chapter vi

GENESIS OF LATERITE/BAUXITE

In order to set the scene for the author's genetic model a brief account of the major genetic models for lateritization has been given. Here, the previous model as given by Valeton (1983) for the area has been discussed in detail, the drawbacks pointed out and the differences between that model and the author's model highlighted, before giving a detailed account of laterite/bauxite genesis based upon field studies and laboratory analyses.

Brief account of laterite/bauxite genesis

The word 'laterite' was coined by Buchanan (1807), for certain kind of weathered material in southern India, which was initially soft enough to be cut into blocks by an iron instrument, but which became as hard as a brick on exposure to air (Buchanan, 1807, p.440). For this reason it was suitable for making bricks and it is this utilitarian aspect which Buchanan chose to stress in giving the name laterite (later: Latin, Brick). From that time till the early part of the nineteenth century laterite was regarded as a rock type and discussed largely by geologists, (Newbold, 1844; Darwin, 1844; Bain, 1852; Crook, 1909 : Evans, 1910: Maufe, 1933; du Preez, 1949; Reiche, 1950; Prescott and Pendleton, 1952; Johnson, 1959) were some of the workers who endorsed this view.

There were also two very early models of laterite formation
proposed, marine and volcanic origins, which were easily
dismissed by Oldham (1893). A third model involving termite
activity received only very limited support. Erhardt (1951),
suggested that one group of laterites might be 'cuirasses
termitiques', with the termites being responsible for the
structure. Nazaroff (1931) had reported the occurrence of
ferruginized termitaria. Goudie (1973, p.113) considered
the termite channels to be responsible for the aeration of
the profile which encouraged the development of vesicular
laterites, promoting the oxidisation of ferrous compounds to
form indurated ferricrete. Nevertheless, the belief that
termites may be the cause of laterite development is now
largely discredited.

Apart from those early workers who unreservedly believed
laterite to be a rock in the strictest sense of being a
deposit, most who described it as a rock qualified this by
saying that it was a weathered or altered rock, or that the
rock was the product of alteration or weathering of an
original rock (McFarlane, 1976, p.2). Unlike the other
sediments which result from the removal of certain consti-
tuents from a parent rock and their subsequent deposition this
'sediment' was residual. It was what was left behind after
constituents had been removed (Babington, 1821; Benza, 1836;
Clark, 1838).

How the differential removal of part of the rock occurred was not then understood. The formulation of the concept of deep weathering and differential solution under tropical conditions as the differential accumulation of the residuum is usually attributed to Russell (1889); but by 1821, Babington had already outlined the decay of hornblende and felspars into red oxides and porcelain earth from which the soft parts were presumed to have been washed away, leaving a residuum. Shortly afterwards Newbold (1844), characterized the formation of laterite/ bauxite as a "segregation and subsequent rearrangement of the different mineral particles in the substance of the rock itself, by a process in nature's laboratory, approaching to crysta- llization, better known than explained or understood". Russell (1889) provided some data on this process.

The theory that laterite/bauxite was the residuum of extreme weathering and differential removal of material by chemical solution became widely accepted. Glinka (1914) reinforced and elaborated Russell's (1889) theories of tropical weathering and formation of stable (laterite/bauxite) residues. In 1932, the Imperial Bureau of Soil Science defined laterite/bauxite as "a weathered rock product formed by the leaching of igneous and metamorphic rocks whereby the bases and much of the silica are removed leaving a residue containing alumina uncombined".

The concept of laterite/bauxite as a residuum has persisted, often supported by convincing evidence (de Vletter, 1955;

Hartman, 1955; du Bois and Jeffery 1955; Hanlon, 1945; Van Bemmelen, 1941), but from about the first decade of the new century there was, generally, progressively less stress put upon the residual aspect and more upon the precipitationary aspect.

The early concept of laterite/bauxite as a residuum seems never to have precisely formulated, but it appears that essentially the accumulations were attributed to the relative immobility of the constituents. Although they were believed to accumulate as a residuum, nevertheless, two phases of limited mobility of the constituents were implied; first, a short-lived phase when the materials to be concentrated were released from their parent material by weathering processes and re-grouped into relatively immobile precipitates; subsequently, a second mobile phase during the resolution or alteration of the residuum, probably by groundwaters (McFarlane, 1976, p.3,91-92).

Although stress laid on the residual nature of laterite/bauxite would appear at first to imply that it is entirely a mechanical residue, clearly it was recognized even then that laterite/ bauxite is itself a precipitate. Two short-lived phases of mobility of the constituents were recognized, prior to the accumulation of the residuum, the components became mobile and were precipitated in immobile or relatively immobile form. The mobility was short-lived, certainly less than that of the materials which were washed away, but a definite period of

mobility was required for the minerals to regroup, after the breakdown of the parent materials. The accumulation of the precipitates was believed to be essentially a mechanical process and certainly the stress was primarily on the accumulation of the residuum. The second phase of mobility was the subsequent rearrangement of the different minerals which were accumulated (Newbold, 1846). Darwin (1844) for example described the formation process as "alluvial action on detritus abounding in iron". Increasingly towards the first decade of the twentieth century there were references to subsequent re-solution and precipitation in groundwater, e.g. Harrison and Reid (1910).

The concept of laterite/bauxite as a precipitate resulted from recognition of the fact that pallid zones were throught to be typically underlying substrate of laterites/bauxites. This coincided with an increasing understanding of the several ways in which iron and almumina could be mobilized. Thus; it came to be believed that the enrichment was caused by the iron and almunina, in solution, moving into the enriched zones and there being precipitated. The provenance of the concentration was believed to be essentially the underlying pallid zone, but more distant sources were also considered possible if not probable.

The first suggestion that the role of groundwaters in the formation of laterite/bauxite had been grossly underestimated was made by Maclaren (1906), who stated that laterite/bauxite

was not the result of decomposition _in situ_ by groundwaters.
The groundwaters may have derived their mineral contents from
the underlying rocks, but may also have brought it from
sources far distant. With this concept, the stress on the
immobility of the precipitates as the means of the accumula-
tion lost ground to the suggestion that the accumulations were
in large part due to precipitation from groundwaters, and the
source of the enrichment of these groundwaters was below the
laterite/bauxite but not necessarily local.

Campbell (1917) was the first to formulate definitely the
concept of laterite/bauxite as a precipitate. Since its preci-
pitationary aspect was already well recognized, he must be
understood to have meant that the accumulated minerals had a
much greater degree of mobility than was formerly recognized,
that is, that the concentration was due to this mobility.
This was a major turning point in the development of theories
of laterite/bauxite genesis and was responsible for bringing
the material into the sphere of interest of pedologists.

Two mechanisms were suggested for this enrichment of the
laterite/bauxite horizon, capillarity and the seasonal
fluctuations of the water table.

Laterite/bauxite formation by capillary action was favoured
by Maclaren (1906). Simpson (1912) described primary laterite/
bauxite as "a true efflorescence, that is, a deposition on the

surface of the ground by capillarity and there deposited as
solid matter owing to aeration and evaporation of the water".
He implied that it grew progressively upwards, and from this
stemmed the general belief that the thickness of a laterite/
bauxite is a measure of the time for which it developed, that
is, its age (Holmes, 1914; Maclaren, 1906; Vann, 1963). The
evidence against the effectiveness of capillary action in
laterite/bauxite formation is overwhelming (Goudie, 1973,
p.141-4). Not least is the recognition that capillary action
is restricted to a very narrow horizon in the soil (Sivaraja-
singhham et al., 1962; Bayer, 1956) seldom exceeding 2 m
(6.6 ft). Capillarity, as a major factor, has generally been
discredited but not entirely abandoned as a mechanism by
which some duricrusts are believed to accumulate (Loughnan
et. al., 1962; American Geological Institute, 1962;Stamp, 1961).

The belief that upward movement of iron and almunina was
brought about by water table fluctuation was more popular
(Pendleton and Sharasuvana, 1946; Pendleton, 1941; Prescott
and Pendleton, 1952; Fisher, 1958) and it is still very
widely held. Nevertheless, there is a growing awareness that
this model must be treated with reserve (Sivarajasingham et.
al., 1962; McFarlane, 1971; Goudie, 1973, p.145). Essentially
the theory is that enriched solutions are carried upward in
the profile with the seasonal rise of the water table and
precipitated near the upper limits of the range of fluctuation.
However, there are a number of seemingly insuperable problems.

These may be summarized thus:

(a) The postulated mechanism cannot explain almunina enrich-
ment since it is inconsistent with principles of chemistry
(Sivarajasingham etl. al.,1962). It also fails in
practice to explain upward movement of iron. By the
Ghyben-Herzberg hypothesis (in Goudie, 1973) fresh ground
-water "floats" on the underlying solutions, thus presen-
ting a barrier to the rise of these solutions in the
profile. Sivarajasingham et. al., (1962) discussed this
and pointed out that the development of water supplies in
Hawaii were based on this principle.

(b) The scale of many laterite/bauxite profiles is so large
that it becomes necessary to invoke seasonal variations
far more extreme than those occurring at present (Walther,
1916). The vast water table fluctuations required to
explain thick laterite/bauxite profiles do not exist.

(c) The concept of laterite/bauxite enrichment and pallid
zone depletion as synchronous complementary processes
is faced with :

i)   the not uncommon occurrence of laterite/bauxite
     directly on fresh rock or unleached material,

ii) the occurrence of laterite over extremely thin
     leached horizons, completely inadequate to account
     for the enrichment in the laterite/bauxite,

iii) the fact that even the deepest pallid zones are
quantitatively inadequate to account for the con-
centration in the crust (Trendall, 1962)

Some of these occurrences may be explained by a contri-
bution made to the laterite/bauxite from topographically

higher positions (Campbell, 1917; Maclaren, 1906), but

there remains the problem of the development of thick

laterites/bauxites with inadequate pallid zones, on

interfluves (de Swardt, 1964; McFarlane, 1971). Nor can

all of these present interfluves be dismissed as examples

of relief inversion. Where they are underlain by resis-

tant rocks, such as quartzites, it is unrealistic to

suggest that these comprised former lowlands which

received a contribution from higher lying rocks(Goudie,1973).

(d) Many laterites/bauxites occur on surfaces of relatively
high relief. Some of the relief may be explained by
modification of the original laterite/bauxite surface,
but some is original. Certainly laterite/bauxite develop-
ment is not restricted to completely stable water tables
level or near level topographies, a prerequisite condition
for this model.

Recently, Thomas (1974) has favoured a third possible mechanism
for the upward translocation of iron. He cited the hypothesis
of Lelong (1966), whereby ionic diffusion may remove rock
alteration products from deep within the weathering profile.

The hypothesis, however, remains unproven.

Two other kinds of models of laterite/bauxite formation have recently received more attention, detrital models and those which compromise between the original concepts of it as a precipitate.

Studies of low-level laterites/bauxites, especially those in a pediment situation, or slope bottom crusts, have been numerous. Considerable detail of their genesis is available, provided largely by pedologists (Maignien, 1966). These laterites/bauxites are predominantly "absolute accumulations" (a term introduced by d'Hoore in 1954) in that they have received a considerable contribution from topographically higher positions (where an older laterite/bauxite may or may not occur). The contribution may be mechanical or in solution, or both. It is generally agreed that there is also _in situ_ development of primary laterite/bauxite development in these situations so that the laterite/bauxite is only partly detrital (McFarlane, 1969; Goudie, 1973). The distinction between primary and secondary laterites/bauxites is often difficult to make in such situations (Roy Chowdhury et al., 1965), but since detrital elements can often be identified (e.g., McFarlane, 1969) the name "detrital model" may be justifiable. Goudie (1973) has pointed out that this model bears a close relationship to _in situ_ models. Pursuing this argument further, since many of the so-called primary laterites/

bauxites are residual and involve the resolution of material
which has mechanically settled or has down-wasted from higher
topographic positions, even these are in a sense detrital. It
is essentially irrelevant whether the detrius has fallen a few
hundred feet down a subcarapace slope into a pediment or
whether it has arrived by a process of mechanical settling and
down-wasting through a few hundred feet of relief. Certainly
the distinction between in situ and detrital laterite/bauxite
is far from clear (McFarlane, 1976, p. 96).

The development of these so-called detrital or slope-bottom
laterites/bauxites is unique in the discussion of laterite/
bauxite formation in that there is little dispute as to how
it occured. The finer details of the chemistry of the altera-
tion or hydration of such semi-detrital laterites/bauxites
may still present problems but on the whole the outline of
their development is based on observation and careful study
of processes rather than on the circumstantial evidence which
provides the basis for theories of high-level laterite genesis.
Dispute does arise, however, when this model is stretched to
explain all laterite/bauxite occurrences, especially the
fossil "high-level" laterites/bauxites now occupying inter-
fluve positions. Thus it has been observed that such low-level
laterites/bauxites can upon further erosion or lowering of
the surrounding unlateritized areas (or areas where the
laterite/bauxite is unindurated) be left standing above the
adjacent country. In effect, the relief becomes inverted.

Many examples of relief inversion have been provided in the more recent literature (Maignien, 1966, p.72; Goudie, 1973, p. 45). Clare's (1960) account of the development of laterite /bauxite "reef" from a catenary soil association provides one example. Brown (1968) has described laterites which occur as long sinous ridges and may have formed as valley laterites/ bauxites. Summit areas where the laterite/bauxite is unexposed and unindurated can be lowered to leave the formerly lower peripheral areas of exposed and indurated laterite/bauxite standing relatively higher (in McFarlane, 1976, p. 97). Laterite/bauxite pediments in Uganda can be seen becoming isolated to form lower mesas, as a result of the erosion of the unlateritized surrounding areas. Thus, it is a demonstrable fact that relief inversion occurs. One may therefore be tempted to explain all the high-level mesas on interfluves in terms of relief inversion, for this is compatible with the one workable model of laterite/bauxite formation, in the form of the so-called detrital or slope-bottom laterites/ bauxites. This hypothesis must, however, be rejected. There are numerous examples of large areas of laterite blanketing uplands underlain by extremely resistant rocks, for example the quartzites in Kyagwe, Buganda. These areas could not conceivably have formed the original lowlands of the old topography. The outstanding problem remains the explanation of these upland areas of laterite/bauxite and various attempts been made to do this by combining the old concept of laterite

/bauxite as a residuum and that of it as a precipitate
(McFarlane, 1976, p.97).

Restating the problem, since these are upland areas and in all
probability were the higher landscape elements at the time of
laterite/bauxite formation, a lateral contribution to laterite/
bauxite must be discredited. Since the underlying pallid zones
are inadequate to account for all the concentrates, an over-
head source must be evoked to explain at least part of the
accumulation. To evoke the existence of an older higher-lying
laterites/bauxites, as the source, evades the issue and in
practice is unworkable to explain very thick laterite/bauxite
resting directly on the highest parts of the landscape. It
becomes necessary to assume that the laterite is in part
residual, or a "relative accumulation"(d'Hoore, 1954).

This is in effect the compromise which de Swardt (1964)
favoured for the development of the groundwater laterites/
bauxites in Uganda. To account for the quantitative inadequacy
of the pallid zones in Uganda (Trendall, 1962), he suggested
both an overhead source and underlying source and postulated
that the profiles moved downwards. He did not, however, move
away from the idea that upward enrichment from the pallid
zone is brought about by the mechanism of a fluctuating water
table. This compromise provides a solution to the problem of
the provenance of concentrates on interfluve areas, reasso-
ciating laterite/bauxite formation with a moving rather than
a static profile. The laterite/bauxite develops as the land

surface is reduced. This theory is however still faced with the problem of the absence of a plausible mechanism for upward translocation of iron, and the incredible magnitude of the water table fluctuations required. It is clear, however, that the role of the pallid zone is changing. Instead of being a means whereby laterite/bauxite accumulations can be explained, it is becoming and end in itself (McFarlane, 1976, p.101).

Du Bois and Jeffery (1955) suggested that not merely part but all the enrichment is derived from an overhead source. The laterite/bauxite is again visualized as a kind of residual precipitate. They suggested that iron goes into solution in the soil and is precipitated on reaching alkaline groundwater. This theory has the merit that it does not require unlikely large-scale upward movement of iron, leaving the formation of the pallid zone to be explained in terms other than as a complement to laterite/bauxite formation. Nevertheless outstanding problems remain. Du Bois and Jeffery did not visualize this process occurring in a lowering profile. They believed that the laterite/bauxite horizon is stable, although the land surface overhead is reduced chemically and mechanically, and this poses the problem that an unlikely thickness of formerly overlying soil material must be postulated to account for the concentrates which may represent the consumption of upto 500 ft (152 m) of parent material (Trendall, 1962). There is no evidence that laterite formation can begin at

such depths. A further objection to this theory concerns the suggestion that iron is mobile in the soil yet stabilized by contact with groundwaters, and du Bois and Jeffery observed in support of this that there is very little iron contained in Ugandan water samples. However, Gear's (1955) study of water supplies in Uganda does not confirm the lack of iron in the groundwaters and this is in keeping with the known mobility of iron under anaerobic conditions. Du Bois and Jeffery's theory requires iron to be mobile under aerobic conditions and stabilized by contact with the anaerobic zone in which it should be innately mobile (after McFarlane, 1976, p. 103).

Trendall's theory of apparent peneplanation (Trendall, 1962) also regards laterite as a sort of residual precipitate. The main source of enrichment was visualised as being the pallid zone. The entire profile was believed to move downwards as the surface is lowered by wash, and thus the zone of water table fluctuation progressively incorporates new material from which it draws iron for the laterite/bauxite horizon. This process was visualized as occurring independently on each interfluve. Surface removal of material was believed to expose a peripheral free-face of laterite/bauxite while the process of laterite/bauxite formation operates, and continued lowering of the profile and surface on each interfluve results in the eventual inversion of the relief within this peripheral

exposure of laterite/bauxite. This theory has several merits.

(a)   It offers an explanation for the inadequacy of the
       pallid zones to account for the concentrates in
       the laterite/bauxite.

(b)   It suggests a mechanism for the formation of the inverted
       summits, or the "soup-plate" form of laterite/bauxite
       mesas.

(c)   It offers reason for the wide variety of altitude at
       which laterite/bauxite mesas occur in Buganda for the
       process is a "steadily acting cause which produces a
       morphological discontinuity" (Penck,1953,p.160). He
       thus considered the Buganda surface to be an "apparent
       peneplain", still forming today.

       The significance to denudation chronology studies of
       this last point is enormous. If both laterite/bauxite
       formation and the development of the breaks of slope-
       bounding laterite/bauxite mesas are acyclic, then the
       use of such features for denudation chronology analysis
       and in particular the use of the Buganda surface as a
       datum are entirely unfounded.

The theory is, however, faced with the same problems as de.
Swardt's (1964):

(a)   It invokes an impossibly large range of water table
       fluctuation :

(b)   There is no known mechanism for such translocation
        of iron;

(c)   In addition, there is no evidence to suggest that the
        present-day water table ever reaches as high as the
        laterite/bauxite on the mesa.

The merits of this theory have been diminished by more recent
studies which suggest :

(a)   that the "soup-plate" form of the mesa is a post-
        incision modification of the surface, and

(b)   that the apparently haphazard altitude range of the mesa
        can be resolved into two groups of in-situ laterite-
        capped mesa with intermediate detrital laterite-capped
        mesas, the products of modification process (after
        McFarlane, 1976, p. 105).

The main contribution of Trendall's theory, therefore, remains,
like de Swardt's (1964), that it offers an explanation for the
quantitative inadequacy of the pallid zone to account for the
concentrates in the laterite/bauxite, again associating
laterite/bauxite formation with a lowering landsurface and
lowering profile.

A further theory of compromise, has been evolved in Uganda
(McFarlane, 1971). It also regards laterite/bauxite as a
residual precipitate. The groundwater laterite is believed
to accumulate as a mechanical residuum during the late

stages of reduction of a downwasting landsurface. The original
precipitates form within the relatively narrow range of
fluctuation of the groundwater table, which sinks as the
land surface is reduced by erosion. They become incorporated
into the lower parts of the soil mantal where they accumulate
as an increasingly thick layer. When down-wasting has ceased
and the water table has stabilized, the residuum is hydrated
and altered, and a massive variety of laterite/bauxite
develops which has every appearance of a true precipitate.
This alteration of a residuum or detrital laterite/bauxite
is very similar to the so called detrital model, but the
vertical lowering of the low-relief landsurface allows the
detritus to cover thickly all parts of it. Like du Bois and
Jeffery's theory (1955) no contribution is believed to have
been provided by the pallid zones which underlie the high-
level laterites/bauxites. This theory is in part based on a
study of the low-level laterites/bauxites which can be seen
to be at various stages of this sequence of landsurface
reduction and laterite development (McFarlane, 1969).
Since the high-level laterites are essentially similar, a
similar process of development was proposed for them also,
and no unlikely magnitudes of water table oscillation are
required. This zone is merely a narrow zone on which iron is
segregated from the saprolite to form discrete bodies or
pisoliths. Large vertical spreads of such precipitates, for
example, those found below the planation surface laterite/

bauxite on mesas are believed not to indicate large fluctuations of water table, but merely the path through which the narrowly oscillating water table migrated as it lowered in response to landsurface erosion. It associates laterite/bauxite formation with a surface of some original relief and not exclusively to planation surfaces, although the end-product, the mature laterite/bauxite, is exclusive to very low relief. This model is in fact merely a mechanical variation of Nagell's model for the development of laterites/bauxites of Cuba in which the laterite/bauxite profile lowers and accumulates its residual content by a continuous process of solution in the upper horizons and deposition in the lower. Since pallid zones occur below some laterites/bauxites, a causal relationship must exist, and it is suggested that the permeable nature of in-situ laterites/bauxites allows the substrata, the saprolite, to be leached after the laterite/bauxite is incized (McFarlane, 1976, p. 107).

The so-called typical laterite/bauxite profile consisting of massive laterite/bauxite underlain by spread of pisoliths or mottles, underlain by pallid zones is thus believed to be the product of two cycles of erosion, (the end of the first and the beginning of the second) and the pallid zone may in fact be currently forming i.e., acyclic, if the permeability of the laterite/bauxite has been maintained since the incision.

Ida Valeton (1983) described the formation of lateritic/ bauxites world-wide in Cretaceous and Tertiary coastal plains. The bauxites form elongated belts, sometimes hundred of kilometers long, parallel to Lower Tertiary shorelines in India and south America and their distribution is not related to a particular mineralogical composition of the parent rock. The lateral movement of the major elements Al, Fe, Ti is regarded by Valeton as dependent on a high level and flow of groundwater. Varying efficiency of subsurface drainage is believed to produce lateral facies variations. Interfingering of marine and continental facies indicate a sea-land transition zone where the type of sediments also varies with minor tectonic movements or sea-level change. A typical sediment association is found in India, Africa, South and North America. It consists of (i) red beds rich in detrital and dissolved material of reworked laterites/bauxites, (ii) lacustrine sediments and hypersaline precipitates, (iii) lignites intercalated with marine clays, layers of siderite, pyrite, macasite and jarosite, and (iv) marine chemical sediments rich in oolitic iron ores or glauconite. Lateritic bauxites are considered to be part of an alteration blanket, which is formed by in-situ pedogenic processes leading to extremely intensive geochemical separation of Si, Al, Ti and Fe. This process always leads to a vertical division into three major soil horizons:

Horizon rich in oxides   .. B_{ox} (Fe,Al)

Horizon rich in silicates(saprolite).. B_{sap}

Horizon of fresh parent rock   ..   - C

Normally the soil sections are truncated. The A-horizon is always eroded, Valeton (1983). After the Soil Taxonomy of the U.S. Department of Agriculture (1965), this type of lateritic bauxite belongs to the subgroup of aquox in the group of oxisols which are soft during the time of formation. During uplift above the groundwater level, the Fe-rich parts form hard ferricretes, whereas the Al-rich parts become hard alucretes (Goudie, 1973).

At Mewasa a definite pattern of lateral petrographic and geochemical differentiation is developed. The lateral sequence shows enrichment of Fe to the north-east and enrichment of Al in the opposite direction (Veleton, 1966). Since the well preserved relic textures indicate that the original volume of the parent rock is also preserved, the isovolumetric method of Millot and Bonifas (1955) may be used for calculating the geochemical balance. Thus it is possible to prove that besides the relative enrichment, there is absolute enrichment of Fe in the north-eastern part, whereas Al and Ti are enriched absolutely in the south-western areas. The only explanation for this phenomenon is the lateral movement of all major elements (Al, Si, Fe, Ti) leading to a lateral facies differentiation from a kaolinitic laterite to an Al-rich bauxite.

For the solution, migration and precipitation of major and minor elements within the bauxitic alteration blanket, the following ground-water conditions must be fulfilled (after Valeton, 1983).

(1)   net flow towards the sea;

(2)   ground-water levels must be high and oscillatory in nature;

(3)   Eh - conditions must be reducing.

Lateral differentiation is especially well developed in the uppermost zone. Iron-rich ferricretes are exposed on the landward side and pass seawards into an Al-rich alucrete. It is suggested that the groundwater level intersects the transition zone and that Fe was also removed from this level by groundwater flow. Al, which is less mobile than Fe, remains and both zones are indurated to form crusts when the region finally emerges beyond the reach of the water table. In coastal plains, the groundwater level rises periodically to form superficial lakes (e.g., monsoon or seasonal floods). During high groundwater level, Fe migrates upward in the bivalent state, and during the dry period it is oxidized to Fe^{3+} and transported (Valeton, 1983). Iron can only be dissolved and transported in the bivalent state under reducing conditions. As long as the alteration blanket is water-saturated, it has a soft colloidal consistency. Al as well as Ti, Fe, Si migrate in solution, but because of their varying

mobility they are transported to different parts of the altera-
tion blanket. Elements with the highest mobility are most
easily transported by the groundwater to the sea. Eh and pH
conditions are affected by vegetation and groundwater
circulation. As the latter is influenced by basin topography.

McFarlane (1983) has raised objections to Valetons' extension
of this model to all elevated bauxitised plateau in India and
elsewhere by stating that in such a littoral palaeoenviron-
ment for the formation of bauxite/laterite, there must have
been a string of islands along a former coast, but the absence,
on one side of the belt of islands, of a more or less conti-
nuously bauxitised strip corresponding with the former
postulated coastline argues against this hypothesis. Also it
seems a quite incredible coincidence that scarp retreat has
so consistently reached precisely the bauxitised part, neither
progressing beyond it nor falling short of it. Moreover, if
a palaeocoastal environment is relevant here, the bauxitiza-
tion should be at a constant altitude around the plateaux,
whereas, it flanks plateaux of considerable relief. It seems
unlikely, therefore, that a littoral palaeo-environment
explains the present peripheral enrichment.

Recently, McFarlane (1987), has put forward a new aspect for
the genesis of bauxite, emphasizing upon the key role of
micro-organisms. According to her, geochemistry has been the
main input in the interdisciplinary study of bauxite and
laterite, whereas bauxitization can occur on many rock types.
Emphasis on a geomorphological control is made, with sites

favourable to aggressive leaching being predisposed to bauxi-
tization. Better bauxitization on higher and older land-
surfaces appear to indicate that time could be as effective
as leaching aggression. However, alternative explanations
for the variation in bauxitization with altitude, in terms of
present and palaeoclimates, require adequate assessment of
the relative roles of leaching aggression and time. Though
data indicates increased bauxitization during hot and wet
periods in the past, these fluctuations are set within a
pattern of overall increase to the present time, where in
the world climates have become cooler and drier since the
Oligocene. This points to another control-biological, which
becomes even more logical by the failure of geochemical
explanations for both the accumulation of Fe- and Al-
enriched residua, following kaolinite dissolution. The
simultaneous removal of Al and Si in solution during congruent
kaolinite dissolution is impossible as immediate co-preci-
pitation occurs.

Following incongruent kaolinite dissolution, Al enriched
residua, are difficult to explain in conjunction with removal
of iron. Up-profile changes in Fe minerals and loss of Fe
from the pallid zone, similarly present serious difficulty.
The geochemical constraints on element mobility, the source
of the difficulty, do not apply to biologically complexed
materials.

The author's genetic model is based on the following :

(1) Ambient climatic conditions during the Early Eocene
    times for latertization/bauxitization in Jamnagar.
    This is based on palaeoclimatological projections made
    by Bardossy (1981) and on the studies of drift tectonics
    as related to latertization in NW-India made by Sychan-
    thavong and Patel (1987). This type of correlation has
    not been made in previous genetic models for the study
    area.

(2) Valeton (1983), has not adequately taken into account
    the role of geomorphology in her genetic model. The
    author places a lot of emphasis on geomorphology. He
    agrees with McFarlane's (1983) statement "In a tecto-
    nically stable area, lateritization can be placed
    within the late stages of landsurface reduction".

(3) The author agrees with Valeton's (1983) premise that
    the lateritization/bauxitization in Jamnagar took place
    in a near shore environment. The argument in favour of
    this and incorporated in the present model, is that
    the leading edge of the Deccan Trap basalts which came
    into contact with the early Tertiary sea, developed
    extensive jointing and pillow structures. This made that
    entire portion and some area inland, highly amenable to
    weathering by groundwater. This could also be a possible
    reason for the lateritization of a narrow strip of

Deccan Trap basalt, while the whole region experienced
a similar climatic regime.

(4)   In contrast to Valeton (1983), the author has processed
        his chemical data by using a Ti-retained mass-balance
        model of several profiles. From this, it is clear that
        Fe and Al enrichment was associated with a lowering land
        surface and hence implying an overhead source of enrich-
        ment in contrast to Valeton's model of upward enrichment
        which requires zones of Al depletion below the bauxite.
        This is in contradiction with Valeton's premise that
        upward enrichment was followed by lateral segregation.

Genesis of the Laterites/Bauxites of Jamnagar

Despite earlier abortive attempts to exclude genesis, the most
modern redefinition of laterite/bauxite has clear genetic
implications: "Laterities/Bauxities are products of intense
subaerial rock weathering whose Fe and/ or Al content is higher
and Si content lower than in merely kaolinized parent rock
(Schellmann, 1981)".

In order to achieve such a selection, several physical and
chemical factors come into play and they are:
(a) climatic conditions, (b) morphology, (c) parent rock,
(d) chemistry of weathering of Deccan Trap basalt, and
(e) the process of lateritization/bauxitization.

In order to arrive at a proper understanding of the exact
modus operandi of lateritization/bauxitization in Jamnagar

it would be worthwhile to discuss in detail all the above points.

Climatic Conditions

The early Eocene laterite/bauxite profiles of Jamnagar are
supposedly fossil in nature having been formed in the past.
Applying the concept of uniformitarianism to these laterites/
bauxites, it would be logical that the same climatic conditions
were responsbile for the formation of present day laterites/
bauxites in Jamnagar. To have an idea of the climate of
formation we have to rely on the science of palaeoclimatology.
The present knowledge in this field can be summarized as
follows (Bardossy, 1981):

i)   During the Archaean Era the surface temperature was $50°$
      to $80°C$. The palaeoatmosphere consisted mainly of CO_2
      with much N_2, H_2, NH_3, CH_4 little or no O_2. There was
      no vegetation on the land surfaces resulting in a fast
      and intensive erosion. Chemical weathering was intensive,
      but had a more alkaline and more reducing character
      than today.

ii)   During the Proterozoic Era plus the Cambrian, Ordo-
      vician and Silurian periods, the surface temperature
      was $30°$ to $50°C$. The atmosphere had a slowly growing O_2
      and a diminishing CH_4 and NH_3 content, H_2 disappeared
      totally. Chemical weathering and the intensity of
      erosion were essentially the same as during the Archaean
      Era.

iii) The most important landmark of palaeoclimatology is the appearance of land vegetation during the Devonian period. As a consequence, the intensity of erosion diminished, the distribution of precipitation on the continents changed and finally the photosynthesis of the plants increased the O_2 content of the palaeo-atmosphere.

iv) The Carboniferous period was characterised by a warm climate, by abundant forest and marshy vegetation, but the palaeoatmosphere had still more CO_2 and less O_2 than today and the surface weathering conditions had a more reducing character.

v) Since the Permian period, palaeoclimatic conditions grew similar to the recent one although some important palaeo-climatic fluctuations - mainly in the surface temperature - have been detected during the Mesozoic and Cenozoic eras too.

The climatic conditions of bauxite and laterite formation are currently satisfied only between the latitudes 30°N and 30°S. But some Mesozoic bauxites extend to 60°N and some Palaeozoic ones even to 70°N beyond the Arctic circle - as for example on the Taymir peninsula and in the polar Urals, USSR.

The tropical climate necessary for the formation of laterites is restricted to the linear equatorial zone with the exception of topographically controlled areas. In order to explain the

formation of the Jamnagar laterites/bauxites along with thick
forests present then, we have to take into consideration the
drift tectonics of the Indian plate as it was moving across
the equatorial zone. As shown in (Fig. 52)the Jamnagar
laterites/bauxites when plotted on a map of India along with
the other Palaeocene and Eocene laterites/bauxites of Gujarat,
Rajasthan, NW Uttar Pradesh and Jammu-Kashmir states of India,
show a very conspicuous linear alignment (Sychanthavong and
Patel, 1987). This linear belt is now trending in a NE-SE
direction. If we consider the palaeoposition of the Indian
plate during its early stages of drifting from the Gondwana
land, it is found that it was trending E-W coinciding with
the alignment of the latitudinal positions (Fig. 53). It
can be implied that these Palaeocene laterites must
have developed when the Indian plate was in the equatorial
zone. The timespan for the development of these laterites/
bauxites was quite short. This corresponds to the speed and
the time spent by the Indian plate in the equatorial zone as
determined by the studies of magnetic anomalies of the Indian
Ocean and the Arabian sea floor (Sychanthavong and Patel,
1987). The thick tropical forest of this period would not
have survived under a climate with lesser rainfall which was
encountered when the northern part of the Indian plate moved
above latitude 0°N prior to 53 million years. These forests
were ultimately destroyed and deposited as lignite seams in
depressed areas during the early Eocene. Hence it is logical

FIG. 52.
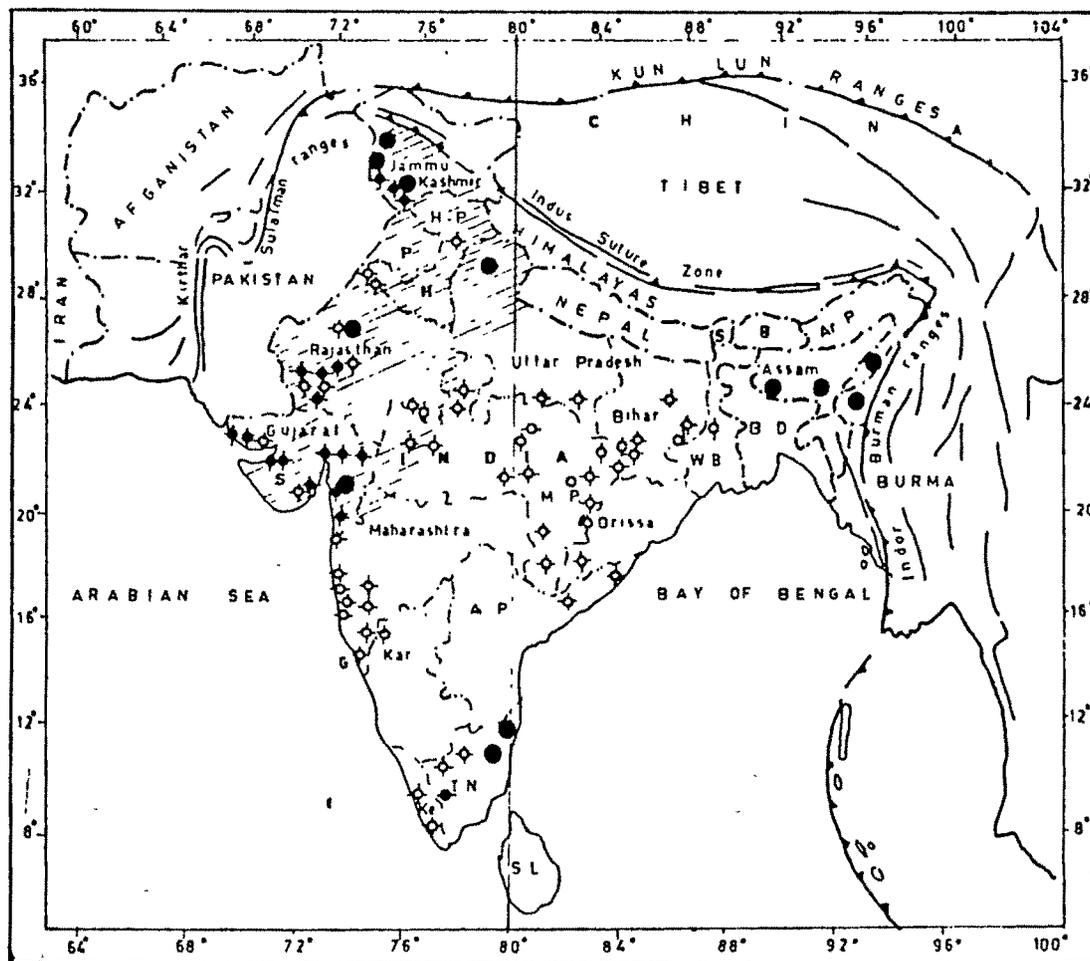
Distribution of Tertiary laterites, bentonites, bauxites and lignites (with gradual decrease in age from north to south). The plots within stripped lined area are Palaeocene in age

Filled circles with four-sided dashes represent laterites and bauxites under discussion; open circles with four-sided dashes are also laterites and bauxites, the details of which are under preparation; open circles with two-sided dashes denote bentonites and Fuller's earths; and solid circles are lignites and coals. K and S in Gujarat state indicate Kutch and Saurashtra respectively; and the other alphabetical symbols correspond to the names of various Indian states

FIG.53
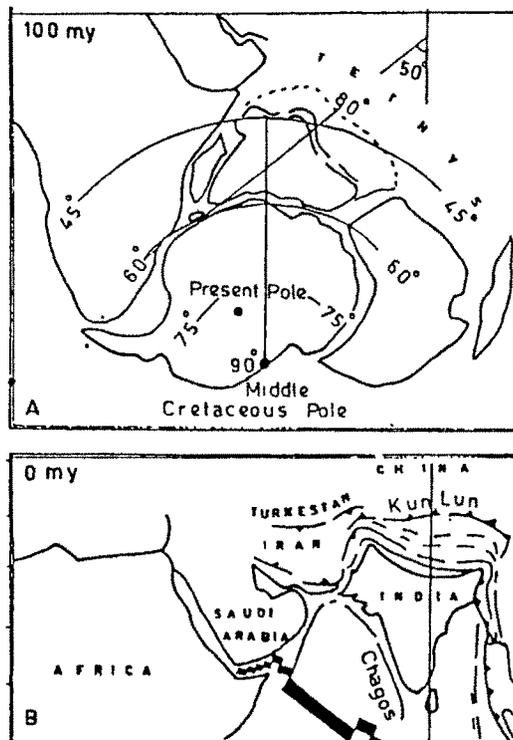
A. Palaeopositions of the Indian plate and other surrounding continents in the Gondwanaland (after the best fit of Smith and Hallam[28]). This illustrates the position of the Indian plate with the alignments of the then latitudes and longitudes. The location of the Middle Cretaceous pole is after Creer (Earth Science Reviews, 6, 369–466). The shape of India is presented in terms of Greater India's Concept, indicated by broken line. B. Present configuration of the Indian plate having been rotated anticlockwise for a total amount of 50° with respect to its original position in the Gondwanaland.

to suggest that the Indian plate was rotated by 40° in an anticlockwise direction, after this particular linear laterite/bauxite belt had crossed the equatorial zone while the total rotation was 50° (Fig. 54). Thus the Indian plate was rotated by only 10° or even less during its journey in the southern hemisphere. This geological evidence is in agreement with the reconstruction of the palaeoposition of the Indian plate and the age of the ocean floors, right from the early stage of its break up and the opening of the Indian Ocean and the Arabian sea (Sclater and Fisher, 1974). According to this reconstruction, it is found that southern India spent a longer time in the equatorial zone, i.e.,between 53 m.y. and less than 32 m.y. It has been discovered that the initial speed of drifting of the Indian plate was very fast. 17 cm/year total rate, it decelerated and then stopped around 56 m.y. ago, and again started drifting with a much slower rate (McKenzie and Sclater, 1971). This has been possibly attributed to its leading edge having reached the subduction zone in the Tethys Sea to the north. This must be the only logical reason to explain why the southern Indian continental plate was spending a lot of time in the equatorial zone (Syschanthavong and Patel, 1987).

The age of the whole Indian Tertiary laterites/bauxites and lignites decreases from north to south in concordance with the drift tectonic history of the Indian plate across the

FIG.54
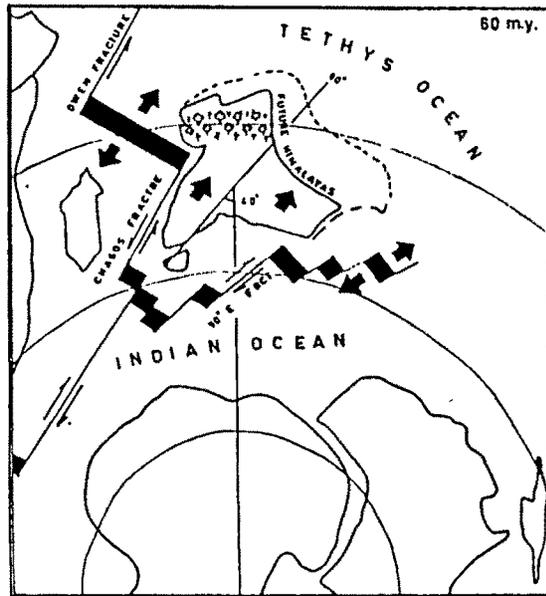
Palaeoposition of the Indian plate during which the northwestern laterite and lignite belt was being formed, indicated by forested area. Broken line indicates the possible extension of Greater India which we believe to have drifted away much earlier than the main Indian plate

equator. Based on these data, the palaeoclimatic reconstruction in this continental plate under equatorial conditions can be suggested following the concept of climatic distribution and precipitation over various hypothetical continents of different shapes and sizes in the equatorial zone - (Robinson, 1973) (Fig. 55).

Frakes and Kemps (1972), completed the continent reconstructions by ocean-current evaluations, by sea water temperature determinations - based on oxygen isotope measurements - and by palaeobotanic data about the land vegetation. The resulting palaeoclimatic map shows that during Eocene (Fig. 56) the conditions were extremely favourable allowing bauxite formation until 50-55° latitudes. Actually, all Eocene bauxites were situated in the tropical monsoon areas.

Conversely, Bardossy (1973, 1979) questioned the validity of the fact that bauxites were formed when conditions were particularly hot and wet. He published data on the percentages of world karst bauxite in the stratigraphic succession and provided estimates of silicate bauxite. The pattern for silicate bauxite broadly follows that of karst bauxite, for which greater detail is available (Fig. 57). Karst bauxite maxima, coinciding with hot, wet periods occur in the Carboniferous, Late Cretaceous to Eocene and the Mio-Pliocene. Adjustment to an equal class interval (Fig. 58) clarifies these maxima and also highlights their insetting within an

FIG. 55
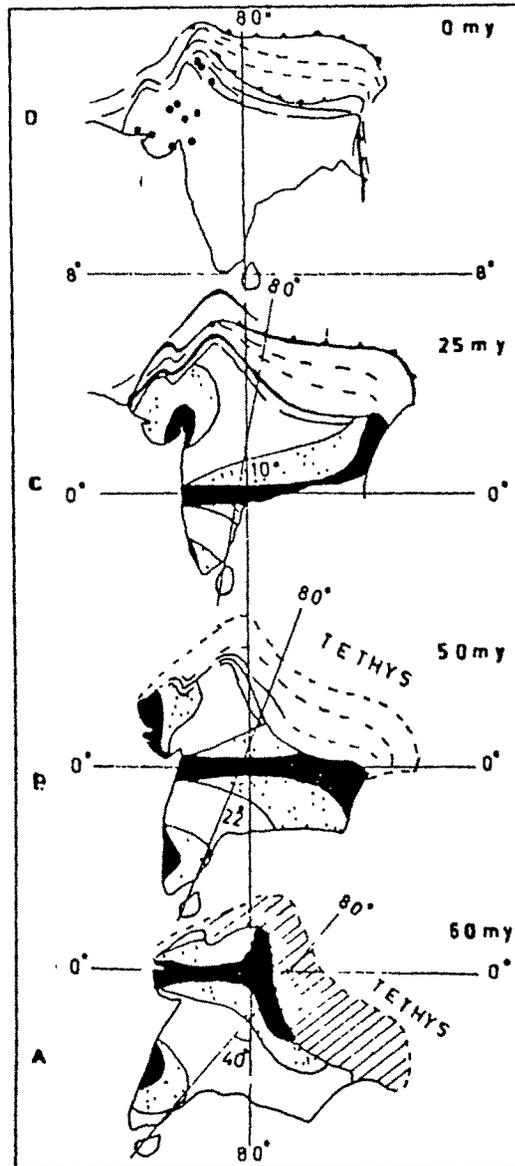
A, B, C. Palaeoclimatic reconstruc-
tion of the Indian continental plate during its course
of drifting across the equatorial zone. Construction
is based on the available laterite and lignite data
with respect to the recent wind circulation and
climatic classification in terms of precipitation (Ear-
ly Palaeocene, Early Eocene and Late Oligocene
respectively). D. Present-day configuration with the
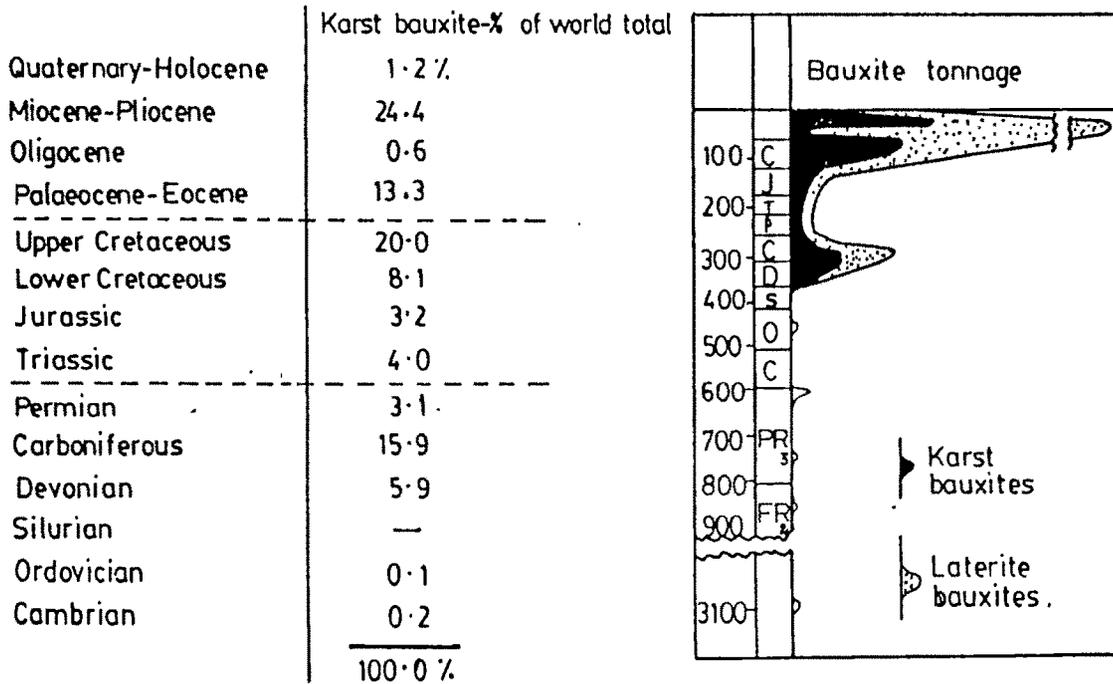distribution of the northwestern laterite and lignite

FIG. 56

RECONSTRUCTION OF WEATHER PATTERNS IN EOCENE
(After Frakes and Kemp, 1972)
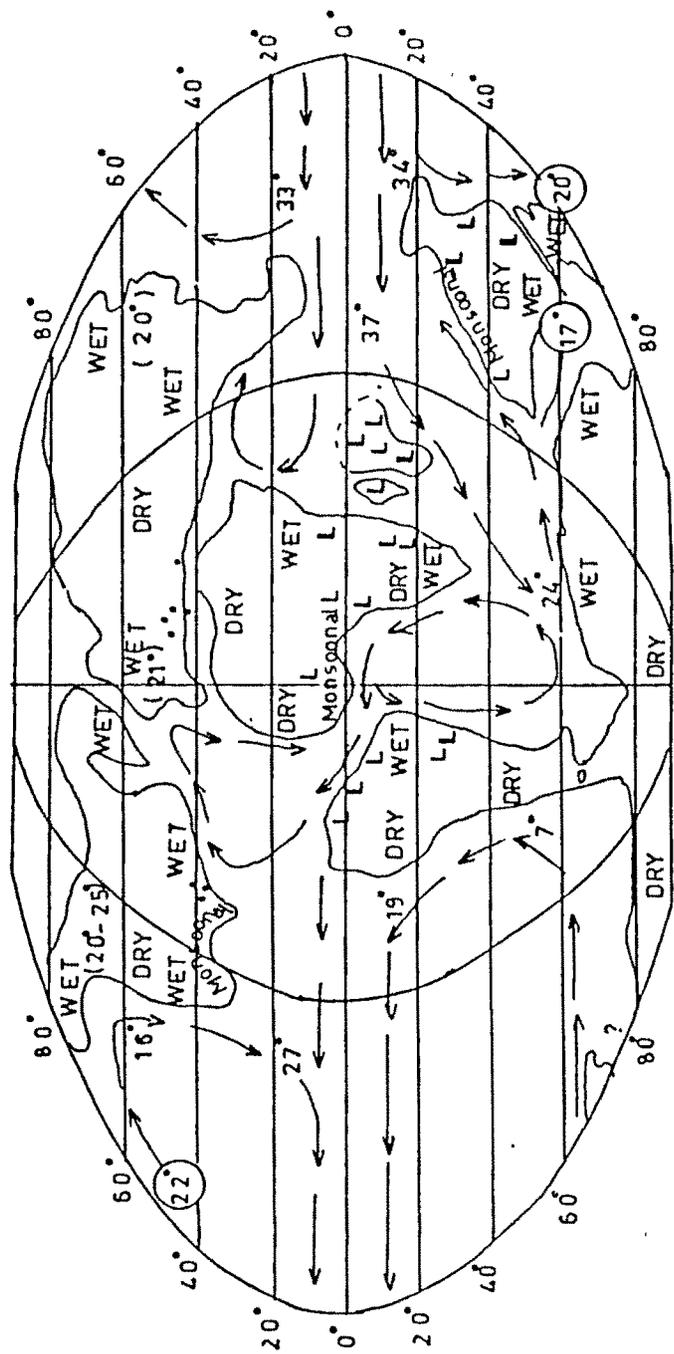
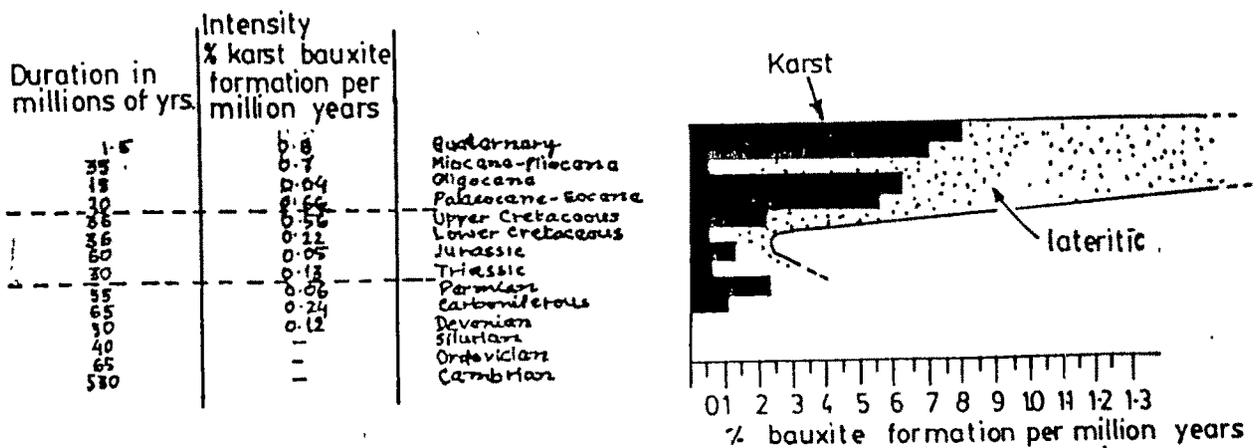20° OXYGEN ISOTOPE PALEOTEMPERATURE

(20°) MEAN ANNUAL TEMPERATURE (AIR)

L LATERITIC BAUXITE

KARSTIC BAUXITE

FIG. 57   318

	Karst bauxite-% of world total
Quaternary-Holocene	1·2 %
Miocene-Pliocene	24·4
Oligocene	0·6
Palaeocene-Eocene	13·3
Upper Cretaceous	20·0
Lower Cretaceous	8·1
Jurassic	3·2
Triassic	4·0
Permian	3·1·
Carboniferous	15·9
Devonian	5·9
Silurian	—
Ordovician	0·1
Cambrian	0·2
	100·0 %

(after Bardossy 1979, 1973; in McFarlane 1987)

FIG.58

Duration in millions of yrs.	Intensity % karst bauxite formation per million years	
1·5	0·8	Quaternary
35	0·7	Miocene-Pliocene
15	0·04	Oligocene
30	0·66	Palaeocene-Eocene
36	0·56	Upper Cretaceous
36	0·22	Lower Cretaceous
60	0·05	Jurassic
30	0·13	Triassic
35	0·06	Permian
65	0·24	Carboniferous
50	0·12	Devonian
40	—	Silurian
65	—	Ordovician
580	—	Cambrian

01 2 3 4 5 6 7 8 9 10 11 12 13
% bauxite formation per million years

Variations in the intensity of bauxitisation during the different geological periods (after McFarlane 1987)

overall pattern of progressive increase to the present time (McFarlane, 1983). This pattern of general increase, established for karst bauxite, is now confirmed for silicate bauxite (Bardossy, 1983). If aggressiveness of leaching is the key control on bauxitisation, this poses a severe problem, that of explaining this general increase, particularly since the Oligocene, from which time there has been a long slow decline in radiation balance, and effectively deteriorating conditions for bauxitisation (Fig. 59).

GEOMORPHOLOGY OF THE STUDY AREA

The arcuate outcrops of laterite-bauxite are always convex towards the gentler flank (slope 2° to 7°) along which bauxite deposits have developed. The concave side, on the other hand is a steep escarpment (slope 70° to 85°) facing the exposures of Deccan Trap basalts. Whether the outcrops are arcuate or round to oval amphitheatre-like, the bauxite deposits occur, almost as a rule, along the outward gentler radial flank. A closer study of the topography of the belt would reveal more or less satisfactory explanations of the fact that, the concentration of major bauxite deposits has taken place in the northern part where the bauxite is also of high grade, but frequently rich in the lime content. The deposits of the southern part are scattered, smaller in size, poorer in grade and rich in combined silica.
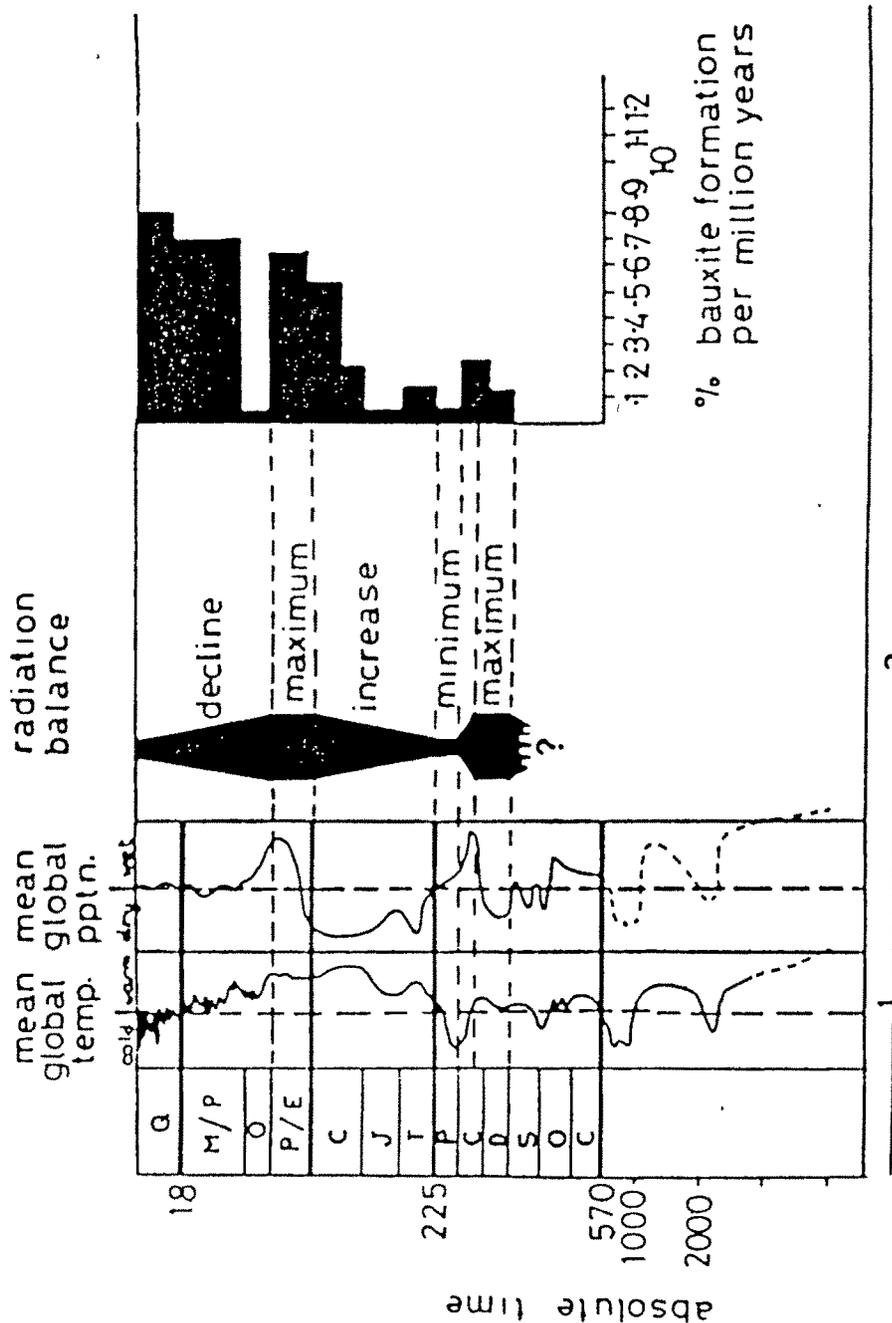
FIG. 59

1 — after Frakes 1979   2 — after Bardossy 1979a & b

The relationship between intensity of bauxitisation and palaeoclimatic conditions.
(in McFARLANE, 1987)

The laterite-bauxite horizon of the northern and southern area shows the following contrast in their geomorphic setting:

In the northern area, there is a conspicuously greater frequency of occurrence of round to oval conical structures, with which laterite-bauxite is associated.

The laterite-bauxite profile in the north generally shows a higher gradient (3° to 7°, average 5°) in contrast to the southern area, showing a sub-horizontal to a maximum of 3°.

All these points tend to suggest that the development of bauxite is (i) genetically related to the geomorphology of the volcanic cones, (ii) probably favoured by gentle slopes rather than a flat surface and, (iii) facilitated by a better drainage condition. A comparison of the laterite-bauxite profiles of the north and south indicate that laterite-bauxite profile of the north show a greater degree of post-bauxite erosion with subsequent re-deposition of bauxite which has been partly preserved along the lower part of the slopes or along the axis of a valley. No redeposition, concealed or exposed bauxite zone is encountered in the south. The variation in the degree of post-bauxite erosion can be attributed to the fact that the northern area is at higher level from the base level of erosion (mean sea level), while the southern area was nearer to it during and subsequent to the formation of laterite-bauxite.

There are also cases of bauxitisation being restricted to, or
more deeply developed, in the vicinity of faults which afford
preferred passages for through flowing drainage (McFarlane,
1987). In short, there is now little doubt that topographic
situations conducive to freedom of drainage constitute an
important control on the chemical routes taken by lateriti-
zation processes.

In the context of cyclic landsurface development, the formation
of a lateritic/bauxite residuum is placed within the late stages
of landsurface reduction (McFarlane, 1976). It is difficult to
reconcile extremely aggressive leaching with advancement of
leaching in this context because progressive lateritization
is associated with relief reduction and an increasingly
unfavourable hydrological regime, evacuation of solutes
becomes more sluggish as relief is reduced. Locally, therefore,
bauxitisation is best placed as a separate chronological event
(McFarlane, 1987). Elevation of a low relief lateritized
surface, and its incision, would revive vadoze conditions and
initiate the necessary leaching aggression by lowering the
water-table. Thus, bauxitization would post-date the surface
with which it is associated.

The superior bauxitization associated with faults and various
favourable rock textures and structures, sites of facilitated
leaching, could hardly be realised when the water-table lay

near the landsurface and the profile was almost saturated.
Post incision formation is implied (McFarlane, 1987).

In India, degree of bauxitization of elevated plateaux is
related to the degree of dissection (Rao and Ramam, 1979;
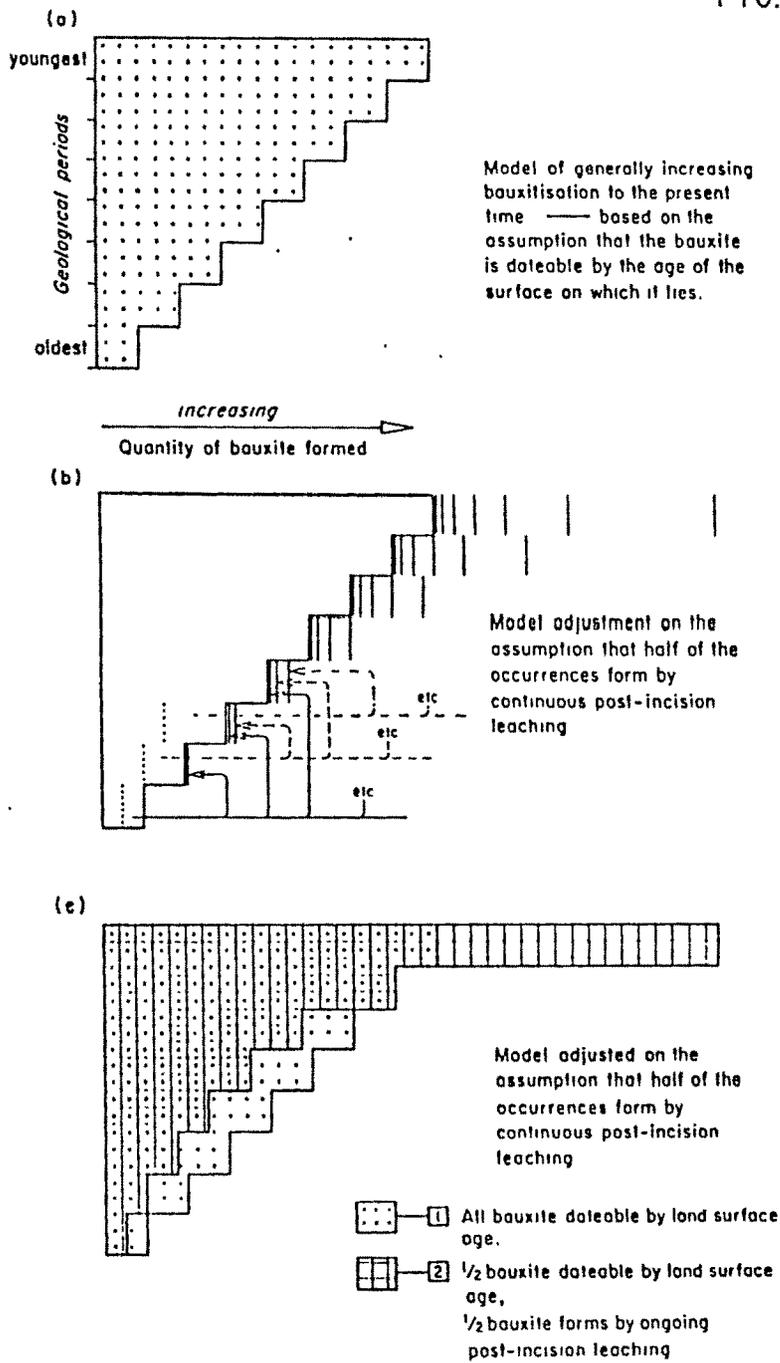Bardossy, 1983).

In the Darling Range, West Arustralia, a bauxitised laterite
occurs draped along the crest of an escarpment, bounded on
the west by a recurrent fault. The protore is a packed
pisolithic groundwater laterite/which could not have formed
on top of the escarpment and must therefore, predate the
emergence of the escarpment as a pronounced topographic
feature. Since bauxitisation closely coincides with the high
rainfall area it must pertain to a time when relative relief
was much as it is today. The formation of the protore and
its bauxitisation appear therefore to be chronologically
separate events (McFarlane, 1987). Contemporaneous bauxi-
tization in high level situations is clearly demonstrated by
the albeit rare occurrence of direct bauxitization, that is
the immediate transformation of primary minerals to gibbsite
at the bottom of the profile; this can be seen in the direct
gibbsitization of the phonolite exposed at the rim of the
Pocos de Caldos caldera in the Minas Gerais district of
Brazil (McFarlane, 1987). In the 50 m peripheral escarpment
of bauxite on Galikonda Hill, Eastern India, there is direct
gibbsitization of aluminous reactive primary minerals at

the base of the profile, developed from khondalite. Such situations provide a clear choice of interpretation. If the bauxitisation is the same age as the surface, then there is no weathering whatsoever today, this despite the monsoonal climate. Or, there is a contemporaneous weathering, that is bauxitization, in which case bauxite formation is younger than the landsurface with which it is associated (McFarlane, 1987).

We have no means of assessing how much of the bauxitisation on ancient plateaux is younger than the surfaces with which it is associated. Even if we assume that as much as half . (Fig. 60) may be original and correctly dated as contemporaneous with the surface, the redistribution of the other half throughout the post-incision period dramatically increases the already established pattern of general increase to the present time (McFarlane, 1987).

As stated earlier, the laterites/bauxites of Jamnagar occur in the Cretaceous-Tertiary coastal plains as an elongate belt, These laterites/bauxites are considered to be part of an alteration blanket which was formed by in situ pedogenic processes acting over the peneplaned surface of Upper Cretaceous - Palaeocene Deccan Trap basalts which had a considerable relief. This is similar to the requirements stated by McFarlane (1983). In order for a chemical residuum

FIG. 60

(a)

youngest

Geological periods

oldest

Model of generally increasing
bauxitisation to the present
time ——— based on the
assumption that the bauxite
is dateable by the age of the
surface on which it lies.

increasing

Quantity of bauxite formed

(b)

etc

etc

etc

Model adjustment on the
assumption that half of the
occurrences form by
continuous post-incision
leaching

(c)

Model adjusted on the
assumption that half of the
occurrences form by
continuous post-incision
leaching

[:::]—[1] All bauxite dateable by land surface
age.

[⊞]—[2] ½ bauxite dateable by land surface
age,
½ bauxite forms by ongoing
post-incision leaching

The temporal distribution of bauxitisation—model of the effects of re-allocation of half of the
lateritic bauxitisation to the entire post-incision period

(After Mc FARLANE 1987)

to accumulate, the relief should be sufficiently low to allow the products of chemical selection to accumulate more rapidly than they are removed by mechanical erosion. Steep slopes therefore, prevent laterite accumulation. As slopes are reduced, a progressively greater part of the rainfall infiltrates the profile to effect chemical selection and a lesser part comprises run-off which may remove the products of that selection. The slope at which the lateritization may begin will vary with the permeability of the materials and also with the vegetation cover which affects the proportion of infiltration and the degree of protection from erosion afforded to the residuum. The efficiency of the process will vary from small beginnings when slopes are sufficiently steep for some mechanical removal of residua to occur, to small endings when slopes are so low that chemical selection is hampered by the proximity of the water-table to the landscape, which inhibits the removal in solution of the more mobile componenents. Thus, in a tectonically stable area lateritization can be placed within the later stages of landsurface reduction (McFarlane, 1983).

During the early Eocene (i.e. the lateritisation period) the Jamnagar area must have been tectonically stable.

Drainage

Most of the laterites of Gujarat State including those of Jamnagar are found on continental margins. The interfingering

of marine, fluvial and terrestrial sediments in this laterite belt (Valeton, 1983) indicates that the alteration which took place from Deccan Trap basalt to laterite occurred in a near-shore environment.

The drainage in the laterite belt, i.e., the edge of the Deccan Trap basalts which came in contact with the early Tertiary sea, can be divided into two. This division is totally dependent upon the cooling structures developed, with a high degree of jointing and pillowing dominant in the leading edge, with a lesser intensity of the same structures inland (Fig. 61).

Naturally, near the leading edge, the drainage would be much freer than in the inland area.

As described earlier, the generalised section in the laterite/bauxite area of Jamnagar is as follows:

Horizon rich in oxides	.. B_{ox} (Fe, Al)
Horizon rich in silicates (saprolite)	B_{sap}
Horizon of fresh parent rock	C

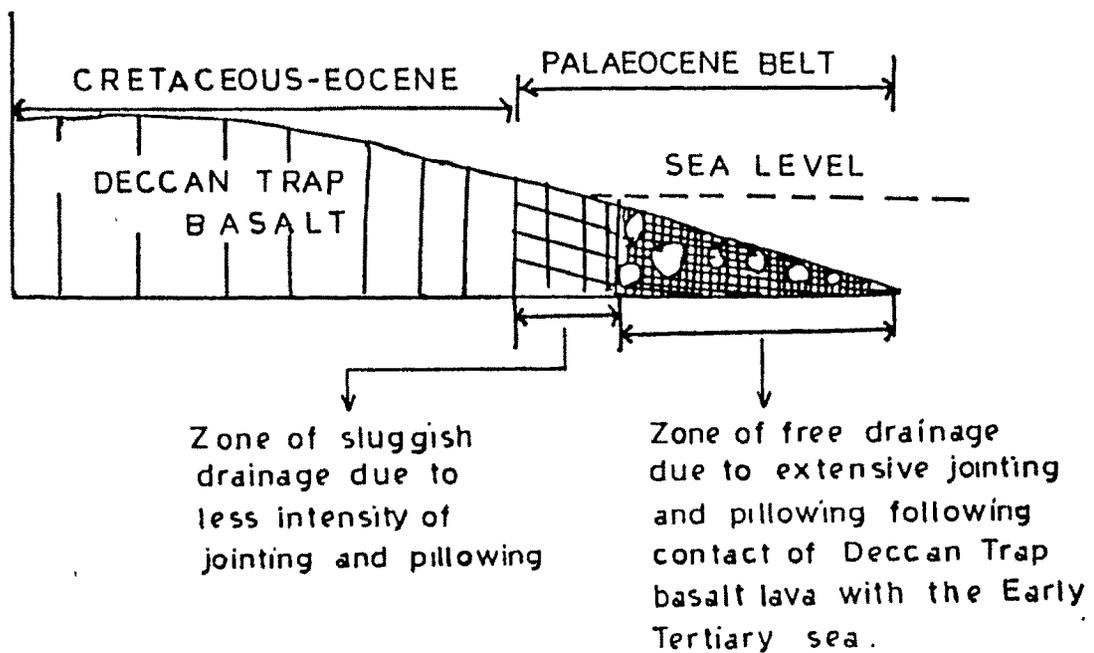For the extensive development of bauxite deposits in Jamnagar, the drainage must have been very good.

Parent Rock

Laterite development has often been related to what are described as suitable rocks (Woolnough, 1918; Hanlon, 1945) but different authors have had conflicting opinions as to what constitutes

DIAGRAMMATIC REPRESENTATION OF THE NATURE OF THE
LEADING EDGE OF THE DECCAN TRAP BASALT WHEN IT
CAME IN CONTACT WITH THE EARLY TERTIARY SEA

CRETACEOUS-EOCENE

PALAEOCENE BELT

DECCAN TRAP
BASALT

SEA LEVEL

Zone of sluggish
drainage due to
less intensity of
jointing and pillowing

Zone of free drainage
due to extensive jointing
and pillowing following
contact of Deccan Trap
basalt lava with the Early
Tertiary sea.

suitability. Woolnough, for example, maintained that there
is very little tendency to laterite formation on anything but
the basic rock types (Woolnough, 1918, p. 389). Simpson (1912),
considered suitable rocks to be largely composed of metallic
silicates, especially granite and greenstones of common types,
as well as amphibolites, epidiorites, chlorite schists and
other similar rocks. Holmes (1914), noted that gneisses and
basalts were particularly suitable, and Maud (1965) noted a
preferential development on sandstones. Pallister (1954),
observed a preference for metasediments, and Wayland (1935)
for igneous rocks.

Certain rocks were considered unsuitable for laterite develop-
ment. Holmes (1914), noted its absence on granites and sedi-
mentaries. Maud (1965), also noted its absence and Pallister
(1954) its poor development over granite. Wayland (1935)
recorded poorer development over metasediments and entire
absence over quartzites.

In fact, it appears that laterite development is not confined
to certain rocks, but occurs over a great variety if not all
rock types (McGee, 1880; du Preez, 1949; Mennell, 1909,
Mulcahy, 1961; Scrivenor, 1933; de Weisse, 1954; Walther, 1915;
Gozan and Vera, 1962; Blondel, 1954; Campbell, 1917; Alley,
1970; Grubb, 1963; Mabbutt, 1961).

Depending upon the chemical and mineralogical composition of the parent rock, laterites are classified into the following groups: (Harder, 1951) :

(1) Those derived from rocks rich in alkali-aluminium silicates, particularly the felspathoids, with alkali felspars, pyroxenes, amphiboles, and micas, but no quartz:

(2) Those closely associated with limestones and presumably resulting from the decay of their residual products;

(3) Those derived from the weathering of hydrous aluminium silicate rocks such as sedimentary clays with little free quartz;

(4) Those associated with intermediate and basic rocks such as diorite, gabbros, dolerite and basalt, containing abundant calcium-aluminium and calcium-magnesium-iron silicates, but little or no quartz:

(5) Those resulting from the intensive weathering of various moderately aluminous igneous, metamorphic and sedimentary rocks such as granite, syenite, gneiss, schist, phyllite, slate, and shale, containing more or less quartz.

These anomalies are informative, for if in one area laterite development is favoured by a particular lithology while in another its development is apparently inhibited by the same lithology. This suggests that other environmental factors are

operative if not dominant in its development.

A classic example of this illustrated by the laterites/bauxites of Jamnagar district. Here, the occurrence is in the form of an elongate early Eocene belt, fringing the Deccan Trap basalts towards their Tertiary contact. From this occurrence itself, it can be deduced that though the whole of the Trap basalts were experiencing the same climatic conditions, only a narrow strip of the basalt underwent lateritization

One can question as to why this narrow belt underwent lateritization with the major portion of the Deccan Trap formation remaining unaffected. A possible cause can be that the linear early Eocene belt, representing the edge of the outpouring of the Deccan Trap basalts came in contact with the early Tertiary sea and this sudden cooling of the lava all along the palaeo-shoreline must have caused extensive pillowing and joint formation. This is manifested in the weathering profiles where extensive relict spheroidal structures are observed. These cooling structures paved the way for the easy access of rainwater and groundwater, which in turn accelerated the process of the chemical decay of the parent Deccan Trap basalt along its leading edges.

Strakhov (1967), has given a sketch of a weathering mantle in areas that are tectonically inactive (Fig. 62). From the diagram it is clear that in a tropical forest zone, the highly leached surface layers consist of a residue of ferric oxide

FIG. 62.
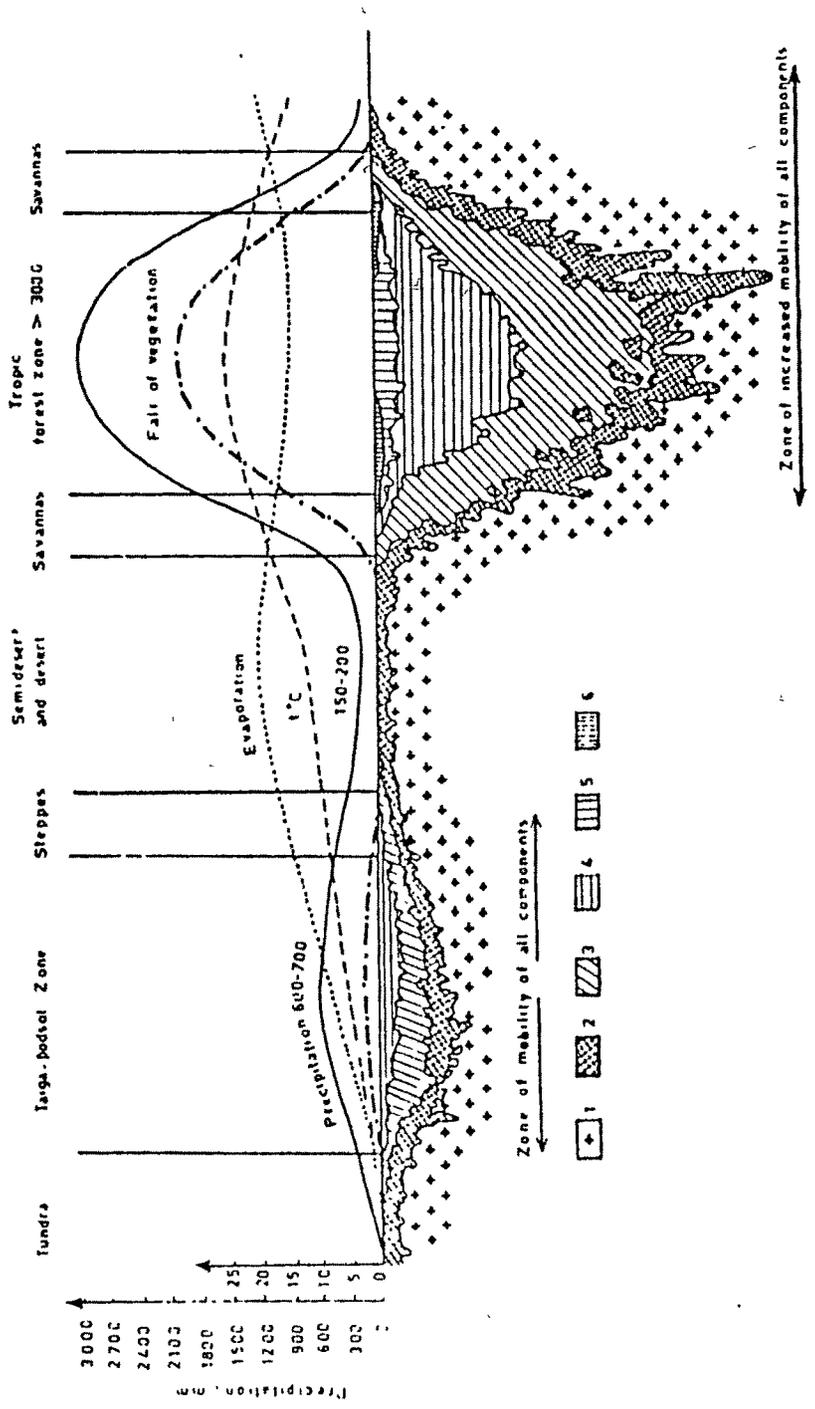
Sketch of formation of weathering mantle in areas that are tectonically inactive (1) Fresh Rock;
(2) zone of gruss eluvium, little altered chemically; (3) hydromica-montmorillonite-beidellite zone
(4) kaolinite zone; (5) ocher, Al_2O_3; (6) soil armor, $Fe_2O_3 + Al_2O_3$.
After Strakhov (1967).

and alumina forming kaolinite, while at still greater depth,
potash and possibly both magnesia and ferrous iron persist
in the structures of illites and montmorillonites. In brief,
not one but a serious of weathering environments exist,
superimposed on one another with the residual products of
each forming the parent material for the succeeding
environment.

Nature and composition of basalt in Jamnagar.

Basalt is not exposed on the surface wherever bauxite quarries
are located. However, basalt is found exposed as a base rock
at the bottom of some quarry pits. The boundary between the
basalt and the overlying $B_{(sap)}$ zone is transitional.

Megascopically, the rock is reddish-brown to brownish in colour
with numerous amygdaloidal cavities pockmarking it. These
cavities are filled up with secondary minerals like zeolites,
secondary silica, etc. Encrustations of gypsum are commonly
found on these corestones. Shining, metallic black specules,
resembling magnetite are found pockmarking the whole rock.
There are occasional dark red tinges on the rocks. Joint
patterns are also seen.

Under the microscope, the pure, unweathered basalts are
hemicrystalline in nature with a good amount of glassy
material present. The bulk of the rock is made up of a fine
grained mixture of ground-mass of plagioclase and augite.

Phenocrysts of labradorite are very common. Olivine is present. in the form of large to medium-sized phenocrysts as well as in the ground-mass. Sometime, the olivine is seen altered to serpentine or foxy-red coloured iddingstie. Augite, the next important constituent is present as small grains in the ground -mass. Magnetite is abundantly disseminated throughout the ground mass. The weathered rims of the corestones, when studied under the microscope, show the alteration of both plagioclase and augite into a cryptocrystalline hazy assemblage of a number of secondary aluminous minerals.

The average chemical composition of Deccan Trap basalts in the study area is as follows:

SiO_2	--	51.50 %
Al_2O_3	--	14.93 %
TiO_2	--	1.77 %
Fe_2O_3	--	3.41 %
FeO	--	9.77 %
MnO	--	0.09 %
CaO	--	9.51 %
MgO	--	4.54 %
P_2O_5	--	0.22 %
Na_2O	--	3.24 %
K_2O	--	1.02 %

Chemistry of Weathering of Deccan Trap Basalt

The weathering of all igneous rocks may be defined as the
response of mineral assemblages which were crystallized in
equilibrium at high pressure and temperature within the
earth's crust to new conditions at or near the contact with
air, water and living matter, giving rise to their irrevo-
cable changes from the massive to the clastic or plastic
state involving increases in bulk, decreases in density and
particle size, and the production of new minerals more stable
under the new conditions (Chorley, 1975). In this process,
water plays a dominant role, which can only be understood by
first examining the structure of silicate minerals which
compose virtually all igneous rocks and make up more than 90%
of all rock forming minerals. The main minerals present in
Deccan Trap basalt are calcic plagioclase (labradorite),
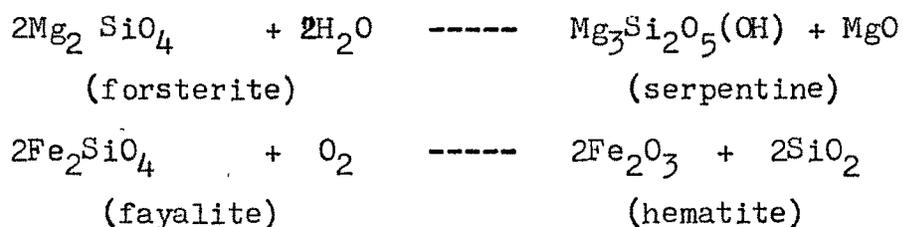olivine, augite and magnetite.

Calcic Plagioclase Felspars

In the framework structure of the felspars, the tetrahedra are
linked through all four oxygen atoms to yield a three-dimen-
sional configuration. Aluminium substitution for silicon within
the tetrahedra creates a net negative charge on the framework
which is balanced by a calcium ion. Break down of the calcic
felspars proceeds through the loss of these calcium ions,
but for their escape, the tetrahedral framework must be

ruptured. In the calcic felspars the aluminium - to silicon ratio is 1:1. Despite the similarities in structure of the alkali and the calcic felspars, a considerable disparity exists in their weathering stability (Loughnan, 1969). Apparently, the greater replacement of silicon by aluminium in anorthite results in a higher degree of polarization of Al-O-Si bonds. With the loss of the metallic ions, the frame-work structure breaks down into chains which tend to poly-merize into sheets in much the same manner as those released from pyroxenes. Where the leaching conditions are inadequate to remove magnesium and ferrous ions as rapidly as they are released from the breakdown of associated minerals, these ions tend to be 'fixed' by the new residual structure and montmorillonite results. Chapman and Greefield (1949), Smith (1957) and Craig and Loughnan (1964) have described the alteration of calcic felspars to montmorillonite.

Olivine

Olivine is composed of discrete silica tetrahedra bonded together by magnesium and ferrous ions in an octahedral coordination. Both octahedral cations are potentially mobile and their loss from the surface of the mineral causes the ready release of the individual tetrahedral units, thereby exposing fresh surfaces to attack. Consequently, olivine decomposes rapidly. However, the rate of release of the silica may exceed its rate of solution, in which case the residual

silica polymerizes into sheets and apparently 'fixes' some of the magnesia, yielding serpentine as the crystalline phase (Loughnan, 1969). Generally, a complete balance of silica and magnesia is attained so that neither free silica nor free magnesia remains within the weathering zone. This and the case with which released silica can polymerize into the sheet structure of the phyllosilicates are phenomena which may be observed repeatedly in the weathering of the silicate minerals. Much of the ferrous iron, if released above the water table, is oxidized, in which state it crystallizes or tends to crystallize as either the oxide, hematite and more rarely meghemite, or the hydroxide, goethite. However, much may persist in an extremely fine state and appear amorphous to X-ray radiation.

$$2Mg_2SiO_4 + 2H_2O \text{ ----- } Mg_3Si_2O_5(OH) + MgO$$
$$\text{(forsterite)} \qquad\qquad \text{(serpentine)}$$

$$2Fe_2SiO_4 + O_2 \text{ ----- } 2Fe_2O_3 + 2SiO_2$$
$$\text{(fayalite)} \qquad\qquad \text{(hematite)}$$

As the weathering intensity increases, magnesia is preferentially leached from the serpentine which becomes progressively unstable and is converted to a new silica enriched phase, saponite (a montmorillonite group mineral).

It is not known whether complete destruction of the serpentine lattice is necessary for this transformation. Ultimately,

saponite becomes unstable and both the remaining magnesia and silica are leached, leaving a residue of oxides and hydroxides of iron (Loughnan, 1969).

Craig (1963), has shown that olivine may alter directly to magnesium-rich montmorillonite without passing through the serpentine stage, while Sherman, et. al. (1962) found nontronite the initial product of the weathering of olivine at Lualualei, Hawaii.

Pyroxenes (Augite)

In the pyroxenes, the tetrahedra are arranged in chains which are bonded together by metallic ions, the most common being those which enter into octahedral coordination with oxygen, such as Mg^{++}, Fe^{++} Fe^{3+}, Al^{3+}. Some alumina may replace silicon in the tetrahedra. Bonding by the octahedral cations is relatively weak and pronounced cleavages with planes approximately normal to each other parallel to the silica chains. Access of water by way of the cleavages promotes solution of the bonding cations and causes rapid breakdown of the structure. Upon release, the chains tend to polymerize into sheets incorporating residual alumina and magnesia, forming chlorite or montmorillonite or both. Ferrous iron is stabilized by oxidation to the ferric state, and at the same time titania crystallizes as anatase. Where the release of calcium from the breakdown of the pyroxene exceeds its rate

of solution, calcite also develops. A general weathering

sequence for the pyroxenes is given below:

| Partial
loss of
pyroxene Mg^{++}
Ca^{++} Fe^{++} ----
Oxidation of
Fe^{++} | : chlorite,
: montmorill-
: onite
: calcite,
: ferric
: oxides,
  anatase | : Complete
: loss of
: Ca^{++},Mg^{++}
: Partial -------
  loss of SiO_2
: | :kaolinite,
: ferric oxides
: anatase |

As the intensity of weathering increases, all the lime and

magnesia are lost together with the silica not required to

saturate alumina, and the residue becomes progressively

enriched in kaolinite, anatase, and oxides and hydroxides of

ferric iron (Loughnan, 1969).

Magnetite

This mineral oxidizes during weathering to yield hematite,
maghemite, and (or) goethite.

The amount of chemical weathering is dependent on the amount
of water that is available to leach rocks and on the drainage
which is determined by the porosity and the position of the
water table. When leached with water, certain ions that are
dissolved from the minerals in rocks are found in the drainage
water that has passed through the rock (Carroll, 1970).
Movement of water in the zone of weathering is controlled by
gravity, capillarity, humidity and heat. There are four types
of water commonly present:

1) Gravitational : percolates downward and drains away carrying soluble ions.

2) Capillary : held by capillary action in pores and small spaces.

3) Hygroscopic : held as thin films on grains, and especially by the fine material.

4) Combined : held in chemical combination and only removed by strong heat or change of mineral into another form,
e.g. gibbsite, $Al_2O_3 \cdot 3H_2O$ to boehmite, $Al_2O_3, 2H_2O$.

Capillary water acts as a solvent, and both it and hygroscopic water are the medium in which ion exchange takes place. In pedochemical weathering, water is the agent that causes the chemical reactions that result in the production of soil profiles. The initial composition of soil water is that of the rain water that falls on it, but the composition is modified by the chemical elements in the hygroscopic water already there (Carroll, 1970).

The pH of natural water is controlled by chemical reactions and equilibrium among the ions in solution in it. The pH of rainwater is primarily due to the absorption of CO_2 and at pCO_2 at 25°C, when it is saturated with CO_2, the pH is approximately 5. Rainwater in clouds has pH of 5.7, but this value varies according to the other cations that are present (Carroll, 1962). Not all rainwater is saturated with CO_2 :

there is a delicate equilibrium between the CO_2, the H_3CO_3, and the HCO_3 Content. which can be thermodynamically stated as:

$$\frac{(H+) \qquad (HCO_3-)}{(H_2CO_3)} = KH_2CO_3 = 10^{-6.4} \text{ aT } 25°C.$$

This constant varies from 6.58 at 0°C to 6.33 at 30°C (Garrels and Christ, 1965, p.89), which is the pH range in which weathering takes place.

All water that comes in contact with rocks is slightly acidic. This is the most important fact of chemical weathering.

GENETIC MODEL

There now seems little doubt that laterites/bauxites are essentially residual accumulations of chemically resistant minerals (McFarlane, 1983). From an overall point of view, the system of accumulation is entirely relative. Laterites/ bauxites would not exist were not Fe and Al less readily mobilized than other components during tropical weathering. However, from a medium range view point, laterite blankets can be subdivided into areas where either relative or absolute accumulation predominates. The distinction between these two types of accumulation was stressed by d'Hoore (1954), relative accumulations owing their concentration to the removal of more mobile components and absolute accumulations owing their concentration to the physical addition of materials.
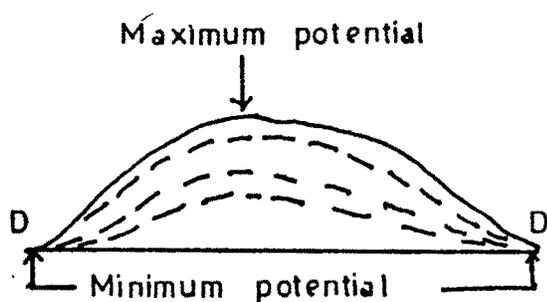
From a medium range view point, the relative importance of
relative and absolute accumulation varies with topographic
position (Fig. 63). Interfluve positions are areas where
there is maximum potential for surface lowering (Fig. 63 a & c)
In Jamnagar, the palaeogeomorphology was controlled by the
Deccan Trap flows. The residual relationship between basalt,
bentonite, lithomarge and laterite/bauxite point towards an
in-situ or residual (relative) accumulation derived by the
weathering of the Deccan Trap basalts. Closer examination
of field characters and chemical data reveals that absolute
accumulation has also taken place. There was not one, but a
series of weathering environments which existed superimposed
on one another with the residual products of each forming the
parent material for the succeeding environment.

The initial belt which underwent lateritization was, as discu-
ssed earlier, highly jointed and with many pillow structures
due to rapid cooling. This physical condition of the parent
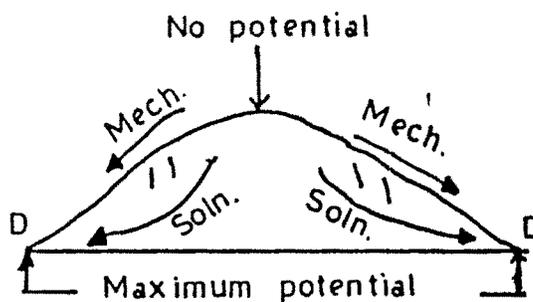rock made it amenable to rapid chemical deterioration.

In this laterite/bauxite belt, due to the differing geoche-
mical environments on either side of the width, attributable
to the topography, both relative and absolute accumulations
have taken place. The inland positions are predominantly
sites of relative accumulation, as there is maximum potential
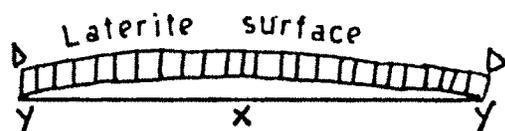for surface lowering.

FIG. 63

(a) Vertical surface movement

Maximum potential

D

Minimum potential

D

(b) Lateral enrichment

No potential

Mech.

Mech.

Soln.

Soln.

D

Maximum potential

D

(c)

Laterite surface

Y   X   Y

D - Drainage line

Y - Absolute accumulation predominates

X - Relative accumulation Rredominates

RELATIVE AND ABSOLUTE ACCUMULATION
(after Mc Farlane, 1983).

Nearer the sea, downslope mechanical movement of residua from higher topographic positions is more common.

In the laterite belt, material escaping retention in topographically higher positions inland would move downprofile and downslope and tend to be precipitated in slope-bottom situations where the water-table approaches the landsurface near the sea. There is also downslope mechanical movement of residua from higher topographic positions. Since the early stages of lateritization, when the slopes were relatively steep, downslope movement was most favoured, slope bottom situations were usually the first to show accumulation, and with progressive slope reduction the accumulation in effect extended upslope to cover the interfluve.

In short, within this narrow laterite belt, there are areas in which relative and absolute accumulation predominate and are identifiable.

Fig. J represents the initiation of weathering of the edge Deccan Trap basalt, inland, percolation exceeded run-off, whereas, it was inverse seawards. This resulted in residual accumulation inland with mechanical movement downslope, seawards.

The earlier stated slightly acidic rain water initiated the hydrolysis of the parent rock mineral assemblage of labradoriteolivine-augite below the water table. This produced

Mg, Fe, Al, montmorillonite minerals (lower B_{sap} horizon) as alteration products.

The most mobile elements were evacuated by the seawards moving ground water (Fig. **64 b**).
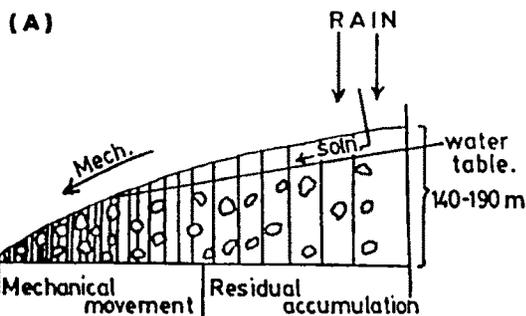
The montmorillonite zone occurred at progressively lower levels as the weathering front lowered below the ground water table level. The other profile interfaces including the overlying kaolinite, laterite/bauxite and the landsurface interface followed suit above the groundwater table level. The products of each stage of weathering provided parent material for the succeeding stage and the accumulation of the most resistant components which characterized the laterite zone thus derived from an overhead source.

Because the interface was moving vertically downwards, relatively resistant residua must, of necessity, accumulated there. In effect, the landsurface was "shrinking like a rotten apple" and lateritic residua were trapped at the lowering interface (McFarlane, 1987).
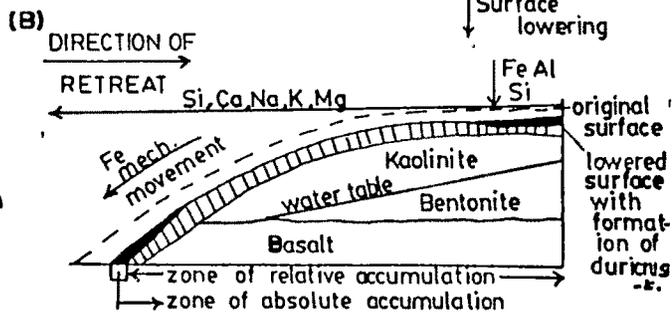
From the Ti-retained mass balance studies of selected profiles, it is seen that Fe and Al behave antipathetically. Geochemical laws fail to explain the mobilities of both in these profiles and this will be discussed later on in detail.

The montmorillonite zone, which occurred below the groundwater table level started decomposing into kaolinite above the water
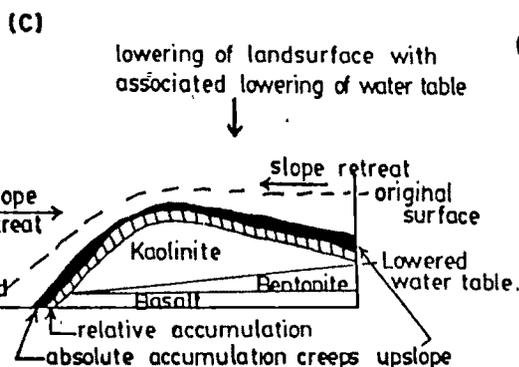
FIG. 64

346

DIAGRAMMATIC   REPRESENTION OF LATERITE GENESIS IN JAMNAGAR, GUJARAT, INDIA.

(A)

RAIN

water table.
140-190 m

Mech. Soln.
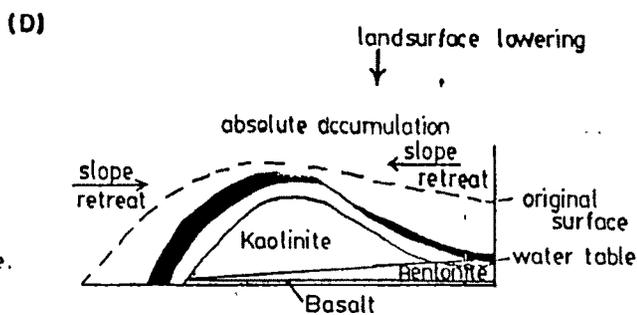
Mechanical movement | Residual accumulation

Initiation of weathering of the edge of the Deccan Trap basalts. Residual accumulation predominates inland while mechanical down-slope movement predominate sea-wards.

(B)

Surface lowering

DIRECTION OF RETREAT

Si,Ca,Na,K,Mg

Fe Al Si

original surface
lowered surface with format-ion of durics -r.

Fe mech. movement

Kaolinite
water table   Bentonite
Basalt

zone of relative accumulation
zone of absolute accumulation

The early stage of weathering involve breakdown of the least stable minerals of basalt and evacuation by groundwater of the least stable elements. The surface begins to lower with the formation of different stages downwards i e. kaolinite and bentonite respectively with bentonite occurring below the water table.

(C)

lowering of landsurface with associated lowering of water table

slope retreat

slope retreat
original surface
Kaolinite
Lowered water table.
Seaward   Bentonite
Basalt

relative accumulation
absolute accumulation creeps upslope

Reduction of landsurface predominates inland followed by slope retreat from both the inland as well as sea-ward sides. Absolute accumulation starts creeping upslope at both ends, covering the entire slope and part of the crest.

(D)

landsurface lowering

absolute accumulation

slope
slope retreat
retreat
original surface
Kaolinite
water table
Bentonite
Basalt

A further continuation of the processes of land-surface lowering and slope retreat.

(E)

landsurface lowring

Bauxite protore formation

slope retreat
Seaward
slope retreat
Kaolinite
watertable
Bentonite
Basalt
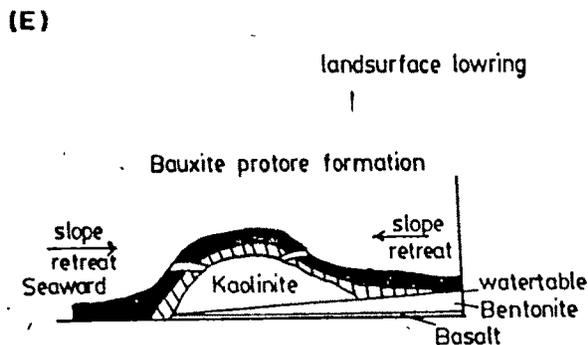
Development of bauxite protore on both sides of the hillock giving rise to two different types of sections
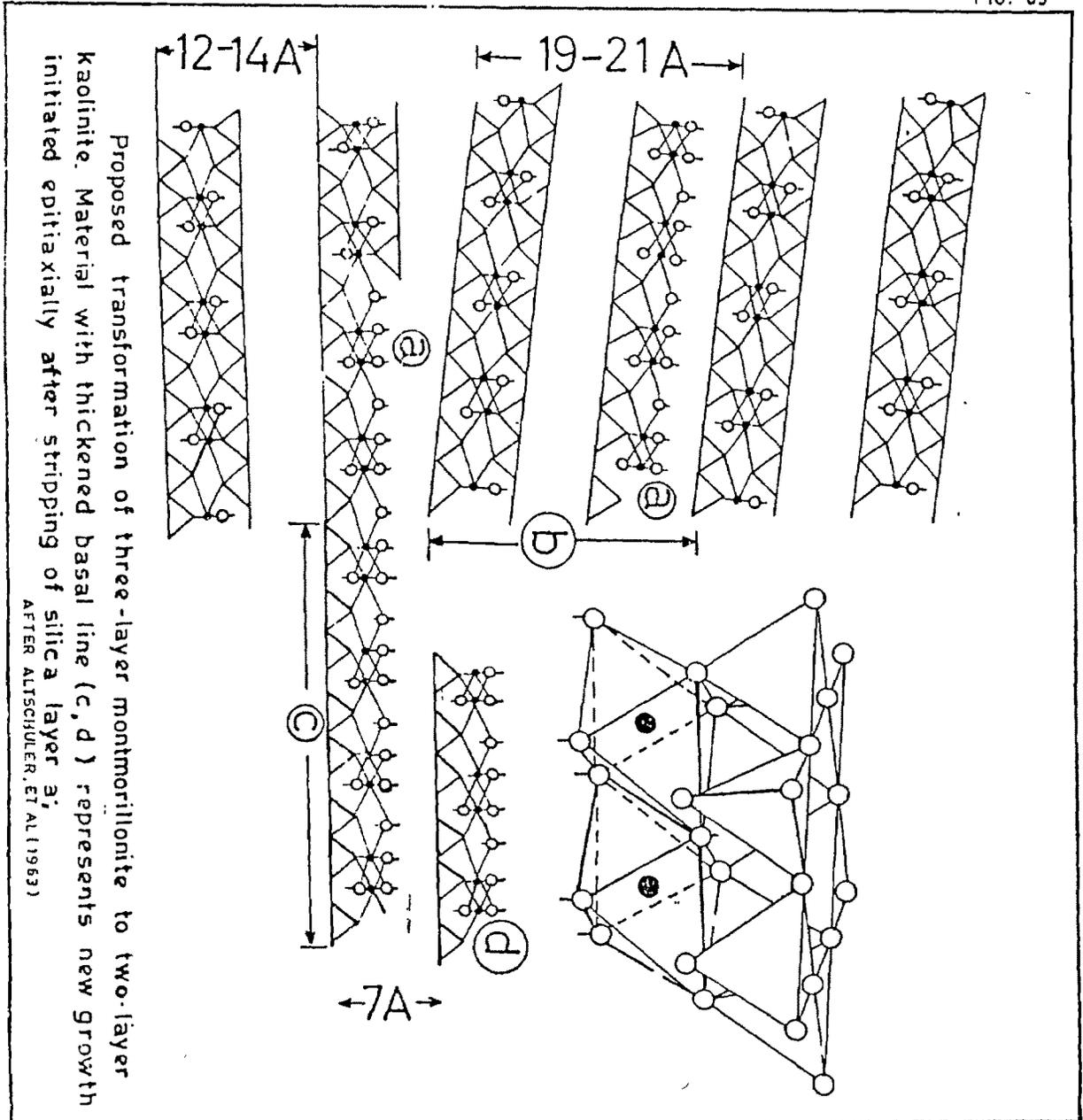
This can be attributed to better drainage conditions seawards. The development of the bauxite protore postdates laterite formation, formed after the faulting depicted in Fig. The removal of Fe can be attributed to microbial activity.

table due to freer drainage conditions, by intracrystalline leaching of interlayer cations and tetrahedral silica layers as has been suggested by Altschuler et . al. (1953). This consisted of:

(1) Acid leaching of interlayer cations and synchronous or immediately subsequent hydration and stripping (leaching of interlayer cations and synchronous or immediately subsequent hydration and stripping) (leaching of silica layers, (Fig. 65 a)

(2) Replacement of vacant tetrahedral oxygen sites by hydroxyls to create a highly polar kaolin-like arrangement in the residual 1:1 sheet. (Fig. 65 b).

(3) The highly charged outside layer of hydroxyl protons contracts the interlayer space of that of kaolinite by identical charge polarity. (Fig.65 b)

(4) Extension of the kaolin-like sheet laterally by epitaxial growth of true kaolinite and development of hexagonal modification outgrowths at the edge of the montmorillonite flakes.

(5) The primitive kaolinite crystals are nourished and enlarged (Fig.65 c) , as the montmorillonite continues to breakdown. New layers of kaolinite are added (Fig. 65 d)

The formation of the kaolin belt marked the threshold for lateritization. The then kaolinized saprolite, must have been

FIG. 65

Proposed transformation of three-layer montmorillonite to two-layer kaolinite. Material with thickened basal line (c,d) represents new growth initiated epitiaxially after stripping of silica layer a; AFTER ALTSCHULER, ET AL (1963)

dominated by kaolinite, quartz, iron and aluminium minerals. This saprolite could only be lateritized if the kaolins broke down and quartz was leached out. McFarlane (1987), has stated that "the removal of quartz is common to both iron and aluminium enriched residua. It is the nature of dissolution of the kaolinite which is central to the question of whether the lateritic residuum is enriched in iron or aluminium. In the case of iron rich residua (Fig. 66)the kaolinite is congruently dissolved. Si and Al are both evacuated. For the development of an aluminium-rich residuum, kaolinite is incongruently dissolved, Si is leached out and Al remains as gibbsite. This is accompanied by leaching of Fe". The question of where bauxitization is achieved therefore requires an assessment of the criteria which control these two routes, beyond the kaolinization stage, into lateritization.

Although some extremely resistant primary minerals survive in the residuum , it is ultimately dominated by iron minerals (especially goethite and hematite) or aluminium minerals (especially gibbsite).

In the case of Fe enrichment, the most common kind of lateritization, congruent kaolinite dissolution is necessary, yet there is no known means by which both Al and Si can be evacuated in solution. Even if Al is present only in trace amounts, this causes immediate co-precipitation of Si and Al (Okamato et al., 1957). In the case of bauxitization, although
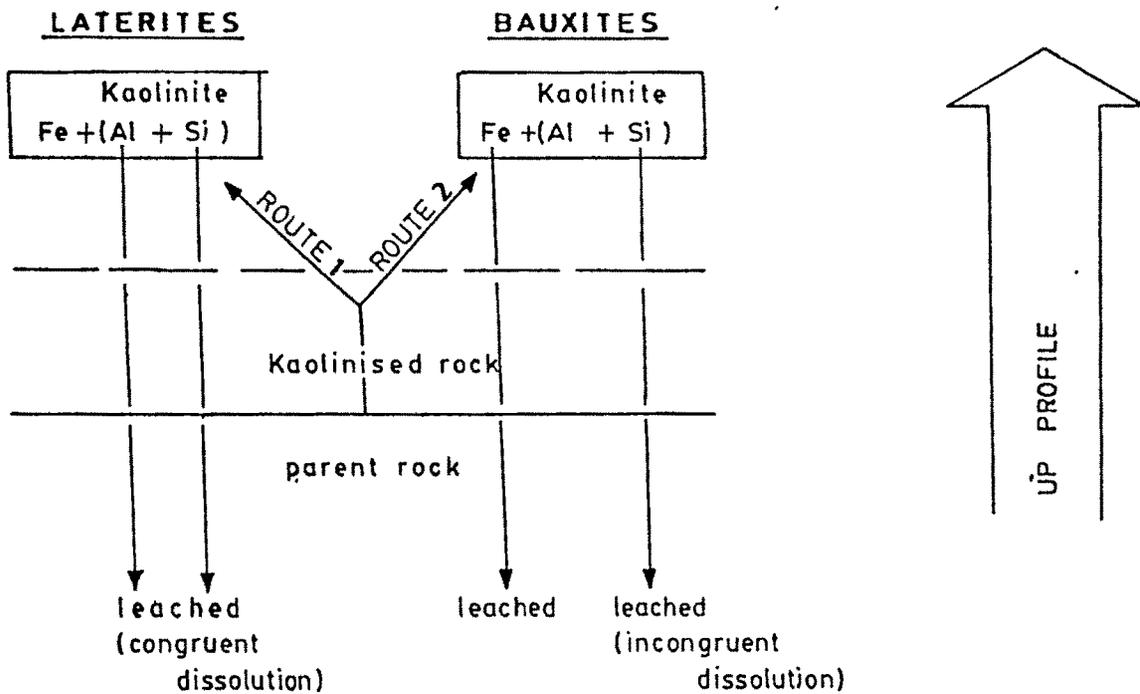
FIG. 66.

LATERITES

| Kaolinite |
| Fe +(Al + Si) |

BAUXITES

| Kaolinite |
| Fe +(Al + Si) |

ROUTE 1   ROUTE 2

Kaolinised rock

parent rock

leached
(congruent
    dissolution)

leached

leached
(incongruent
    dissolution)

UP PROFILE

Diagrammatic representation of the progress of lateritic weathering. Lateritisation
follows kaolinisation. Relative enrichment in iron and aluminium is achieved by
dissolution of kaolinite and leaching of quartz. (McFARLANE 1987)
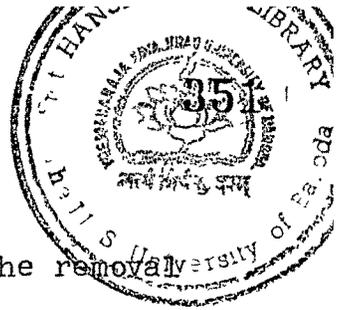
congruent kaolinite dissolution can be achieved, the removal

of Fe with the Si cannot. Extensive leaching experiments

concerned with extraction of Al from kaolinitic materials,

inevitably with Fe as a contaminant, have shown that the Fe

and Al are inseparable. Yet in nature this separation is

common with Fe and Al behaving antipathetically (McFarlane,

1987), as in the case in Jamnagar. It is hypothesised that

Fe enrichment (laterite protore formation) came first,

followed later on by Al enrichment due to favourable environ-

mental conditions.

All along, the process described in (Fig. 64 b) was continuing,

with further reduction of landsurface accompanied by retreat

(Figs.64 c,d,e)   . The slope bottom absolute Fe accumu-

lation crept upslope to such an extent, that it covered the

entire slope and part of the crest also. That gave an apparent

illusion that Fe crest was residual in origin formed by the

upward migration of Fe. During this time, the Al was retained

in the kaolinite zone.

Much is known about the factors effecting the formation of

metallic oxides and hydroxides in the weathering profile

(Segalen, 1971). Selective removal or retention depends in

large part on the pH and Eh (Berge, 1971, Norton, 1973),

organic complexing (Huang and Keller, 1970) and rates of

reactions. However, attempts to explain the mineral and

chemical assemblage in each horizon of the lateritic profiles

in Jamnagar in terms of pH and Eh have met with considerable frustration. Norton (1973), observed that the assemblages of minerals in many laterites do not confirm with the stable assemblages which should occur under the varying conditions of pH and Eh which are held to define the limits of mineral stability. The main reason for this appears to be the inheritance effect (Fig. 67) in which weathering products of each horizon may survive into higher-lying horizons where more advanced chemical selection and its products predominate (McFarlane, 1983). This is adequately demonstrated in Jamnagar, as revealed, by X-ray studies. There are no zone of pure products, but remnants or neo-formed products of preceeding or succeeding stages respectively are seen interspersed with the main mineral constituent of that particular zone. Further proof of the inheritance effect, is evident in the proliferation of relict parent rock textures, in the montmorillonite zone with gradual destruction of the same upwards in the profile. This process of inheritance has resulted in a structural and mineralogical assemblage which is not in a state of equilibrium at any particular horizon, an assemblage which cannot be explained in terms of a single set of hydrological history (McFarlane, 1983).

Failure of geochemical explanations for the varying elemental mobilities in laterite/bauxite sections of Jamnagar for Al enriched residua following the above mentioned kaolinite
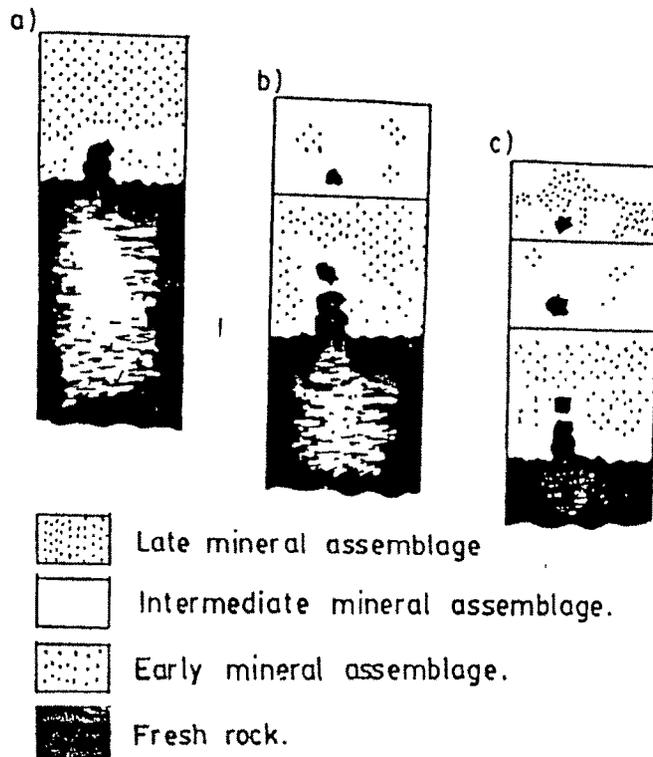
a)

b)

FIG. 67

c)

	Late mineral assemblage
	Intermediate mineral assemblage.
	Early mineral assemblage.
	Fresh rock.

The inhertance effect. (a). (b).and (c). represent succesive stages of profile development . Early and intermediate mineral assemblage survive to coexist with late mineral assemblage. (after McFARLANE 1983)

dissolution leads one to point towards an important biological control (McFarlane, 1987). Geochemical constraints do not apply to Si, Fe and Al co-mobilities when biologically complexed material come into the picture. Hence, biological activity seems to be the obvious choice. Humus complexing is is unlikely to be the main mechanism since lateritic profiles are notoriously poor in humus and efficient nutrient re- cycling is essential to the maintenance of plant communities in humid tropical areas (Kronberg and Melfi, 1987). Microbial complexing would seem the best candidate. Field evidence in support of a microbial role has long existed in the form of casual observations. The waters issuing from the base of profiles may be strongly carbonated (Fox, 1927). Local bauxitization is not explained by continuous pisolithic textures across the boundary of the bauxitized zone, influence of parent rock, protore texture , climate or vegetation, hence an extremely repeated local and subtle factor must have been in operation; microbial activity appears to be the only reasonable explanation (McFarlane, 1987).

The suggested role for microbial complexing in the progress of lateritization faced an initial objection from the earlier work of soil scientists, which had led to the belief that below about 1m, microbial activity is negligible or non- existent for want of a nutrient supply, provided at and rapidly exploited near the surface. Lateritized and bauxitized profiles extend to tens of metres in depth (McFarlane, 1987).

This objection is no longer valid. Micro-organisms have been
successfully isolated from lateritic and bauxitic profiles at
various depths far in excess of 1 m(Button, 1981, Williams,
1981, Perviz, 1983).

As concerns the mobility of Fe in lateritic profiles micro-
biologists have long known that even where Fe is in abundance
in soil profiles, the supply of ionic form does not satisfy
the metabolic requirements of the microbial population and
an ability to attack already formed iron hydroxides has been
deduced (McFarlane, 1987). The ability results from the secre-
tion of special chelating agents with a high specific affinity
for iron, the hydroxanates and phenolates ("catechols")
(Byers, 1974). We know therefore that iron minerals can be
broken down by microbial activity. We also know that some
micro-organisms are capable of precipitating iron from
solution. Iron is clearly mobilised in contexts geochemically
inconducive to mobilisation and micro-organisms which are
capable of iron mobilisation exist there (McFarlane, 1987).

In Jamnagar, the bauxitization of the lateritic protore must
have been initiated during the Eocene marine transgression,
with an enhancement of this activity during the post-Tertiary to
pre-Recent times. During this time the above mentioned Fe-
mobilising micro-organisms must have acted upon the kaolinitic
saprolite, leaving behind an Al-rich residua on crest-tops

and upper parts of the slopes, removing the Fe in solution downslope.

The Saurashtra peninsula has been affected by countless minor tectonic activities along with several marine transgressions and regressions. The very fact that the present position of bauxite pockets is above Mean Sea Level, point to the fact that bauxite enhancement could have taken place at a later period, when traditionally speaking, the conditions were inconducive for bauxitization. May be the bauxite profiles matured during the Quaternary in accordance with the studies of international bauxite formation made by McFarlane (1983) and Bardossy (1983, 1990).