh (1902). According to the AGI Glossary of Geology (Jackson 1997), ferricrete is (a) a sandstone or conglomerate consisting of surficial sand and gravel cemented into a hard mass by iron salts derived from the oxidation of percolating solutions of iron salts (b) A ferruginous duricrust Most recent Australian authors appear to have accepted definition (b)

Bourman (1993) seems to agree with Pain & Ollier (1992) in preferring not to use the word 'laterite'. He wrote:

> *"The term 'laterite' may ultimately disappear, to be replaced by ferricrete, ferruginous duricrust "*

It appears that Bourman is equating 'laterite' with the upper ferricrete crust

McFarlane (1983)uses 'laterite' in much the same way as is found in the compilation of Aleva (1994):

> *"The typical laterite profile is said to comprise laterite overlying mottled and pallid zones "*

that is, to McFarlane, 'laterite' is both a profile and a material Davy (1979) defined 'laterite' for the purposes of his study of Darling Range bauxite as

> *"a general term for surface or near surface material composed largely of iron and/or aluminium sesqui-oxides Though bauxite is a better known term for aluminous laterite, the general term, laterite, will be used for both varieties except in discussions of their origins, when it will be restricted to the dominantly ferruginous variety"*

Davy's usage has elements of Schellmann's definition in not being restricted to ferricrete or bauxite: "near surface material composed largely of iron and/or aluminium sesqui-oxides", but seems to lean somewhat toward restricting the term to kaolin-poor material This is not surprising, as Davy found almost no kaolin in his Darling Range profiles Granite saprolite is overlain by quartz-sesquioxide regolith, all of which can be classed as 'laterite' on Schellmann's definition, though strict adherence to Schellmann contradicts some of Davy's field classifications. The lack of kaolinite is unusual for the Darling Range bauxite Giedans (1973) writes :"the principal source material of bauxite is kaolinite" and Hickman et al (1992) describe kaolinite as "present throughout the profile" and indicate it constitutes of the order of 15% of the granitic derived basal clay

'Laterite' is not a useful word to describe a hard ferruginous duricrust and we suggest the word not be used for such materials.

SOME AUSTRALIAN 'LATERITES'

THE YILGARN PLATEAU

Western Yilgarn (Darling Ranges)

Many so-called 'laterite profiles', referred to by Ollier & Pain (1996) as Walther profiles, are found in southwestern Western Australia from the Darling Range escarpment eastward through the wheat belt 'Laterite' (largely as bauxite) mantles the hills and slopes across the Darling Ranges, conforming very much to the topography (Geidans, 1973, Hickman et al 1992) East of the Darling Ranges the 'laterites' take the form of mesas or breakaways with Fe-oxide cemented resistant flat upper surfaces, the softer parts of the profile below providing the steeper slopes of "breakaways" Jutson (1914) concluded from the conformity of the mesa surfaces that they represented the dissected remnants of a former peneplain, now uplifted to form the "Great Plateau" Weathering of the peneplain produced a broadly extensive 'laterite' "as thin surface caps on the underlying rocks" The present landscape he interpreted to have resulted from erosion which has since removed most of that prior plain, leaving lateritic surfaced remnants as evidence of its original extent Although Jutson defined 'laterite' as "A rock which usually forms in dry climates as a cap on the surface of other rocks generally containing iron", and considered 'laterite' to be a "rarity with the granites", in some instances he appears to extend the use of 'laterite' to include the siliceous or ferruginous 'hard cap' at the surface (of granites), for he writes: "A thin layer of laterite caps a large area of the old peneplain" without making any distinction between granitic and greenstone terrains Both Jutson and Walther very clearly regarded the iron crust to be genetically related to the underlying bedrock.

According to various authors, across the Darling Ranges the generalised profile below the topsoil, is summarised in Table 1

Table 1: *Darling Range bauxite profile*

DAVY (1979)	GIEDANS (1973)	HICKMAN ET AL. (1992)
pisolitic laterite massive laterite	surficial laterite	duricrust
pisolitic or nodular laterite with lateritic clay	mottled zone	mottled friable fragmental zone
lateritic clay (may be pallid or mottled)	clayey, bleached or pallid zone,	pallid zone/basal clay
saprolite (displays residual textures of bedrock)	decomposed bedrock	altered bedrock
bedrock	bedrock	bedrock

Two of Davy's analyses are presented in Table 2 Using Schellmann's definition, material that Davy clearly observes to be dolerite saprolite (samples A42424 & A42425) would be classed as 'laterite', for they have no Al in primary minerals and the SiO_2:(Al_2O_3+Fe_2O_3) ratio is lower than that of the kaolinised parent rock - in this case only A42425I contained any kaolinite. In the granite profile the persistance of microcline into rock that Davy classes as bauxite ('laterite') would not be so classed by Schellmann, because his mineralogical definition permits aluminium to be only in Al hydroxides and kaolinite

Mulcahy (1960) examined small regions of the West Australian wheat belt between York and Quairading, and differed from Jutson in finding "laterites may develop not only under peneplain conditions of low relief, but also on the valley sides and floors" Mulcahy defined the Quailing Erosional Surface as occupying the highest parts of the landscape. Where exposed at breakaways, the profile shows:

0 0-1 5 m	Ferruginous zone	Yellowish-brown hard ironstone becoming slightly softer toward the base
1 5-7 0 m	pallid zone	White and slightly pinkish clay with dark red patches. Quartz grains are bleached in the white clay, stained with iron oxide in the red. Occasional mica flakes throughout.
>7 0 m:	transitional zone	Pale brown and rusty mottled weathered gneiss.

Table 2: *Analyses of Bauxite from the Darling Ranges (from Davy, 1979)*

SAMPLE #		SIO$_2$	AL$_2$O$_3$	FE$_2$O$_3$	SI/(AL$^+$FE)	QTZ	PLAG	HBL	SCHELL DEFN
A									
42425UN	Dolerite	48.0	12.7	3.6	2.9	5	40	50	rock
42425I	brown dol	30.5	17.5	16.7	0.9	10	5	35	saprolite
42425W	yell/brn	21.3	21.0	24.5	0.5	10	5	20	saprolite
42424	cortex	10.7	27.7	31.9	0.2	10	0	0	laterite
42423	saprolite	2.3	28.4	40.6	0.0	2	0	0	laterite
42422	bauxite	2.0	23.3	46.2	0.0	2	0	0	laterite
42421	caprock base	6.8	30.1	34.2	0.1	5	0	0	laterite
42420	caprock	3.0	38.5	31.0	0.0	5	0	0	laterite
42419	soil	36.8	29.5	17.2	0.8	35	0	0	laterite
F								mica	
42412	granite,wthrd	73.5	13.9	0.9	5.0	35	55	10	rock
42411	wthd granite	73.2	13.7	1.3	4.9	40	60	10	saprolite
42410	decomp granite	70.5	15	2.8	4.0	55	35	10	saprolite
42409	saprolite	66.8	18.4	2.1	3.3	50	25	10	saprolite
42408	nod bauxite	53.9	26.7	3.7	1.8	45	15	5	saprolite
42407	nod cem bx	27.6	37.2	11.4	0.6	25		10	laterite
42406	cap-rock bx	28.2	41.2	7.2	0.6	30		5	laterite
42405	cap-rock bx	22.1	41.8	10.7	0.4	20		5	laterite
42404	soil	24.7	42.1	13.5	0.4	25		5	laterite

It is evident that Mulcahy's use of "erosional" is diametrically opposite to the later use of the term by Anand and others. For Mulcahy, the whole landscape is erosional, whereas for Anand et al. (1997), erosional is used only for that part of the landscape where mottled or pallid zones or saprolite or bedrock are exposed.

Finkl & Churchward (1973) applied the concept of etchplains to the southwestern region of Western Australia. At the heart of this concept is the presumption that a continuous Walther profile covered the entire area now classed as etchplain. Where the Walther Profile is complete and continuous the landform is said to be an incipient lateritic etchplain. Where the duricrust is intermittent but the mottled or pallid zones are continuous is partial lateritic etchplain, and where duricrusts are widely spaced with pallid zone or bedrock between is semi-stripped lateritic etchplain. As early as 1961 Mabbutt had described the Yilgarn as an area stripped of regolith (an etchplain) exposing rock surfaces. Ollier (1984) presents an etchplain map of the Yilgarn simplified from Finkl (1979). The Kalgoorlie region sits well within the zone of incipient lateritic ectchplain on these maps.

Eastern Yilgarn (Eastern Goldfields)

This view of the Western Australian landscape has become the key for a series of papers by Anand (1997), and Anand & Smith (1992). They accept the concept of a formerly extensive lateritic peneplain, and classify the present landscape into three regimes (compare with Finkl 1979):

residual	where the full lateritic profile is preserved
erosional	where the duricrust has been lost but parts of the mottled zone, pallid zone, saprolite or bedrock are exposed, and,
depositional	where the products of the erosion of the adjacent lateritic profile have been deposited

Pain & Ollier (1995b) suggest a very different interpretation of the evolution of this landscape. They note that few of the ironstone mesas actually are flat; rather they dip gently away from the breakaway. Drilling through the back-slope at some distance from the ironstone edge of the breakaways discloses sediment, not a Walther profile. Such observations, argue Pain & Ollier, do not conform to the concept of a former extensive lateritised land surface, and rather suggest valley-flanking deposits. However Finkl & Churchward (1973) did not suggest that the surface before etching was flat. In their idealised cross-sections few of the lateritic duricrusts are flat-lying over any of the etch-plain types. In the Darling Range dipping lateritic bauxite duricrust is commonplace where bauxite mantles the whole undulating landscape. Both Geidans (1973) and Hickman et al. (1992) emphasise that across the Darling Range residual bauxite profiles are thickest on the slopes and thinnest at the crests. Thus the most extensive Western Australian duricrusts are neither completely continuous nor remotely planar. The detailed mapping of the Darling Range bauxite reveals that they are thickest on the hill slopes, which might suggest that with prolonged erosion, the remnants would be these thickest, valley flanking duricrusts.

Another, but controversial, view is expressed by Glassford & Semeniuk (1995) who suggest that the eastern Yilgarn lateritic profiles are a composite of in situ weathering and sedimentary deposits. The contend that the profile consists of in situ saprolite overlain by aeolian and fluvial facies which now form the mottled and pallid zones of the "traditional laterite profile." The 'laterite', ferricrete and bauxite they contend is formed from altered sandy duststones. While this is a radical view it has not been tested and their ideas bear some resemblance to the view of Ollier & Galloway (1990)who contend most lateritic (or Walther) profiles contain within them unconformities. Brimhall et al. (1991) also advocates significant aeolian accession to the profiles of the Yilgarn.

CAPE YORK, QUEENSLAND

Pain & Ollier (1992) describe a range of ferricretes from Cape York, including deposits on valley flanks, around shallow depressions (melon holes) and at plateau edges or scarps (jumpups or breakaways). Many of these ferricretes are of quite limited size, sometimes extending as narrow belts along water courses, or *"no more than a few tens of metres back from the scarp edge"*. Some such ferricretes have mottled regolith below them and pallid regolith below that, with saprolite and bedrock lower still. That is, some Cape York ferricretes are part of a lateritic profile as defined by Aleva and as Pain & Ollier define it.

Pain & Ollier also refer to more extensive ferricretes within the Weipa bauxite weathering profile. They report three levels of ferricrete; one within the zone of bauxite pisoliths, a second within the otherwise pallid zone consisting largely of kaolin, and a third lying at the top of recognisable Cretaceous Rolling Downs Group fine sandstone. COMALCO mapping and mining shows that the upper ferricrete (or ironstone) is a continuous horizon of varying hardness and cementation. According to Foster (1997):

"The ironstone band at Weipa is composed of irregular nodules of ferruginised kaolin in a matrix of loose pisoliths and sandy clay. The nodules may be up to 15 cm in diameter and they contain hematite, goethite, kaolinite and quartz. Hematite and goethite are most prevalent in this zone. Induration of the ironstone into a vermiform structure sometimes occurs."

The vermiform ironstone is commonly found around creeks and near the coast (Campbell, 1990). The ironstone grades down into a sandy mottled zone that contains weakly ferruginised patches and mottles (Morgan 1991, Evans 1975).

"In places the ironstone is rock hard, but mostly it is not greatly more resistant to bulldozing than the bauxite." Adjacent to the Mission River the pisolitic bauxite has been eroded leaving the more resistant ferricrete as outcrop. The lowest of the three ferricretes at Weipa is probably part of a paleosol described by le Gleuher et al. (1994) occurring below an unconformity between the Cretaceous Rolling Downs Group and the Palaeogene Bulimba Formation. Both the upper ferricrete and lower paleosol can be regarded as similar in origin; having formed at, or near, the top of a typical 'laterite profile'.

CHARTERS TOWERS REGION, QUEENSLAND

Flat lying Tertiary sediments of the Palaeogene Southern Cross and Neogene Campaspe Formations are exposed as cliffs at the edges of plateaux and mesas in the Charters Towers region of Queensland The upper edges of these cliffs are typically very red in colour, with patchily red (mottled) quartz-sand rich regolith a few metres below, grading paler in colour with depth, to kaolinised regolith In many instances the sediments are difficult to distinguish from granitic saprolite which forms the landscape of the regions between the mesas and plateaux (e g Rivers et al 1995)

Models for laterite development

Because all these regolith profiles have some similar characteristics, they are generally given the same name (laterite or lateritic) and are generally thought to have the same mode of formation But just what this mode is varies according to the particular experience of the protagonist We present three models for the development of regolith profiles such as these, and conclude that the processes of all three are involved to varying extents in the establishment of a Walther profile

Model 1: Lateritic (Walther) profiles develop beneath an extensive, flat-lying land surface under a climate that is seasonally wet

If this model is correct, one should first investigate places where these conditions obtain, to see if lateritic profiles do indeed develop The Weipa plateau of northern Cape York, Queensland provides such a test

At Weipa and Andoom, and in the surrounding country, there is a major bauxite and kaolinite resource A number of publications have described the regolith of the region; the following description is based on that work and five years of research that we have undertaken The bulk of our results are based on examination of Comalco Limited's bauxite and kaolinite workings, on four air-core drill holes and on regional mapping and reconnaissance

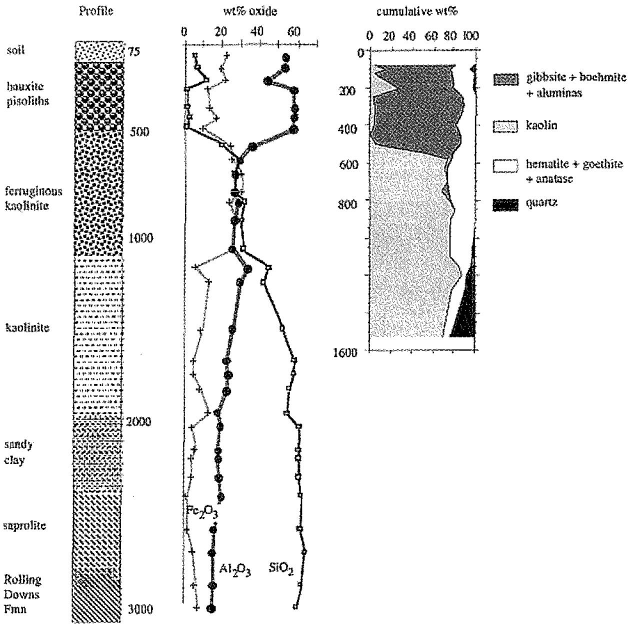

Figure 1 *Profile and geochemistry from the Jacaranda drill hole at Andoom near Weipa, northern Queensland*

JACARANDA PROFILE (FIGURE 1)

Below a thin (75 cm) grey skeletal soil is up to 4 m of pisolitic bauxite, uncemented except for some near surface patches which are weakly cemented by boehmite and lesser amounts of hematite.

The lower boundary of bauxite is marked by a transition over a distance of 50 cm from pisoliths to a hard, cemented layer of ferruginous kaolinitic nodules (ironstone) that corresponds to the wet season watertable high. This layer marks the limit of bauxite mining (Figure 2b). Below the "iron-stone" is a 5 m thick zone of mottled ferruginous kaolinite, which grades downward into a clay rich layer of the order of 10 m thick. This part of the profile is colour mottled in white, purplish brown and fawn. The clay-rich zone grades from about 20 m depth to 25 m into a sandy clay-rich saprolite, which in turn grades to the blue-green unweathered Rolling Downs Formation at about 30 m.

The major element chemistry of this profile is presented in Figure 1. The region of iron enrichment; the iron-stone at the base of the bauxite and the ferruginous kaolinite region below are clearly shown by the marked rise in Fe_2O_3 and concomitant fall in silica and alumina. In many respects, the Weipa bauxite regolith is a Walther, or lateritic profile. The Weipa plateau has very slight relief (Figure 2). The profile is never exposed naturally in the vicinity of the exploration and mining leases. But, 45 km east of Weipa there are broad valleys (10 km wide) that slope up to the plateau, giving rise to steep breakaways (jumpups), similar in character to the breakaways of the Yilgarn. If the Weipa Plateau were incised by 100 m or so most of the bauxite would be eroded, and the plateau would be dissected, leaving, at some late stage as the streams incised, separated flat-topped hills with very prominent lateritic profiles exposed around their edges. The observation that today ironstone is most prominent and hardest at existing valley edges supports the concept of edge-hardened resistant mesas or jump-ups evolving as the landscape erodes. It does not appear to be essential that there be a continuous hard ironstone sheet beneath the bauxite, only that the zone of iron enrichment be roughly a horizontal plane, so that as any part of it becomes exposed it becomes cemented. That is, the Weipa plateau forms a very believable model for the landscape imagined by Jutson (1914) of southwestern Western Australia in some past time.

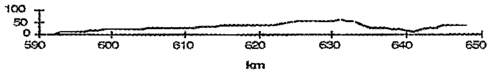

Figure 2a *Topographic profile across the Weipa Plateau from west (left) to east*

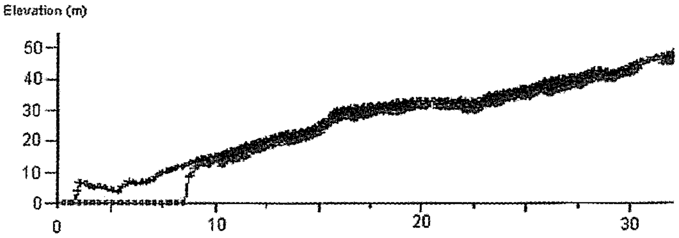

Figure 2b. *Topography, thickness of bauxite, =depth to iron-stone layer at Weipa. Data for bauxite thickness are lacking on the left (west) side of the profile.*

Model 2 *Lateritic profiles develop by the deep weathering of flat-lying rocks, with the iron-stone carapace developing by lateral migration of iron in solution, which on emergence at scarps precipitates as iron oxyhydroxide cement*

THE CHARTERS TOWERS REGION

To the west and to the south east of Charters Towers, Queensland, flat-lying Palaeogene and Neogene sediments overlie Paleozoic rocks, largely granites and volcanics and form low relief plains and mesas The Tertiary sediments comprise the fluvial facies Southern Cross Formation, its suggested equivalent, the Suttor Formation and overlying Campaspe Formations (Henderson 1996) These sediments generally terminate at escarpments 2-30 m high, below which is a gently undulating landscape of Paleozoic bedrock and its regolith of saprolite, lithosols or red brown earths Some of the scarps have gently dipping back-slopes extending a kilometre westward, beyond which is a landscape underlain by essentially horizontal Palaeogene and Neogene sediments for many 10's km Other scarp faces rise to forward dipping surfaces, while others border essentially horizontal plateaux

The upper-most 1-8 m of most of the scarps are composed of strongly rubified gravels and sands of evidently fluvial origin, based on the evidence of rounded quartz pebbles and sand grains, together with mostly angular quartz sand and gravel Some exposures show graded stratification and crossbedding A few scarps, by contrast, are formed of indurated granitic saprolite (Rivers 1993)

The rubified upper few metres of the scarps contain quartz, kaolin, hematite and goethite Although the redness and hardness of these scarp edges suggests the use of the term "ironstone", much of the hardness is caused by an alumino-silica cement

Generally topographically lower than the duricrusted mesas and plateaux surfaces, extensive pisolitic ironstone sheets and vermiform ironstone provide a second tier in a stepped landscape

Underlying both the rubified regolith and nodular and vermiform ironstones, are 1-10 m of mottled saprolite, developed in either granite, Palaeogene and Neogene sediments or paleosols Thickness and morphological variations of these mottle horizons is common across the landscape The mottles vary from 3-10 cm red/white units to 0 5 -1 cm elongated mottles along biogenic channels, the latter is responsible for the hardness at the base of red earths With depth, the extent of mottling and amount of hematite decrease, grading to a pale-coloured kaolin-rich sandy regolith overlying granitic or sedimentary saprolite

The conformity of the elevation of mesa and plateau surfaces, and their stratigraphic horizontality, are strong indications that the Palaeogene and Neogene sediments formed an extensive sheet across the Charters Towers region, and that erosion has removed them in those areas where the Paleozoic bedrock is exposed An alternate view is that the sediments only occurred in broad shallow channels having Paleozoic bedrock as the interfluves If this were so, the valley sediments must have become sufficiently indurated before incision for them to be more weathering resistant than the interfluves, leading to a reversal of topography Rivers et al (1995) interpretation of the regolith at Puzzler Walls follows the latter model of landscape evolution in that region

Argument in favour of one or other of these models may be entirely semantic The present higher parts of a partly eroded sediment sheet must have originally been deposited low in the topography Similarly fluvial sediments that were never laterally extensive were confined to a valley Thus a landscape inversion model could be applied to any eminence on the Palaeogene and Neogene sediments

The evidence in the Charters Towers region is that at some time during the Cainozoic there was a more extensive deposit of flat-lying sediments At their margins, these sediments now have escarpments which show many features of a Walther profile, sufficiently so that it may be concluded that the whole landscape was formerly an extensive lateritic plain, as in the Jutson (1914) model for the Yilgarn

Detailed examination of the landscape and regolith on the Tertiary sediments away from the escarpments (Rivers 1993) cannot sustain this model Behind the escarpment edge induration only extends for 10-50 m, occurs only as minor patches below red earths Red earths, 2-15 m thick grade downward into mottled fluvial sediment saprolite with fresh sediments below It appears that the duricrusted 'lateritic profiles' of the escarpments only occur exactly there, and we conclude from this that it is the escarpment that leads to the hardening of the surface lateritic profile, and not vice-versa In this model, hydromorphic activity carries Fe, Si and Al in solution from the interior to the exposed margins (as argued by Ruxton & Taylor, 1982 and Taylor and Ruxton, 1987, where cementing agents precipitate forming a slabby ferricrete similar to those described by Bourman (1989)

There are two ways the induration occurs at the edges:

- the in situ hardening of the lower regions of the red earths due to drying out once they are incised; and/or,
- as a result of Fe-Al-Si migration towards the edges due to a more conducive hydraulic gradient created in response to incision.

The simple drying out and consequent hardening of the lower parts of the red earth profiles is possible considering the almost year round moisture presence within them is eliminated when they are incised, and ferrihydrite converts to hematite on drying out. Continuing development of red and yellow earths induces dissolution of quartz and kaolin and also Fe-oxides depending on profile hydrology, and all these ions in the interior move downwards slowly into a regional groundwater flow system. As a result of incision at the edge, the hydraulic gradient is locally increased towards the edge and the ions are rapidly carried in local groundwater to the edge rather than to the deeper system. The ions carried in solution travel along the local groundwater interface and either crystallise at the edge upon oxidation of Fe^{2+} with a consequent drop in pH, or to a fall in the threshold of supersaturation followed by recrystallization after transport from tight pores in the interior to the more porous environment created at the incision point. In fact, both the drying out hardening and precipitation at the edges is likely to occur at some depth in the profile (< 1 m). Consequently the upper loose surface or soil is eroded leaving the slope towards the escarpment, or when inward drainage evolved with time, a slope away from the escarpment. This lateral migration and precipitation model only operates on local recharge or groundwater systems which are connected and not in the regional flow systems which operate much deeper and discharge at the base or into the major rivers.

Although the main ferricrete at Weipa is controlled by the wet season watertable, escarpments cut into the profile there also cement by similar processes to those just described. The difference between the main processes of cementation is probably climatically controlled. At Weipa the seasonal fluctuations of the watertable have formed an extensive ferricrete; at Charters Towers intermittent rain only established local groundwater flows.

This model provides a very different method for the development of laterite at breakaways from that of Model 1. It does not imply a former extensive duricrust, but rather it implies that the duricrust forms in response to a particular landscape environment, and that such a weathering profile is essentially in equilibrium with the extant climate.

Model 3. Lateritic profiles develop in the landscape as part of a catena. Later erosion of bedrock causes the hardest part (ironstone) to become outstanding, leading to topographic reversal.

Pain et al. (1994) describe ferruginised gravely stream sediments lying on slightly weathered metamorphic rock in eastern Cape York northern Queensland. These sediments are well-cemented alluvium but are not in any sense associated with any lateritic or Walther profile. They clearly result from Fe2+ in groundwater seepage oxidising on exposure to the atmosphere and cementing the sediments.

Pain & Ollier (1995a), also on Cape York, document valley ferricretes ('laterites') formed by the cementation of alluvium where the ferruginisation has progressively moved downvalley as the headwaters have experienced relief inversion. In this case the ferricrete is obviously diachronous. Again there is no significant weathering profile underlying the ferricrete or 'laterite'.

Figure 3: *Marginally cemented palaeochannel fill at Fingals Pit near Kalgoorlie. The darker curved mass on the upper left of the pit wall is the ferricrete. Photo B.N. Opdyke*

At Fingals Pit northwest of Kalgoorlie a similar situation is observed where a palaeochannel filled by sands and gravel at the top of a hill is cemented at its margins by ferricrete (Figure 3).

Milnes et al. (1985) followed by Ollier and Galloway (1990) suggest that the ferricrete found on top of mottled and pallid saprolite is always unconformable, and hence is not genetically related to the underlying profile. They further suggest that ferricretes, once formed, are resistant to weathering, and in time may become the high point in the landscape, and that this may happen in adjacent places at different times. Multiple generation of ferricrete, according to Ollier & Galloway, makes correlation between them absurd.

Source of iron

An important part of all Walther profiles is the high degree of iron enrichment at the surface. There has been considerable discussion in the literature about the source of the iron (e.g. Ollier & Pain 1996), but at Andoom there is ample evidence that it was largely sourced vertically. The parent Rolling Downs Formation has between 6% and 8% Fe_2O_3, and the ironstone layer about 30% Fe_2O_3 (Table 3). The concentration factor of 5 is the same as for TiO_2 and Al_2O_3, and a little less than for Zr (x6), from which it might be concluded that the iron (and alumina, titania, and zirconium) represent the comparatively insoluble elements from chemically weathered sediments which formerly occupied a greater thickness. Calculations from the concentrations of these 'immobile' elements integrated over the full weathering profile show that at Andoom, where the depth to unaltered rock is now between 21 and 27 m, the thickness of sediment that has been weathered to produce the present profile was between 35 and 52 m. In other words, solution weathering and compaction have lowered the landscape by between 15 and 25 m, though erosion must have added significantly to this, and all the iron in the ironstone has been derived from 'above'. Inevitably there will have been some lateral movement of iron, but since extensive exploration drilling and mining shows that the ironstone extends across the whole of the mine lease, and well beyond, significant Fe derivation laterally would demand uniform derivation from an immense distance.

Table 3: *Geochemistry of the upper 18.5 m of the Jacaranda Profile, Andoom, Cape York.*

MINERALOGY

DEPTH (CM)	%			
	SiO_2	TiO_2	Al_2O_3	FE_2O_3
75	5.53	2.65	53.68	22.82
125	6.66	2.58	52.8	19.48
200	11.06	2.23	44.13	21.76
250	1.43	2.84	57.75	12.22
350	1.22	2.94	58.24	12.72
400	2.41	2.79	58.15	17.3
450	1.31	2.97	57.47	9.8
550	20.29	1.63	35.49	24.72
625	28.75	1.23	29.12	25.26
700	28.19	1.08	26.16	30.59
800	28.15	1.12	26.52	30.56
850	32.09	1.4	28.43	23.69
950	30.52	1.33	26.79	27.76
1100	31.62	1.32	25.63	25.49
1200	45.26	1.4	33.53	6.56
1275	42.44	1.27	29.51	13.16
1525	52.6	1.16	25.25	10.08
1700	59	0.83	22.26	5.86
1750	58.36	0.79	22.98	5.3
1775	58.95	0.84	22.94	4.84
1850	56.51	0.79	22.66	8.62

At Weipa, the bauxite, unlike at Andoom, is developed on fluvial sediments of the Bulimba Formation. Above an unconformity with the Rolling Downs Formation, the Bulimba Formation is almost pure quartz (at 16 m, Table 4), with sandy clays above. The iron content of the sediments is of the order of 2%. The ironstone is only about 1 m thick, carrying about 24% Fe_2O_3 compared to 5.5 m of >24% Fe_2O_3 at Andoom. The concentration factor of at least 12 suggested by this at Weipa would require the compaction by chemical weathering to be 12 m or more, little different from that deduced for Andoom. The argument here is, however, less robust, as the fluvial Bulimba Formations is unlikely to have been as uniform as the marine Rolling Downs Formation and the initial Fe content may be significantly different from that assumed.

Examination of Davy's (1993) data indicates that assuming Ti, Zr, Nb and Th are relatively insoluble, the iron in the profile is largely derived locally. In the dolerite, the enrichment of iron in the bauxite relative to fresh rock is the same as the enrichment of the so-called immobile elements, whereas for the granite profile the enrichment in iron in the bauxite somewhat exceeds that of Ti and Zr. Because Davy's sampling is not systematic with depth, it is not possible to interpret the iron mobility as the same way as can be done with the Weipa profile (Figs 4, 5).

Table 4: *Cod profile, Weipa, above the unconformity between the Rolling Downs Formation and the Bulimba Formation*

MINERALOGY

DEPTH (CM)	%			
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3
150	5.45	2.39	59.1	5.54
175	5.66	2.41	58.82	5.21
225	7.18	2.25	56.53	6.75
300	24.47	0.83	28.02	30.99
400	36.95	1.24	33.11	14.22
400	31.72	0.91	29.67	23.83
550	40.04	1.67	32.11	6.38
700	47.34	1.96	34.48	2.32
825	56.12	1.61	29.43	1.85
975	52.32	1.6	32.02	1.92
1175	68.98	1.11	20.53	0.8
1325	78.77	0.38	14.61	0.47
1600	98.2	0.08	1.59	0.05

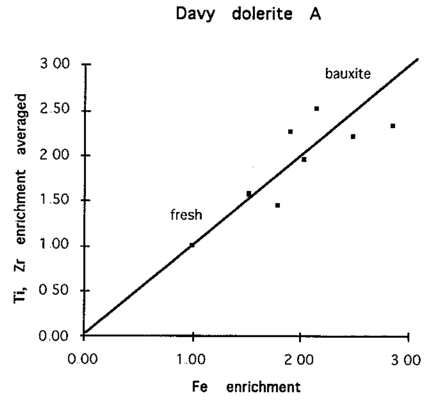

Figure 4: *Comparison between Fe enrichment in weathered dolerite and bauxite relative to fresh dolerite and the average of the enrichment of TiO2 and Zr in Davy's samples from profile A (1993). The line represents 1:1 enrichment.*

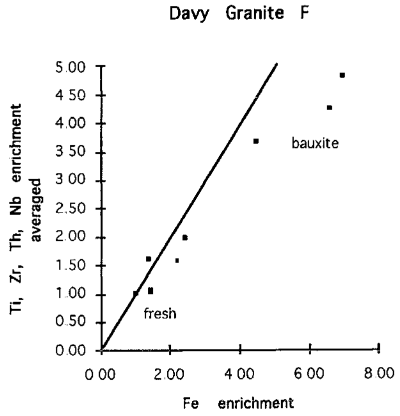

Figure 5: *Comparison between Fe enrichment in weathered granite and bauxite relative to freshest granite and the average of the enrichment of TiO_2, Zr, Th, and Nb in Davy's samples from profile F (1993). The line represents 1:1 enrichment.*

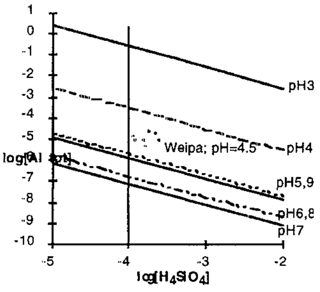

Figure 6: *Stability relations for kaolinite at varying $[H_4SiO_4]$, for different pH values. The plotted points are Si/Al measurements for groundwater at Weipa from the kaolinitic regolith, Queensland, Australia (data courtesy Comalco Ltd.). Vertical line is the silica-quartz equilibrium value.*

Age of laterites.

At Weipa, the evidence is quite compelling that the lower part of the bauxite/laterite profile is more or less in equilibrium with the present climate. The various components of the profile conform closely to the current water-table fluctuations, and the groundwater is in equilibrium with its mineralogy (Figure 6). Also ferrihydrite can be seen to be precipitating where water emerges at the end of the wet season and hematite hydrates to goethite in the wet season around the margins of ponds and reverts in dry seasons. There is no doubt that the Fe minerals are "active' under the present conditions.

The bauxite itself, which forms the upper 2-3 metres of the deposit, shows some signs of undergoing retrograde weathering, i.e., resilication of the gibbsite, for the pisoliths are coated with a thin kaolinite shell, possibly the result of reaction between aeolian of organically derived silica and gibbsite. It may be concluded that this deposit is evolving, although it is impossible to say how long it has been developing except in the most general way since it clearly postdates the mid-Cretaceous at Andoom and the Palaeogene at Weipa.

Hickman et al. (1992) summarise many authors' views on the evolution of the Darling Range bauxite in relation to the topography, without committing to a preferred interpretation. Their final comment on the matter is to note that "Terril's theory" (1948, 1956) implies that the topography at the time of lateritisation closely resembled that seen today" (see also figure 7). The topography in the vicinity of the major Darling Range deposits is strongly bed-rock controlled; faults define stream courses, thicker dolerites underlie ridges (Hickman et al. 1992, Davy 1979). If the bauxite formed in the past on a peneplain, which was then uplifted and subsequently eroded, the thickest bauxite would not now lie on the valley slopes. If they formed in the past on topography similar to that of today, it follows that all the erosion that presumably followed the rejuvenation of the streams did not modify the established bauxite/topography relationships. The application of Ockham's razor might suggest that the Darling Range bauxites are in equilibrium with their environment, and are developing today. This has been suggested or alluded to by many authors (e.g. Geidans 1973, Davy 1993). Not least in their arguments is that bauxite grades fall in sympathy with the present rainfall, ie. in an easterly direction.

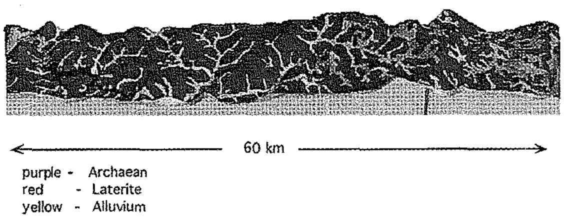

Figure 7: *Topography of a section of the Darling Ranges. Laterite, which is only a few metres thick, clearly covers a rolling topography of many tens of metres relief.*

The studies of Pain et al. (1994) and Pain & Ollier (1995a) on Cape York show laterite or ferricrete is forming today and that some ferricreted surfaces are obviously diachronous. There are other 'laterites' or ferricretes which are clearly not in equilibrium with present environments such as those buried by basalts on the Monaro (Taylor et al. 1992), or some of those on the eastern Yilgarn where 'lateritic detritus is included in Eocene palaeochannel fills (Anand 1997).

CONCLUSIONS

- Laterite is not a good word to use for a rock. Ferricrete is preferred as it has none of the historical baggage of 'laterite'.
- Laterite profile can be used to refer to a weathering profile consisting of some or all of soil, ferruginous crust, mottled zone, pallid zone and bedrock.
- Ferricrete can form in many different ways including by residual accumulation, lateral migration and in valley bottoms.
- Ferricrete can be of many different ages, but many are forming at present, some are old but still being modified, and others are truly fossil.
- Laterite is a word that probably can never be rooted out of the geological lexicon. We suggest its use be always informal or broadly descriptive, never defining.

ACKNOWLEDGEMENTS

We acknowledge with gratitude the contribution made by COMALCO Limited through the provision of access to mine sites, water chemistry and accommodation at Weipa, and for drill samples from surface to bedrock. Many thanks to Mike Morgan for sharing his vast experience of the Weipa deposit, and for field support. Drs Maité Le Gleuher and David Tilley performed many of the XRD analyses and mineralogical studies of the Weipa samples, and Mehrooz Aspandiar allowed us to use his results and insights at Charters Towers. To all those who have helped form our prejudices we offer our sincere thanks and hope that you don't see some of yourself in what you have just read. We also thank constructive comment from colleagues, in particular Professor Bob Bourman and Steve Hill. This work was made possible by ARC Grant A39232594, and by the Australian Government's Cooperative Research Centres Program.

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