

# CHAPTER VI

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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 Valetton (1983) 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 genesis based upon field studies and laboratory analyses.

#### Brief account of laterite genesis

The word 'laterite' was coined by Buchanan (1807), for a 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 parts of the nineteenth century laterite was regarded as a rock type and was discussed largely by geologists

(in McFarlane, 1976, p.1) 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). (in McFarlane, 1976, p.91). 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. Nazarovff (1931) had reported the occurrence of ferruginized termitaria (in McFarlane, 1976, p.91). 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 other sediments which result from the removal of certain constituents from a parent rock and their subsequent deposition this 'sediment' was residual. It was what was left behind after other 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 feldspars 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 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 crystallization, better known than explained or understood". Russell (1889) provided some data on this process.

The theory that laterite 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) residues. In 1932, the Imperial Bureau of Soil Science defined laterite 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 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 as a residuum seems never to have precisely formulated, but it appears that essentially the accumulation were attributed to the relative immobility of the constituents. Although they were belived 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 realeased 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 (in McFarlane, 1976, p.3, 91-92).

Although stress laid on the residual nature of laterite would appear at first to imply that it is entirely a mechanical residue, clearly it was recognized even then that laterite 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 accumlation 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 as a precipitate resulted from recognition of the fact that pallid zones were thought to be typical underlying substrate laterites. This coincided with an increasing understanding of the several ways in which iron and alumina can be mobilized; Thus, it came to be believed that the enrichment was caused by the iron and alumina, 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 (in McFarlane, 1976, p.93).

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decomposition in-situ 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 accumulation 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 but not necessarily local (in McFarlane, 1976, p.4).

Campbell (1917) was the first to formulate definitely the concept of laterite as a precipitate. Since its precipitatory 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 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 horizon, capillarity and the seasonal fluctuations of the water table.

Laterite formation by capillary action was favoured by Maclaren (1906). Simpson (1912) described primary laterite 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 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 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 (Sivarajasingham 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 upwards 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 enrichment since it is inconsistent with principles of chemistry (Sivarajasingham et al., 1962). It also fails in practice to explain upward movement of iron. By the Ghyben Herzberg hypothesis (in Goudie, 1973) fresh groundwater "floats" on the underlying solutions, thus presenting 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 based on this principle.

- (b) The scale of many laterite 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 profiles do not exist.
- (c) The concept of laterite enrichment and pallid zone depletion as synchronous complementary processes is faced with :
  - (i) the not uncommon occurrence of laterite 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.
  - (iii) the fact that even the deepest pallid zones are quantitatively inadequate to account for the concentration in the crust (Trendall, 1962).

Some of these occurrences may be explained by a contribution made to the laterite from topographically higher positions (Campbell, 1917; MacLaren, 1906), but there remains the problem of the development of thick laterites with inadequate pallid zones, on interfluvies (de Swardt, 1964; McFarlane, 1971). Nor can all of these present interfluvies be dismissed as examples of relief inversion. Where they are underlain by resistant 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 occur on surfaces of relatively high relief. Some of the relief may be explained by modification of the original laterite surface, but some is original. Certainly laterite development is not restricted to completely stable water tables in level or nearlevel 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 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, 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 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 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 development in these situations so that the laterite is only partly detrital (McFarlane, 1969; Goudie, 1973). The distinction between primary and secondary laterites 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 are residual and involve the resolution of material which has mechanically settled or has downwasted from higher topographic positions, even these are in a sense detrital. It is essentially irrelevant whether the detritus has fallen a few hundred feet down 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 is far from clear (in McFarlane, 1976, p.96).

The development of these so-called detrital or slopebottom laterites is unique in the discussion of laterite formation in that there is little dispute as to how it occurred. The finer details of the chemistry of the alteration or hydration of such semi-detrital laterites may still present problems but on the whole the outline of their development is based on observation and careful study of actual 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 occurrences, especially the fossil "high-level" laterites now occupying interfluvial positions. Thus it has been observed that such low-level laterites can upon further erosion or lowering of the surrounding unlateritized areas (or areas where the laterite 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 (Malignien, 1966, p.72; Goudie, 1973, p.45). Clare's account (Clare, 1960) of the development of a laterite "reef" from a cantenary soil association provides one example. Brown (1968) has described laterites which occur as long sinuous ridges and may have formed as valley laterites. Summit areas where the laterite is unexposed and unindurated can be lowered to leave the formerly lower peripheral areas of exposed and indurated laterite standing relatively higher (in McFarlane, 1976, p.97). Laterite 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 interfluvies in terms of relief inversion, for this is compatible with the one workable model of laterite formation, in the form of the so-called detrital or slope-bottom laterites. 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 and various attempts have been made to do this by combining the old concept of laterite as a residuum and that of it as a precipitate (in McFarlane, 1976, p.97).

Du Bois and Jeffery (1955) suggested that not merely part but all of the enrichment is derived from an overhead source. The

laterite 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 formation. Nevertheless outstanding problems remain. Du Bois and Jeffery did not visualize this process occurring in a lowering profile. They believed that the laterite 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 be postulated to account for upto 500 ft (152 m) of parent material (Trendall, 1962). There is no evidence that laterite formation can be 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 study (Gear, 1955) 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 visualized 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 horizon. This process was visualized as occurring independently on each interfluvium. Surface removal of material was believed to expose a peripheral free-face of laterite while the process of laterite formation operates, and continued lowering of the profile and surface on each interfluvium results in the eventual inversion of the relief within this peripheral exposure of laterite. 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.
- (b) It suggests a mechanism for the formation of the inverted summits, or the "soup-plate" form of laterite mesas.
- (c) It offers reason for the wide variety of altitudes at which laterite 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 formation and the development of the breaks of slope-bounding laterite 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 fluctuations ;
- (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 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 postincision 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 processes (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, again associating laterite formation with a lowering landsurface and lowering profile.

A further theory of compromise, has been evolved in Uganda (Mcfarlane, 1971). It also regards laterite 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 tabnle, which sinks as the land surface is reduced by erosion. They become incorporated into the lower parts of the soil mantle 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 develops which has every appearance of a true precipitate. This alteration of a resium or detrital laterites 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. This theory is in part based on a study of the low-level laterites which scan 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 unlikelymagnitudes of water table oscilation 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 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 formation with a surface of some original relief and not exclusively to planation surfaces, although the end-product, the mature laterite, is exclusive to very low relief. This model is

in fact merely a mechanical variation of Nagell's model for the development of laterites of Cuba in which the laterite 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, a causal relationship must exist, and it is suggested that the permeable nature of in-situ laterites allows the substrata, the saprolite, to be leached after the laterite is incised (after McFarlane, 1976, p. 107).

The so-called typical laterite profile consisting of massive laterite underlain by spreads 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 has been maintained since the incision.

Ida Valetton (1983) described the formation of lateritic bauxites world-wide in Cretaceous and Tertiary coastal plains. The bauxites form elongated belts, sometimes hundreds 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 Valetton 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, (ii) lacustrine sediments and hypersaline precipitates, (iii) lignites intercalated with marine clays, layers of siderite, pyrite, marcasite 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	Box, Fe, Al
Horizon rich in silicates (saprolite)	Bv
Horizon of fresh parent rock	C

Normally the soil sections are truncated. The A-horizon is always eroded, Valetton (1983). After the soil Taxonomy of the Us 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).

In Kutch, the lateritic bauxites are developed in two distinct stratigraphic horizons, the older one belonging to the Palaeocene, the younger one to the Eocene. The older and major laterites are formed on the peneplained clastic sediments of the truncated Upper Bhuj Formation of Lower, Cretaceous age (Biswas 1977) or on Trap Basalts (Upper Cretaceous to Palaeocene). The peneplained surface of the Bhuj relief of a few metres. The

preserved bauxite belts are a few hundred metres to several kilometres wide, and the alteration blanket is generally 10-20 m thick. The belts extend parallel to the lower Tertiary shoreline in Kutch and the belt continues south-eastwards around the Kathiawar peninsula following the northward indentation of the Gulf of Cambay; north of Ahmedabad it turns southward following roughly the outline of the west coast of India. The distribution pattern of lateritic bauxites resembles a string of pearls around the Deccan peninsula.

The morphology of the alteration blanket reflects the original surface of the horizontal basalt flows or the peneplained sediments of the Upper Bhuj Formation. The absence of deeply incised valleys and the lateral facies variation indicate a dominantly subsurface seaward directed drainage. The 10-15 m deep present day valleys were incised during later erosional cycles. The uppermost ferricretes or alucretes of the main alteration blanket are partly removed by erosion before the transgression of the Lower Eocene Laki Formation. A second and younger lateritic bauxite horizon is formed on the top of the Laki Formation. The end of the lateritisation process is dated by the marine transgression of either the Eocene Nummulitic Limestone or the Miocene Gaj Limestone, which cover large parts of the alteration blanket. An equivalent palaeocene alteration blanket in Kutch has well-preserved relic textures, and show imposing facies variations along both the strike and dip directions of the belt with swells and basins caused by synpedogenetic movements. The differentiation along the strike of the belt is marked by two facies types :

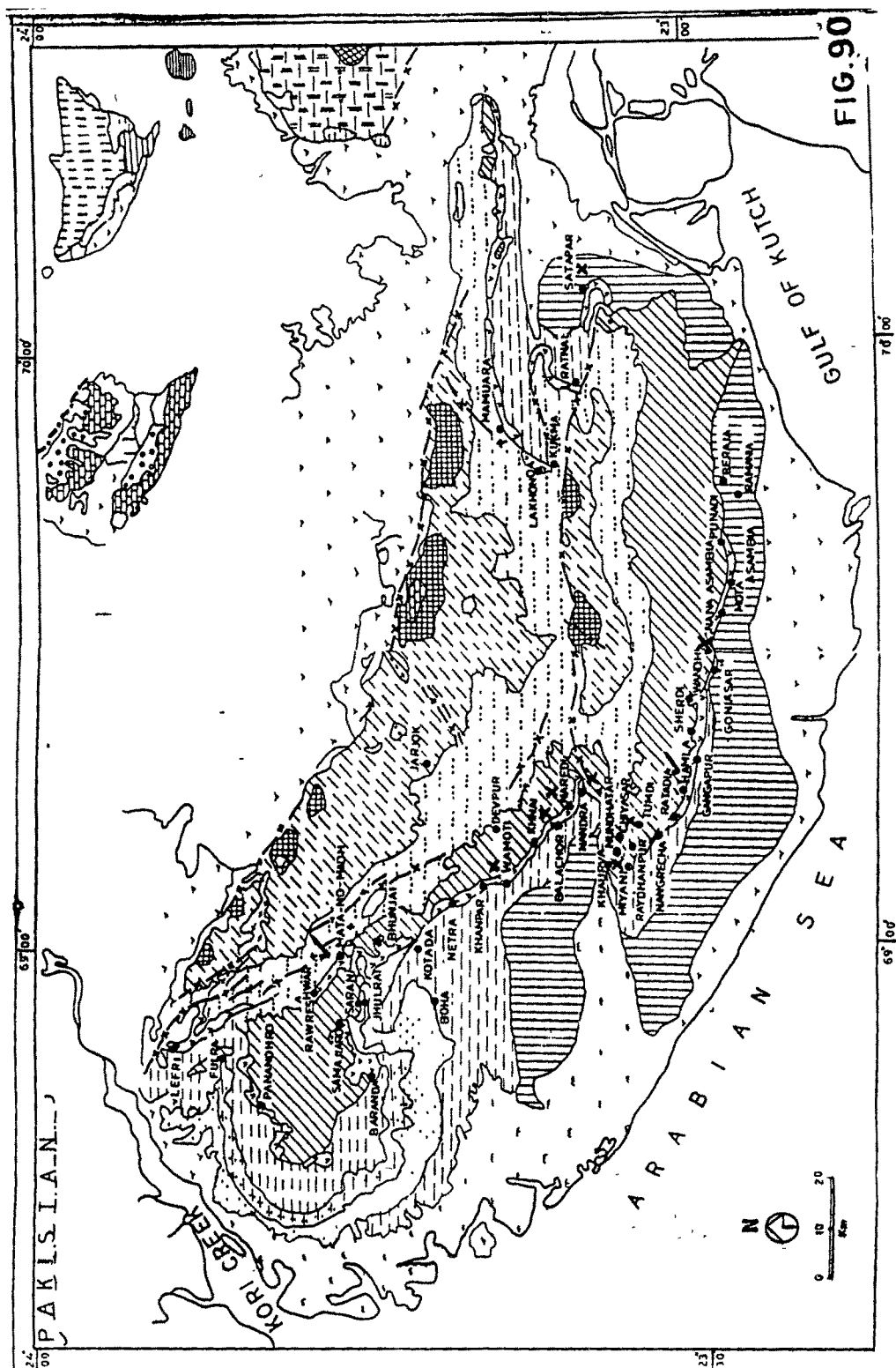
- (i) Low-Silica Type with kaolinitic saprolite (LST in Fig 91 )
- (ii) High-Silica Type with bentonitic and kaolinitic saprolite  
( HST in Fig. 92 )

From the High-Silica Type, Sahastrabudhe (1961) and Talati (1968, 1970) described the bentonitic variation of the saprolite. In addition to this very pronounced vertical geochemical differentiation, there is a lateral transition from nodular to spongy textured gibbsitic bauxite into a pisolitic bauxite rich in boehmite and diaspora.

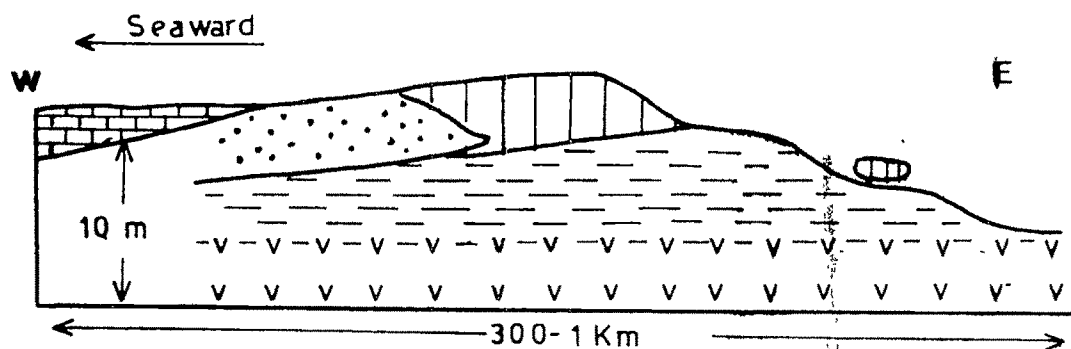
For the solution, migration and precipitation of major and minor elements within the bauxitic alteration blanket, the following ground-water conditions must be fulfilled (after Valetton, 1983 ).

- (1) net flow towards the sea;
- (2) groundwater levels must be high and oscillatory in nature;
- (3) Eh - conditions must be reducing. It is suggested that the Low Silica Type within the B horizon of the lateritic soil sections are produced by differences in drainage intensities. Poor drainage conditions lead to a High-Silica Type because silica is not efficiently removed and combines with Al to form new layered silicates with high silica content (e.g.) smectite. Good drainage conditions produce the Low-silica type and kaolinite is formed. Silica is the most mobile major element.

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

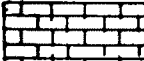



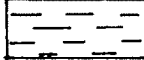
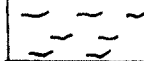
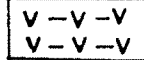
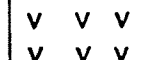


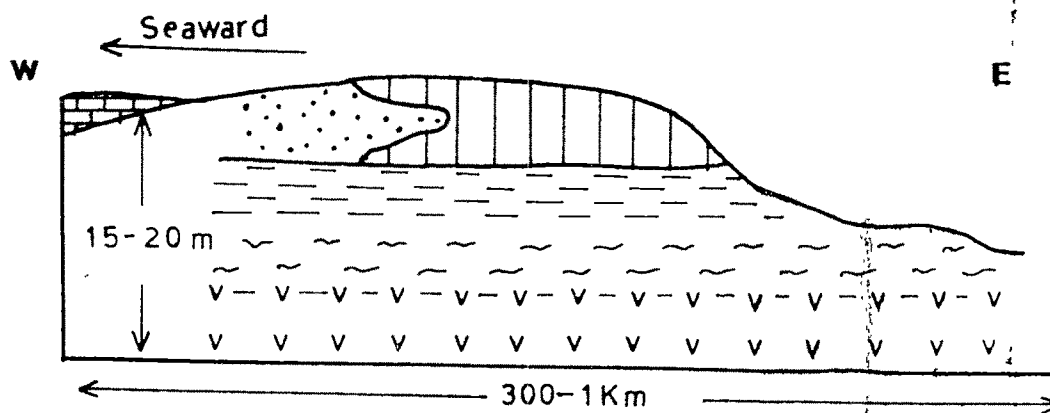
Location of HST and LST profiles.



Low silica Type section ( LST ) with kaolinitic saprolite  
in Kutch

FIG. 91

	Nummulitic limestone ( Mid-up Eocene).	
	Laki formation ( Lower - Eocene )	
	ferricrete = Laterite	Box ( Fe , Al )
	alucrete = bauxite	
	Kaolinitic LST	B
	bentonite HST	
	altered	C
	fresh	
	TRAP BASALT	



High silica Type section (HST) with bentonitic and  
kaolinitic saprolite in Kutch

FIG. 92

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  $\text{Fe}^{3+}$  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 alteration 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, Valeton suggested that the high-silica type bauxite in Kutch region formed in basins with poor drainage, whereas the low-silica type formed on swells with more effective drainage.

McFarlane (1983) has raised objections to Valeton's extension of this model to all elevated bauxitised plateau in India and elsewhere by stating that in such a littoral palaeoenvironment 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 continuously 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 bauxitization 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, emphasising upon the key role of micro-organisms. According to her, geochemistry has been the main input in the interdisciplinary study of bauxite and laterite, where as bauxitization can occur on many rock types. Emphasis on a geomorphological control is made, with sites favourable to aggressive leaching being predisposed to bauxitization. Better bauxitization on higher and older landsurfaces 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 residus, following kaolinite dissolution. The simultaneous removal of Al and Si in solution during congruent kaolinite dissolution is impossible as immediate co-precipitation 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 Palaeocene times for lateritization in Kutch. This is based on palaeoclimatological projections made by Bardossy (1981) and on the studies of drift tectonics as related to lateritization in NW-India made by Sychanthavong and Patel (1987). This type of correlation has not been made in previous genetic models for the study area.
- (2) Valetton (1983), has not adequately taken into account the role of geomorphology in her genetic model. The author places a lot of emphasis on geomorphology, while making a detailed study of it as pertaining to Kutch. He agrees with McFarlane's (1983) statement "In a tectonically stable area, lateritization can be placed within the late stages of landsurface reduction".
- (3) The author agrees with Valetton's (1983) premise that the lateritization in Kutch 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 Valetton (1983), the author has processed his chemical data by using a Cr-retained mass-balance model of several LST and HST 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 enrichment in contrast to Valetton's model of upward enrichment which requires zones of Al depletion below the bauxite. This is in contradiction with Valetton's premise that upward enrichment followed by lateral segregation was responsible for the development of the two types of profiles in the laterite belt of Kutch.

#### Genesis of the Laterites of Kutch

Despite earlier abortive attempts to exclude genesis, the most modern redefinition of laterite has clear genetic implications: "Laterites 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
- f) the process of lateritization.

In order to arrive at a proper understanding of the exact modus operandi of the of lateritization in Kutch, it would be worthwhile to discuss in detail all the above points.

### Climatic Conditions

The Palaeocene laterite profiles of Kutch are supposedly fossile in nature having been formed in the past. Applying the concept of uniformitarianism to these laterities, it would be logical that the same climatic conditions responsible for the formation of present day latrites in Kutch. 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 (Barodossy, 1981).

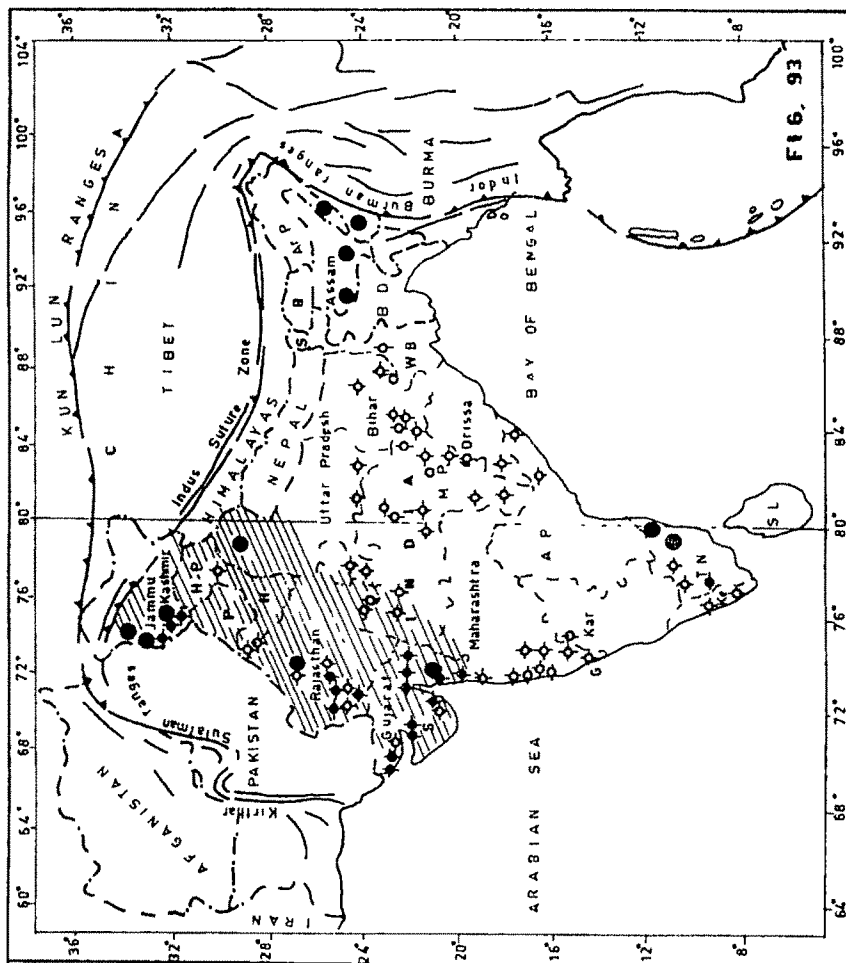
- i) During the Archaean Era the surface temperature was 50 to 80 °C. The palaeoatmosphere consisted mainly of CO<sub>2</sub> with much N<sub>2</sub>, H<sub>2</sub>, NH<sub>3</sub>, CH<sub>4</sub> little or no O<sub>2</sub>. There was no vegetation on the land surfaces resulting in a fast and intensive erosion. Chemical weathering was intensive, but had a more alkaline and more reducing character than today.
- ii) During the Proterozoic Era plus the Cambrian, Ordovician and Silurian periods, the surface temperature was 30 to 50 °C. The atmosphere had a slowly growing O<sub>2</sub> and a diminishing CH<sub>4</sub> and NH<sub>3</sub> content, H<sub>2</sub> 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 palaeoatmosphere.

- 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 palaeoclimatic fluctuations - mainly in the surface temperature - have been detected during the Mesozoic and Cenozoic eras too.

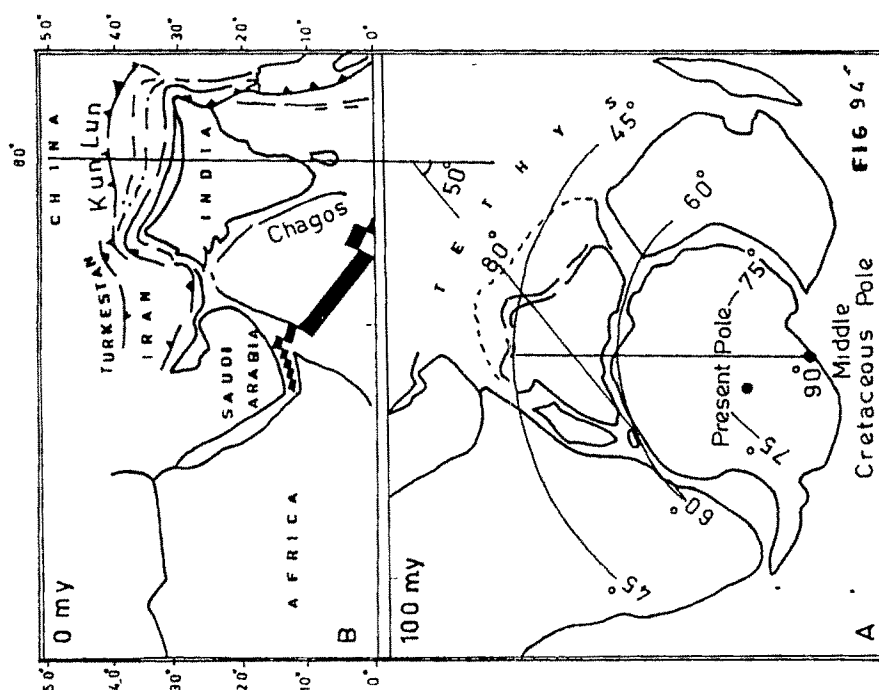
The climatic conditions of bauxite and laterite formation are currently satisfied only between the latitudes  $30^\circ N$  and  $30^\circ S$ . But some Mesozoic bauxites extend to  $60^\circ N$  and some palaeozoic ones even to  $70^\circ N$  beyond the Arctic circle - as for example on the Taymir Peninsula 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 Kutch laterites 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. 93, the Kutch laterites when plotted on a map of India along with the other Palaeocene and Eocene laterites of

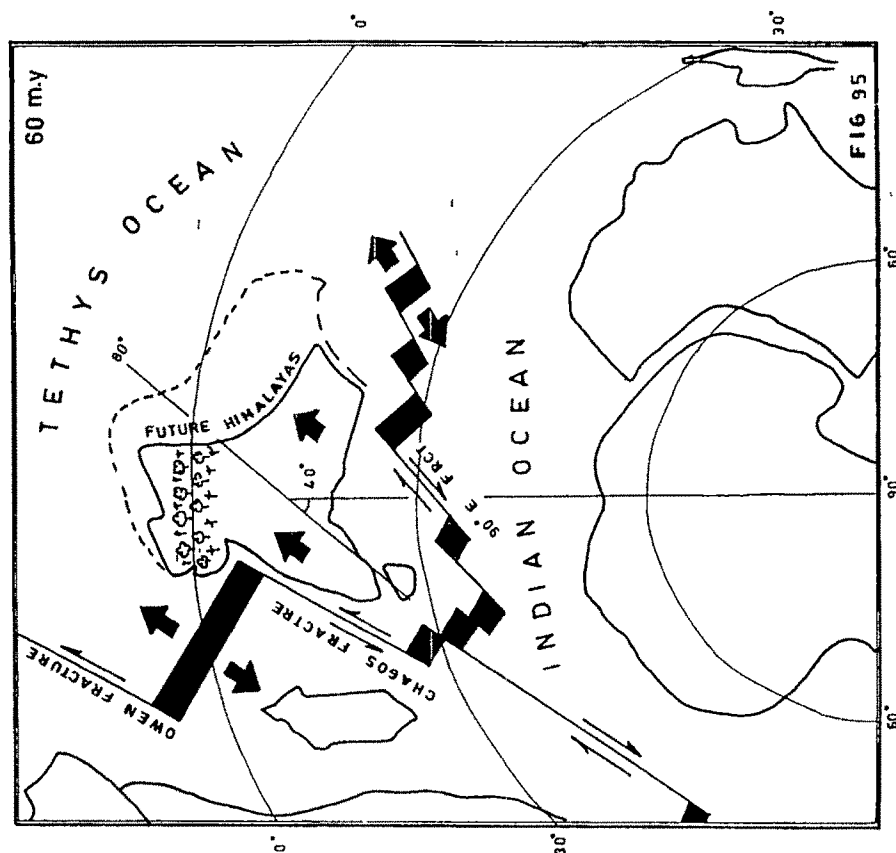


Distribution of Tertiary laterites, bentonites, bauxites and lignites (with gradual decrease in age from north to south). The plots within striped lined area are Palaeocene in age. Filled circles with four sided dashes represent laterites and bauxites under discussion; open circles with four sided dashes 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. T and S in Gujarat state indicate Tutch and Saurashtra respectively; and the other alphabetical symbols correspond to the names of various Indian states. (after Sychanthavong and Patel, 1987)

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 Gondwanaland, it is found that it was trending E-W coinciding with the alignment of the latitudinal positions (Fig. 94 A). 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 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  $10^{\circ}$  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 to suggest that the India plate was rotated by  $40^{\circ}$  in an anticlockwise direction, after this particular linear laterite belt had crossed the equatorial zone while the total rotation was  $50^{\circ}$  (Fig. 94A & B, 95). Thus the Indian plate was rotated by only  $10^{\circ}$  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



A - The palaeopositions of the Indian plate and other surrounding continents in the Gondwanaland (after the best fit of Smith and Hallam, 1970). This illustrates the position of the Indian plate with the alignments of the their latitudes and longitudes. The location of the Middle Cretaceous pole is after Creer (Earth Science Reviews, 6, 769-446). 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. (after Sychanthavong and Patel, 1987)

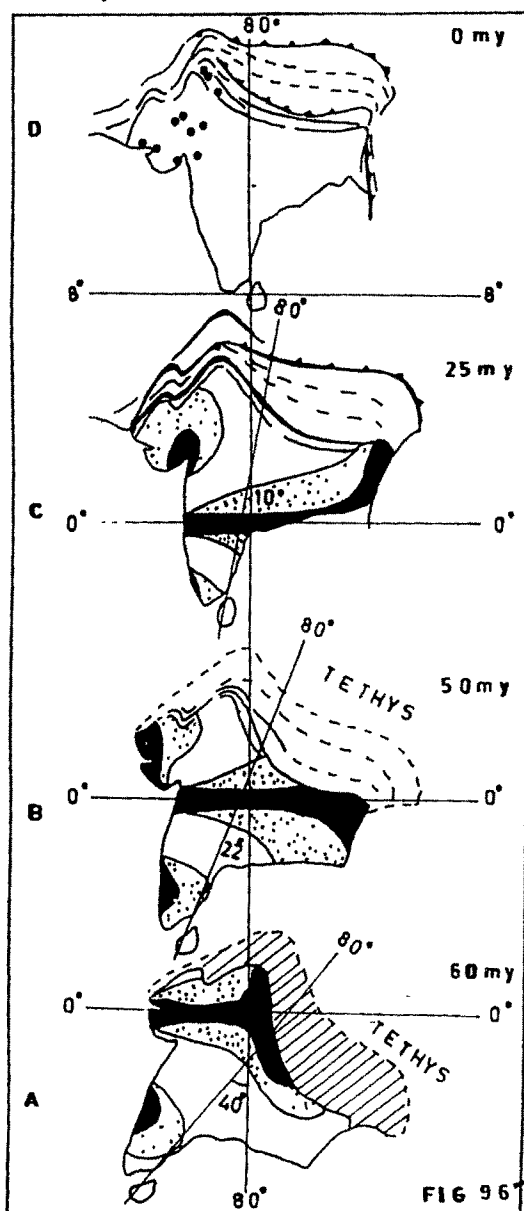


The palaeoposition of the Indian plate during which the northwestern laterite and lignite belt was being formed, indicated by forested area. Broken line indicates the possible extension of Greater India which we believe to have drifted away much earlier than did the main Indian plate. (after Sychanthavong and Patel, 1987)

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, 17cm/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).

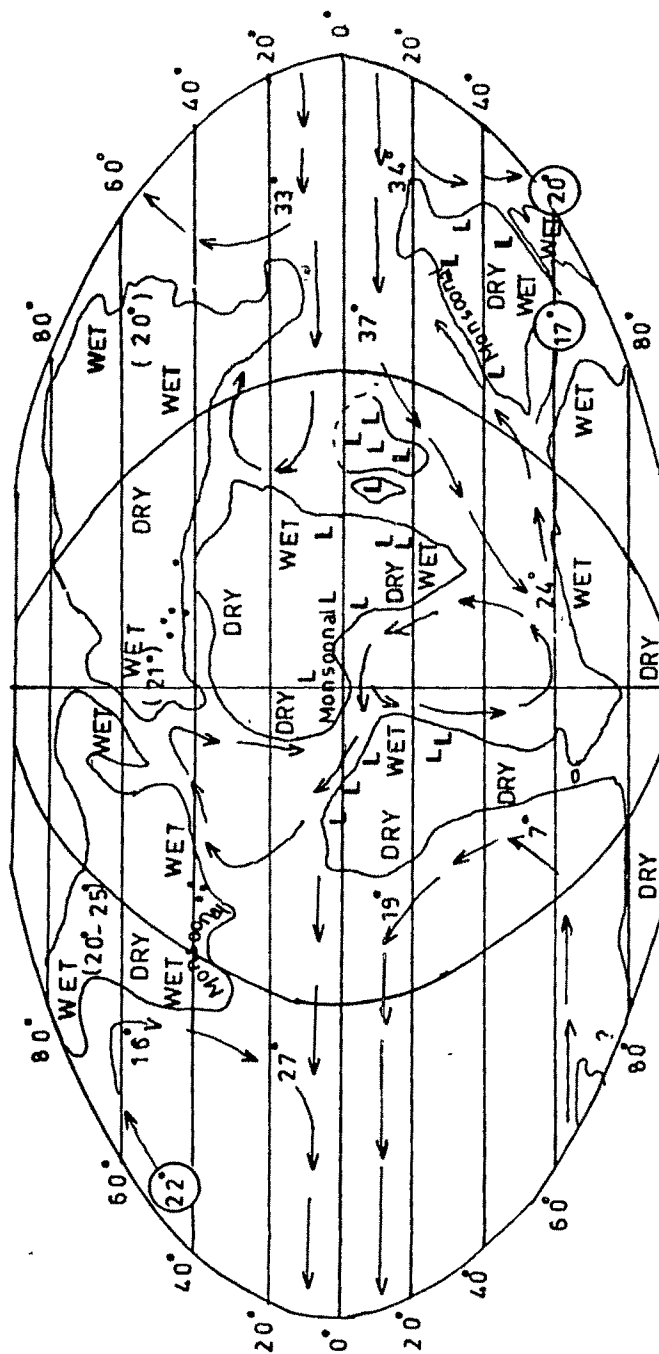
The age of the whole Indian Tertiary laterites and lignites decreases from north to south in concordance with the drift tectonic history of the Indian plate across the equator. Based on these data, the palaeoclimatic reconstruction in this continental plate under equatorial conditions can be suggested following the concept of climatic distribution and precipitation over various hypothetical continents of different shapes and sizes in the equatorial zone (Robinson, 1973) (Fig.96).

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 maps show that during Eocene (Fig. 97) the conditions were extremely favourable allowing bauxite formation until 50-55 latitudes. Actually, all Eocene bauxites were situated in the tropical monsoon areas.



A, B & C- Palaeoclimatic reconstruction 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 (Early Palaeocene, Early Eocene and Late Oligocene respectively). D- Present day configuration with the distribution of the northwestern laterite and lignite belt. Dark area denotes wet climate, suitable for lateritization and thick tropical rain forests; stippled area indicates humid climate with much lesser rainfall; and blank areas represent sub-humid or semi-arid and arid climates. The rotation angles for 50 m.y. and 25 m.y. are approximately calculated based on laterite and lignite data of Central, Southern and Eastern India in comparison with palaeomagnetic results. (after Sychanthavong and Patel, 1987)

# 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

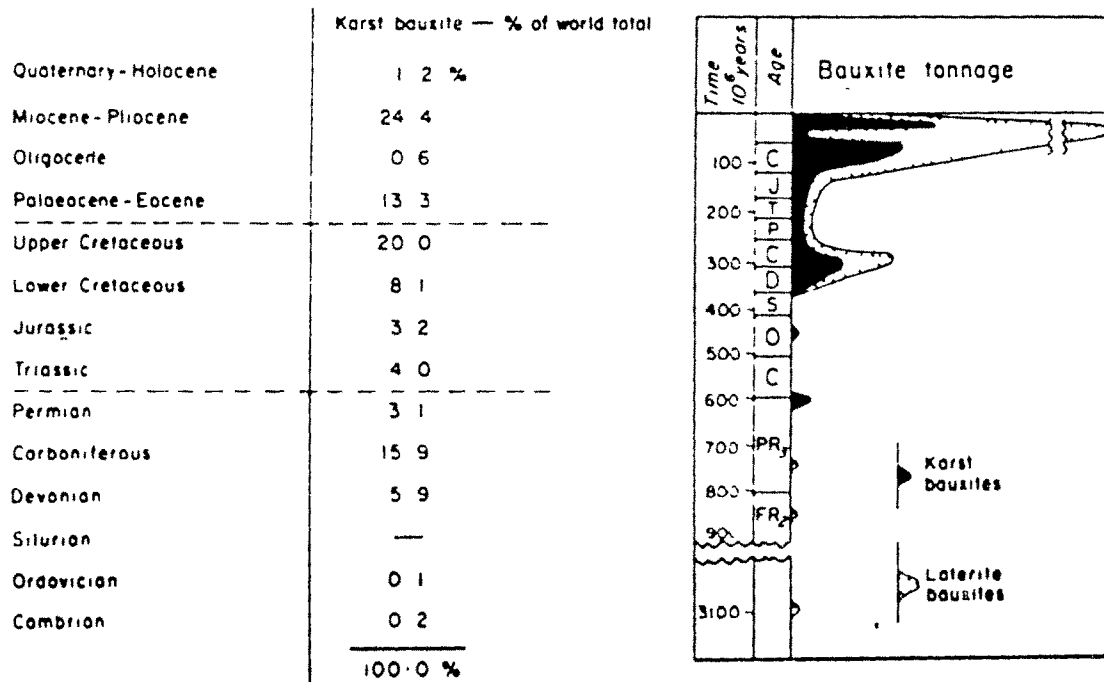
FIG. 97

Coversely, Barodossy (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. 98). 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. 99) clarifies these maxima and also highlights their insetting within an overall pattern of progressive increase to the present time (Mc Farlane, 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. 100).

### **Morphology**

The landscape of Kutch comprises the highlands standing out like 'Islands' amidst the vast plains of the Great and Little Rann of Kutch. Whereas the Rannas and Banni are the depositional plains of Recent time, the highland areas bear evidences of multiple erosional cycles (Biswas, 1974). Four major (Table 68) landsurfaces have been recognised in the landscape of Kutch (Fig. 101 and 102), (a) a widespread surface forming plains at the lower level of erosion (90.9-121.2 m) dated as Early Quaternary, (b) a

12 After Bardossy

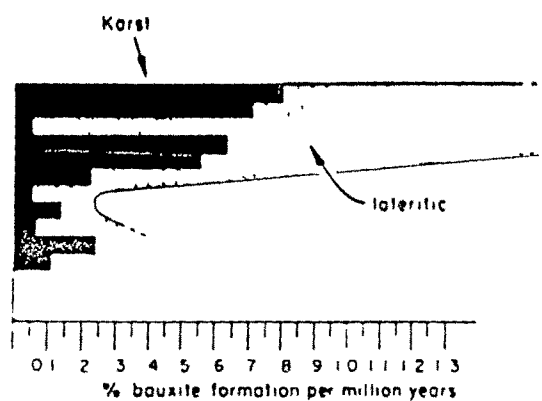


( After Bardossy 1979 ,1973 in Mc FARALANE 1987)

FIG 98

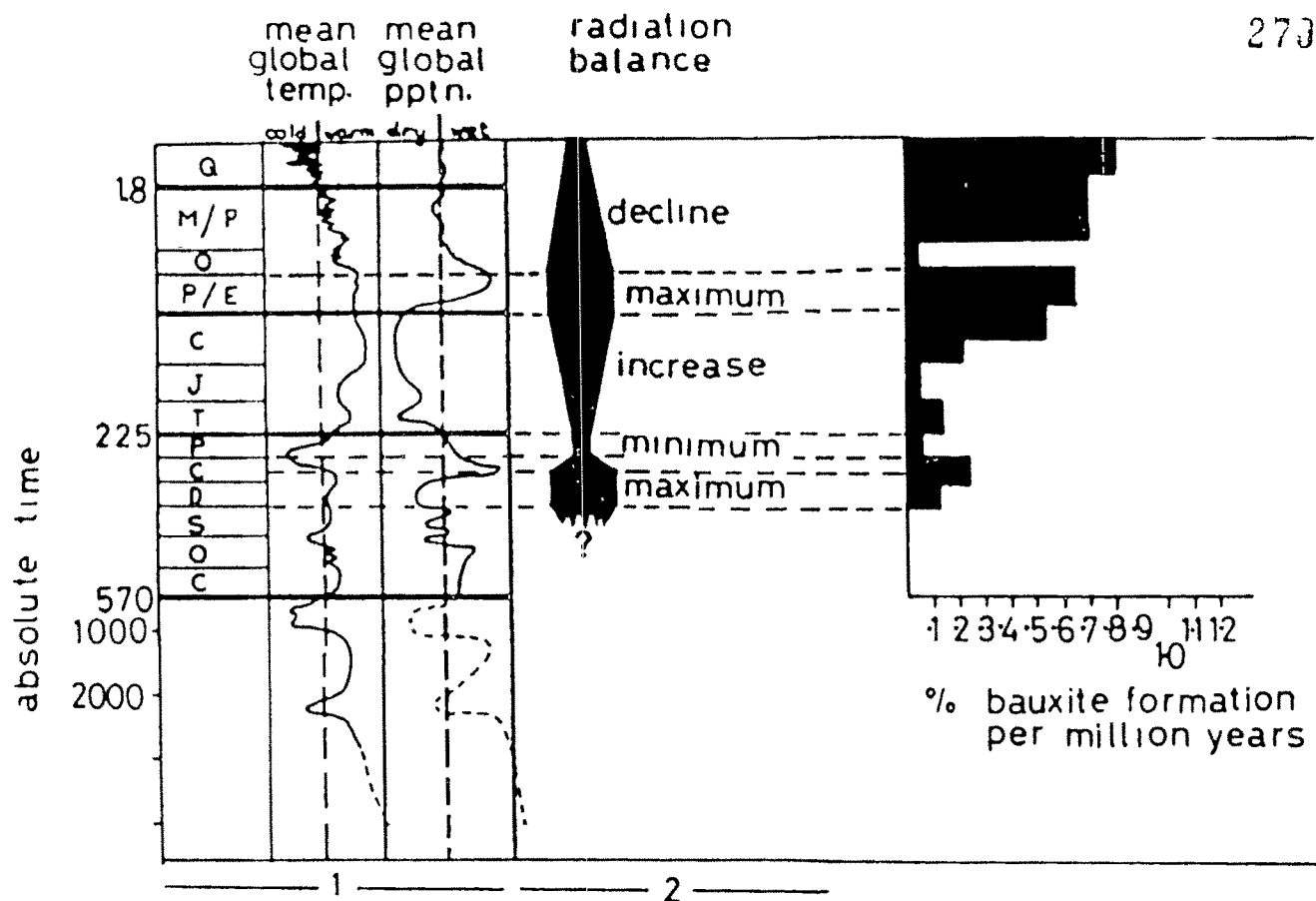
101

Duration in millions of years	Intensity — % Karst bauxite formation per million years	
1.5	0.8	Quaternary
35	0.7	Miocene-Pliocene
15	0.04	Oligocene
20	0.66	Palaeocene-Eocene
36	0.55	Upper Cretaceous
36	0.22	Lower Cretaceous
60	0.05	Jurassic
30	0.13	Triassic
55	0.01	Permian
65	0.24	Carboniferous
50	0.12	Devonian
40	—	Silurian
65	—	Ordovician
530	—	Cambrian



Variations in the intensity of bauxitisation during the different geological periods. (After McFARLANE 1987)

FIG. 99



The relationship between intensity of bauxitisation and palaeoclimatic conditions  
( in Mc FARLANE, 1987 )

FIG 100

less prominent Late Tertiary surface (136.3-151.5 m) forming flat-topped residual hills, isolated plateaus and terraces, (c) remnants of Mid-Tertiary surface (181.8 -212 m), forming discontinuous ridges and plateaus, and (d) the lateritised Early Tertiary surface (303-384.5 m) marked by the accordant summits of the towering hills. The 363.6 - 454.5 m high hills of Upper Cretaceous intrusives, higher than the Palaeocene surface, are considered to be remnants of the Upper Cretaceous landscape (Biswas, 1974 ).

The youngest Early Quaternary surface is cut vigorously by the recent cycles of erosion. These surfaces are correlatable with the African and Australian landsurfaces (Biswas 1974).

The most striking feature of the Kutch landscape is its first order topography. The physiography runs *pari passu* with the geological structure.

As the present work is confined to the laterite occurrences, it is only worthwhile mentioning the Early Tertiary landsurfaces, which are located in the Mainland of Kutch.

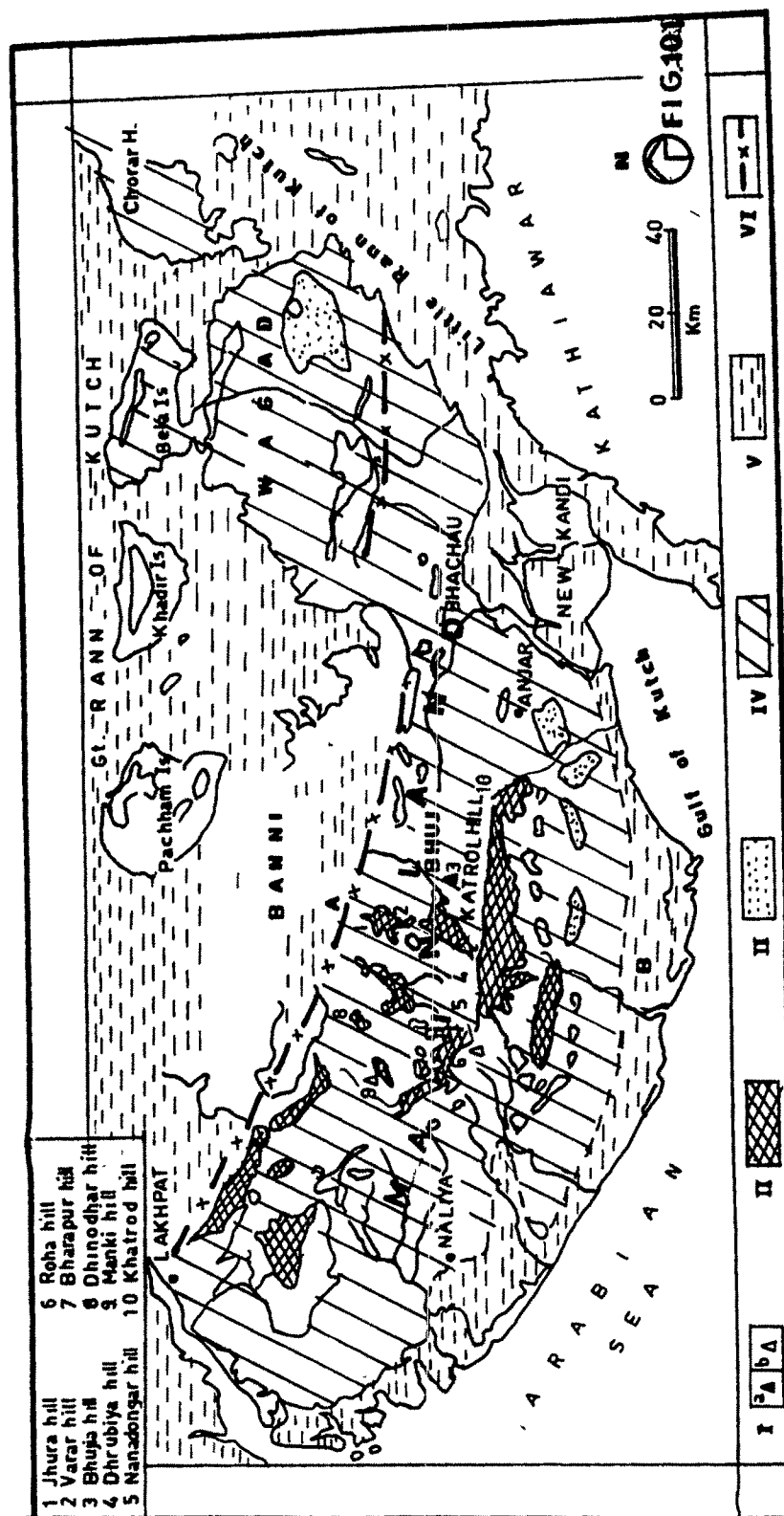
The Mainland is dividable into three distinct physiographic parts : (a) A central part with three main land-surfaces, Early Tertiary, Mid-Tertiary and Early Quaternary cyclic denudational plains, (b) In the western part, three cyclic landsurfaces are noted, Early Quaternary, Late Tertiary and Mid-Tertiary plains. (c) In the eastern part, two landsurface dominate - a vast plain of Early Quaternary age and broken remnants of the Late Tertiary landscape.

Table 68

Planation surfaces of Kutch Mainland (after Biswas, 1974)

Planation Surface & Landscape Features	Approximate Range of Altitude (in m. above m.s.l.)	Associated Physiographic Features	Unconformity in Sedimentary Sequence to which correlated	Remarks
I. Remnants of Upper Cretaceous Landscape	348.5m	Isolated scattered hills of mafic intrusive rocks, highest features in landscape	Pre-Deccan Trap disconformity (Post-Bhuj Formation)	Preserved only in Central Mainland
II. Early Tertiary Surface (Indian Cycle)	303m - 348m in N. part 272.7m - 303m in Central part	Isolated scattered hills with accordant summits	Palaeocene disconformity (post-Trap).	Duricrusted with laterite and correlable with terrestrial Madh Series (Palaeocene)
III. Mid-Tertiary Surface	181.8m - 212.2m in N. part 266.7m - 257.6m S. of Katrol fault 136.4m - 151.5m in S. part	Broken chains and clusters of flat-topped hills, discontinuous ridges, plateaus and cuestas.	? Post-Lower Eocene (Post-Kadai Stage)	Ferricreted surface being resurrected
IV. Late Tertiary Surface	90.9m - 106m in E. part 136.4m - 151.4m in Central part 151.4m - 166.7m S. of Katrol Fault 45.5m - 96.9m in S. & W. part	Low ridges and flat topped hills Terraces, ledges and saddles Residual hills and plateaus Dome hills and residual hills	Post-Miocene (Lower) (Post-Khari Series)	Not prominent where older surfaces of high relief present. Well seen in areas of low relief-E. & S. parts
V. Early Quaternary Surface (Kutch cycle)	96.9m - 121.2m in N. part 30.3m - 45.5m in Coastal areas	Extensive plains-sandy wasteland, rocky plains, and cultivated lands	Post-Pliocene (Post-Tankawati Series)	Most dominant surface in Kutch, covered by Recent sediments. Locally calcreted
VI. Late Quaternary Features	A. 30.3m above valley floor B. 2.0m - 9m above valley floor C. .9m - 1.5m above valley floor	Terraces in deeply incised valleys	Quaternary uplifts	A. Miliolite deposit B. Rubble & clay deposit C. Rubble deposit

# GENERALISED MORPHOLOGICAL MAP OF KUTCH SHOWING CYCLIC DENUDATIONAL SURFACES



- ### T Relics of Upper Cretaceous / Early Tertiary ( Indian Cycle ) landscape .

- ## II Mid - Tertiary land surface

- ### III Late Tertiary landsurface

- IV Early Quaternary landsurface ( Kutch cycle )**

- ## V Depositional plains

- ## VI Fault

( AFTER BISWAS, 1974 )

# PROFILE ACROSS KUTCH MAINLAND SHOWING CYCLIC LANDSURFACES

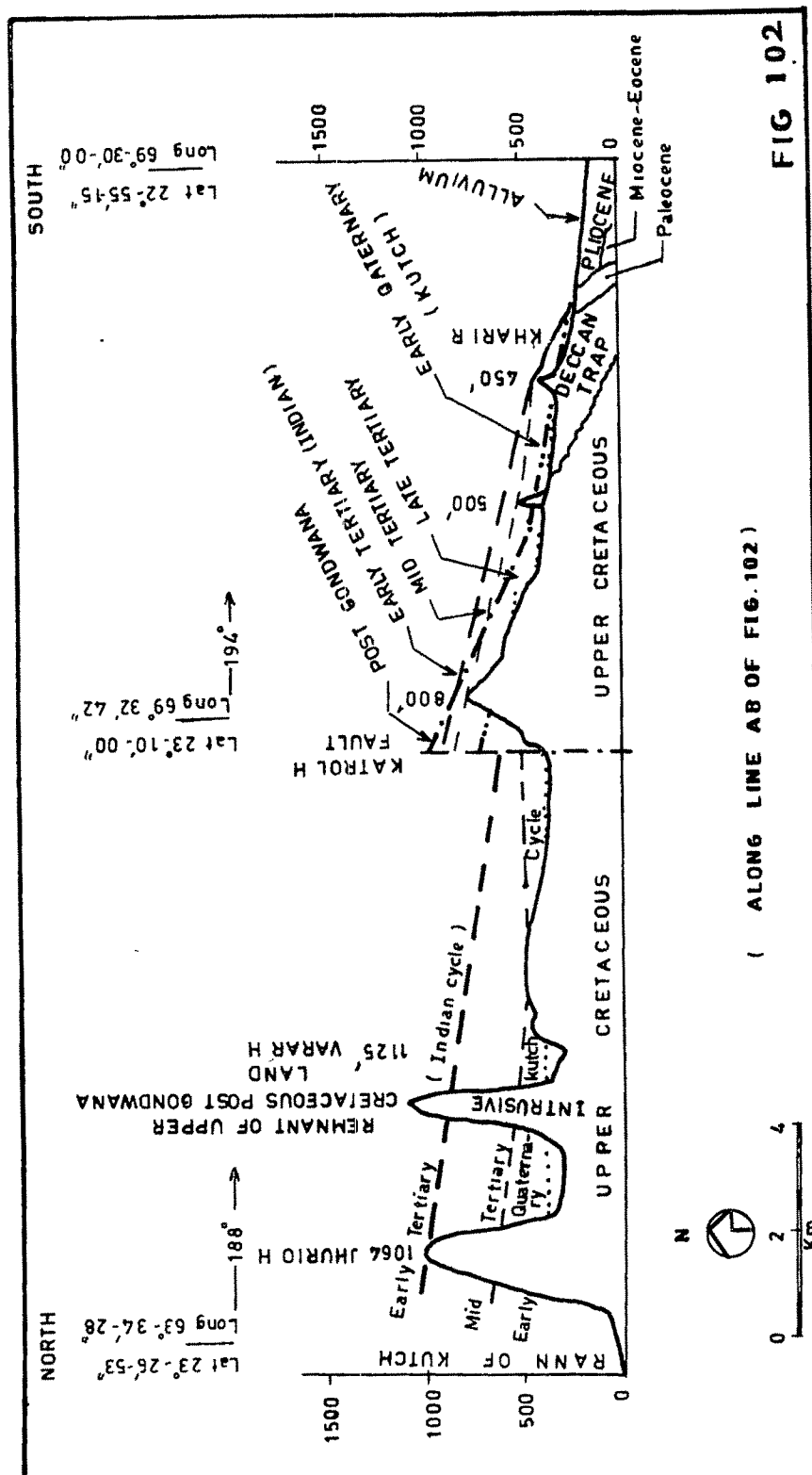


FIG 102

( ALONG LINE AB OF FIG.102 )

( AFTER BESWAS, 1974 )

### Early Tertiary Surface

The highest landsurface, preserved only in the central part of the Mainland, is indicated by the accordant summits of hills (usually flat topped) towering over the Northern Range and scattered on the Bhuj Lowland, e.g. Jhurio Hill (321.8 m), Varar Hill (394 m), Khatrod Hill (396), Lakhadi Hill (360 m), Manki Hill (308 m), the hill to the north of Magwana (323.6 m). This surface thus ranges in height between 303 m and 348.8 m in the Central Mainland but it slopes to the south and southwest towards the outcrops of the Palaeocene rocks indicating later tilting (Biswas, 1974). Here the hills ranging in height between 242 m and 273 m mark this surface, e.g. the group of hills of 272.7-303 m altitude north of Shankar Mahadeo (NW of Sisagadh), Bhopa Dongar (262.2 m), the conical hill (279.4 m), near Kotada and Roha Fort Hill (264.5 m). The tabletop surface of Roha hill made of Deccan Trap, is capped by a thin Palaeocene laterite over which in Kutch.

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 lateritization processes.

In the context of cyclic landsurface development, the formation of a lateritic 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. Logically, 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).

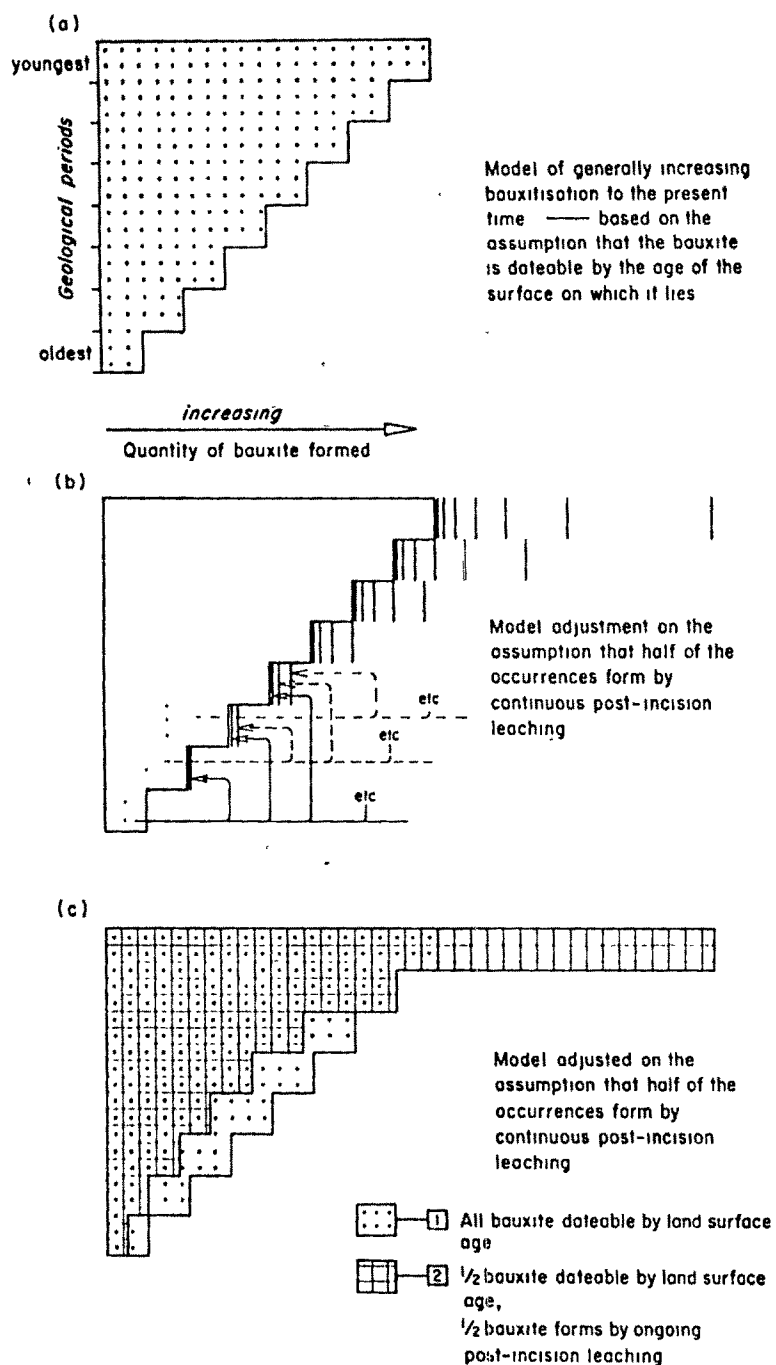
In India, degree of bauxitization of elevated plateaux is related to the degree of dissection (Rao and Ramam, 1979; Bardossy, 1983).

In the Darling Range, West Australia, 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 bauxitization 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 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 103) 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 of Kutch occur in the Cretaceous- Tertiary coastal plains as an elongate belt, hundreds of kilometers long and several hundred meters to nearly two kilometres wide. These laterites are considered to be part of an



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 )

FIG. 103

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 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 components. Thus, in a tectonically stable area lateritization can be placed within the later stages of landsurface reduction (McFarlane, 1983).

During the Palaeocene, (i.e. the lateritisation period) the Kutch area was tectonically stable and was later faulted during the middle and late Tertiary times.

### Drainage

Most of the laterites of Gujarat State including those of Kutch 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. 104).

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 area of Kutch is as follows :

Horizon rich in oxides	B (Fe,Al)
	OX
Horizon rich in silicates (saprolite)	B
Horizon of fresh parent rock	C

Within this major section, there are two types of sub-sections

Present, viz.,

#### High silica type (HST)

#### Low silica type (LST)

Laterite/ bauxite	B (Fe, Al)	Laterite/bauxite
	OX	
Kaolinite )		
)		
) (Saprolite) B		Kaolinite
)		
Bentonite )		
Deccan Trap basalt	C	Deccan Trap basalt

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

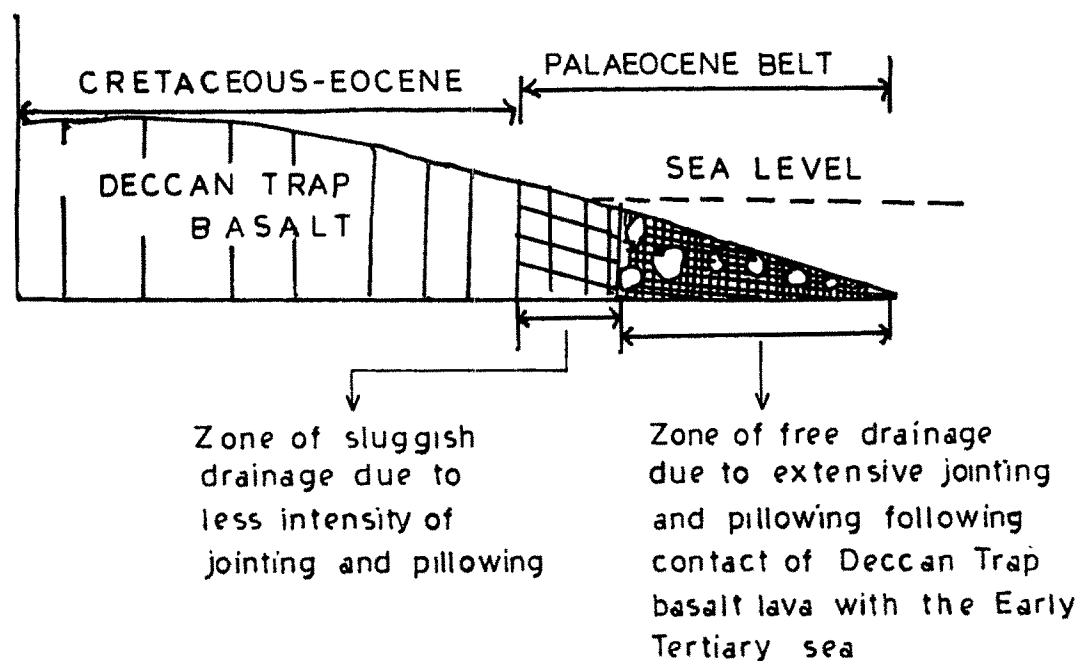


FIG 104

For the formation of such low-silica type and high-silica type sections within one laterite belt, varying differences in drainage intensities is essential. Poor drainage conditions lead to a high-silica type because silica is not sufficiently removed. Good drainage conditions produce the low-silica type.

#### 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 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 are 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 its development. Holmes (1914), noted its absence on granites and sedimentaries. 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 feldspars, 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.

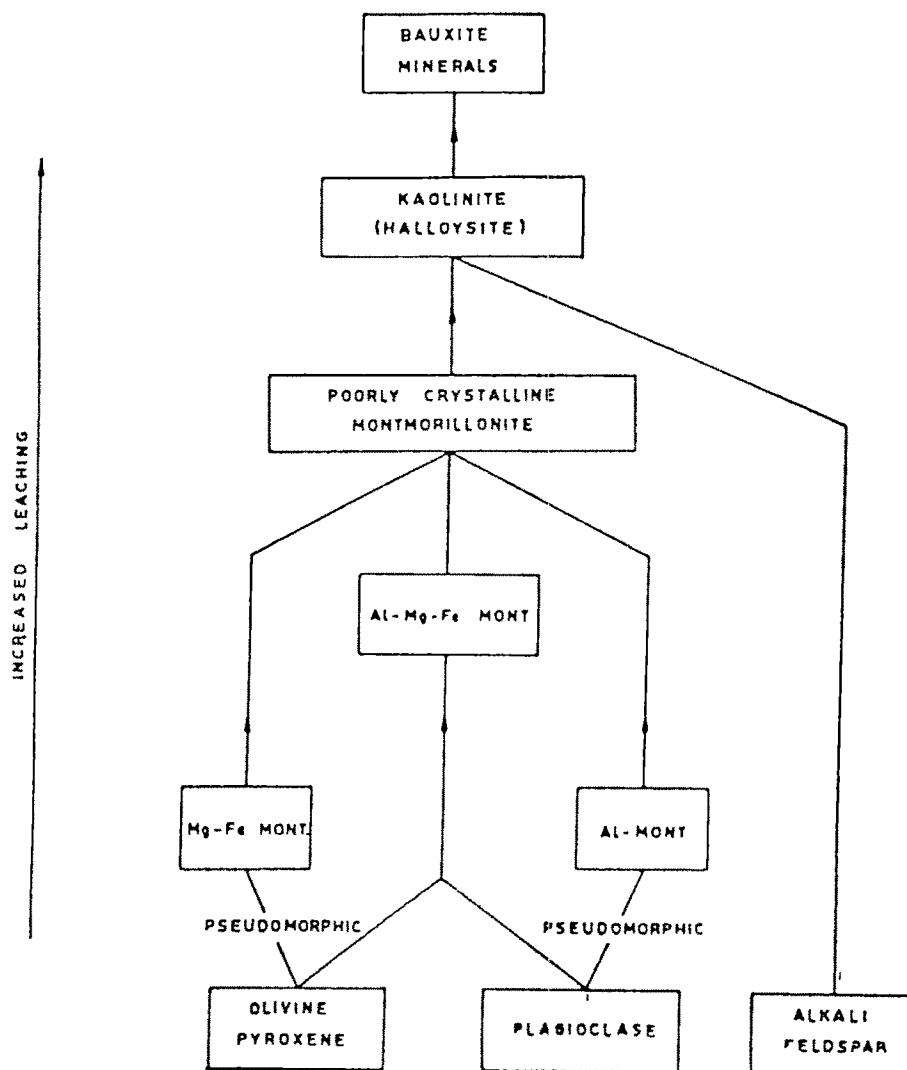
These anomalies are informative, for if in one area laterite development is favoured by a particular lithology while in another its development is apparently inhibited by the same lithology, this suggests that other environmental factors are

operative if not dominant in its development.

A classic example of this is illustrated by the laterites of Kutch district. Here, the occurrence is in the form of an elongate Palaeocene belt, hundreds of kilometres long, 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.

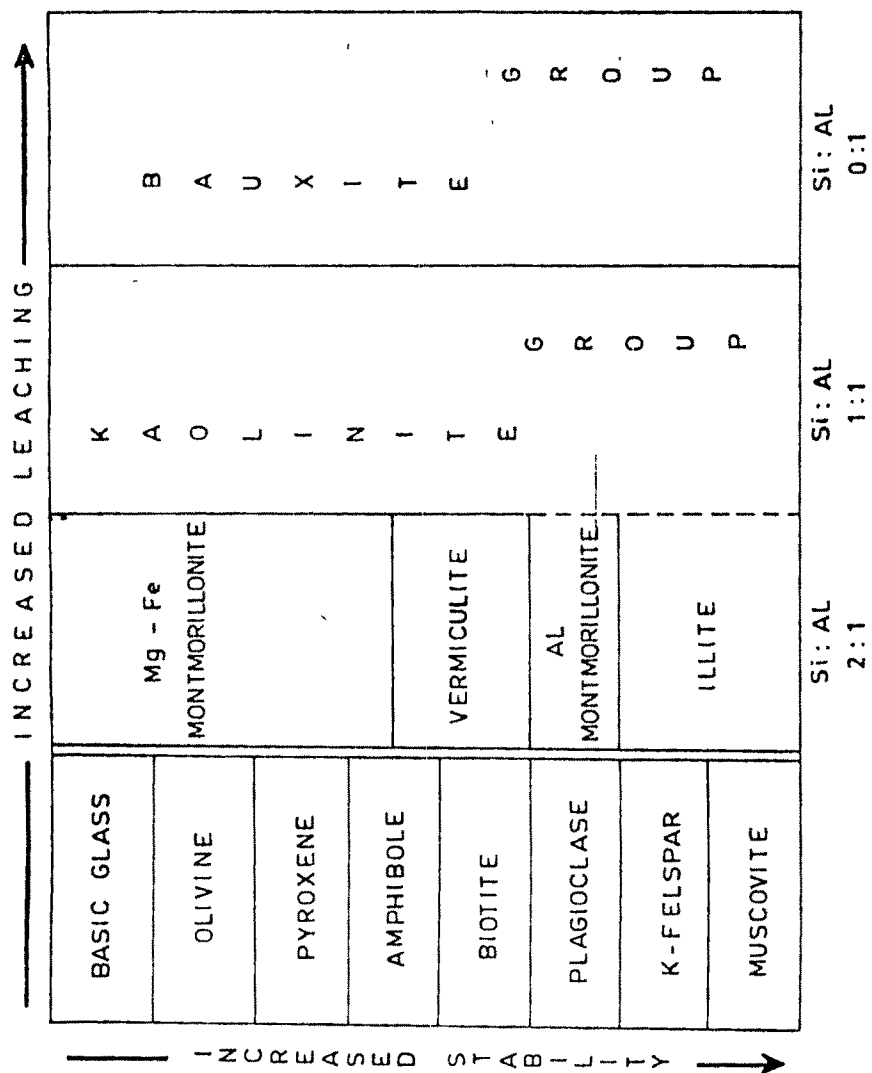
One can question as to why this narrow belt underwent lateritization with the major portion of the Deccan Trap formation remaining unaffected. A possible cause can be that the linear Palaeocene belt, representing the edge of the outpouring of the Deccan Trap basalts came in contact with the early Tertiary sea and this sudden cooling of the lava all along the palaeo-shoreline must have caused extensive pillowing and joint formation. This is manifest 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.

The laterite sequence in Kutch is unique, in the sense that, it contains in its profile, two economic mineral deposits, viz., bentonite at the base of the section, while bauxite occurs in the upper levels. This occurrence with the accompanying relict textures of the underlying Deccan Trap basalt in the bentonite, leads one to postulate that this bentonite was formed as a first stage in the major process of lateritization of the Deccan Trap



Diagrammatic representation of the weathering sequence developed on Tertiary basalts in New South Wales (after Craig and Fourhman, 1964)

**FIG. 105**



Diagrammatic representation of mineralogical changes as weathering proceeds, based on flow charts proposed by Craig & Loughnan (1964).

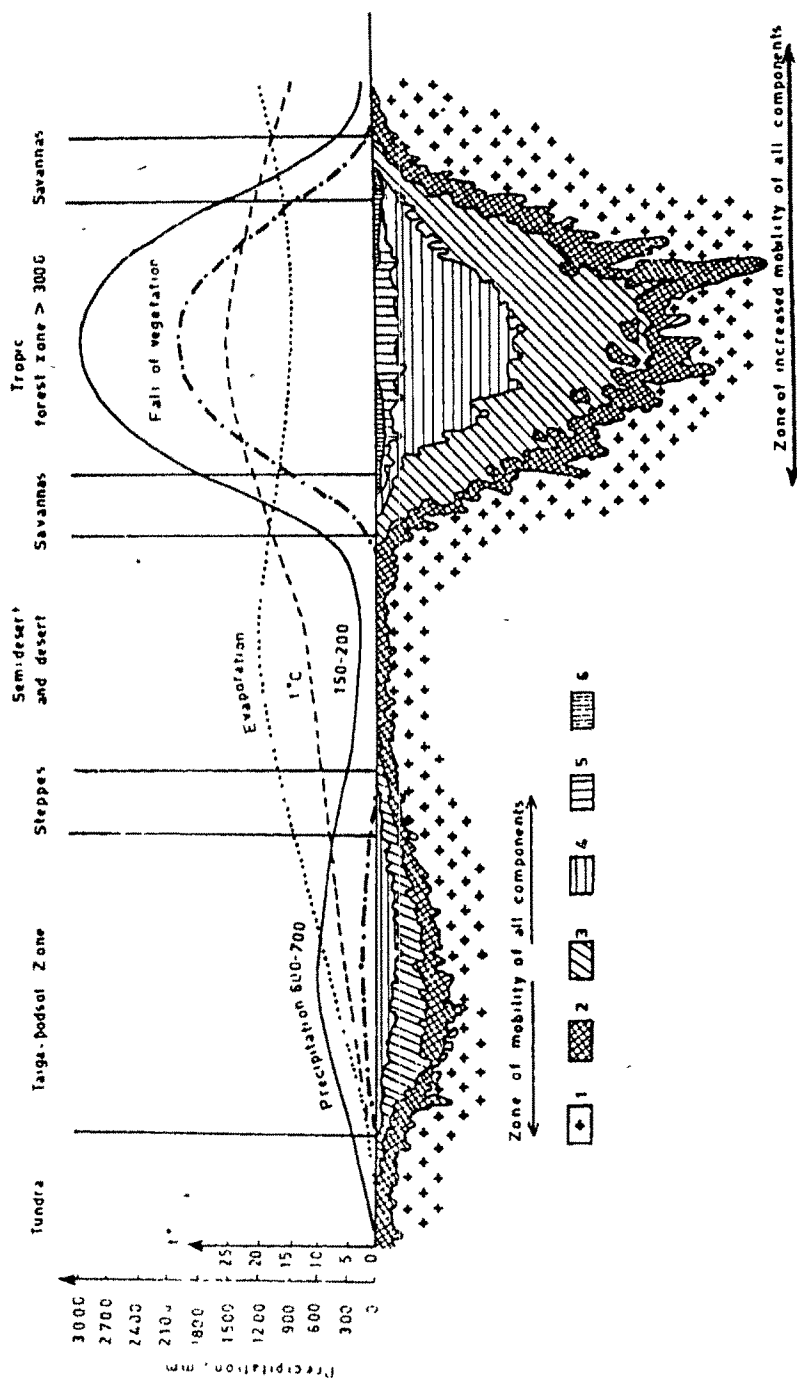
FIG 106

basalts. Such a large scale formation of bentonite derived from the weathering of Deccan Trap basalt is quite unique, in contrast to the common and accepted origin, that it forms from the alteration of volcanic tuff or pyroclastic material. It can also be formed by the hydrothermal action on volcanic material.

On the other hand, reports indicate that basalts have yielded trioctahedral montmorillonites (beidellite, montmorillonite and nontronite) by alteration of olivine/pyroxenes and plagioclase feldspars respectively (Craig and Loughnan, 1964). In the near surface horizons, these montmorillonites are rendered unstable by the more intense leaching conditions resulting in halloysite and kaolinite. Simultaneously, iron oxide as goethite, hematite or an amorphous precursor of these is concentrated in the oxidized parts of the weathering (Fig. 105 & 106).

† Bayliss and Loughnan (1963), have described a Middle Tertiary weathering sequence developed over basalt consisting of a lowermost 4 ft (zone 1) composed of montmorillonite which still retains the vesicular structure of the parent basalt. This is succeeded by 11 ft of clay (zone 2) which also possesses the residual structure of the parent basalt, but consists of kaolinite. Zone 2 grades upwards into a 4 ft-light coloured mottled zone (zone 3), and this, in turn, is overlain by 5 ft yellow bauxite clay (zone 4). A well defined boundary separates the top of zone 4 from 18 ft of light red, mottled clay (zone 5) which grades upward into a deep red, pisolitic zone rich in gibbsite, hematite and (or) goethite, approximately 8 ft thick (zone 6).

Strakhov (1967), has given a sketch of a weathering mantle in



Sketch of formation of weathering mantle in areas that are tectonically inactive (1) Fresh Rock, (2) zone of gross 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).

areas that are tectonically inactive (Fig. 107 ). From the diagram it is clear that in a tropical forest zone, the highly leached surface layers consist of a residue of ferric oxide 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 series 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 Kutch

Basaltic rocks in Kutch extend from east of Anjar upto the mound of Mata-no-Madh. From Anjar, this belt runs in an east-west trend upto Nangrecha where on account of a major fault, it has been shifted northwards to further continue upto Mata-no-Madh in a NW-SE direction. From Anjar to as far as Ramania and Punadi, the Trappean occurrences are demarcated by Pliocene formations in the south and by the mid-Cretaceous formations in the north. Beyond this, the southern boundary of the basalts is demarcated by the formations of the Madh Series.

Basalt is not exposed on the surface wherever bauxite and bentonite quarries are located. However, basalt is found exposed as a base rock at the bottom of some pits of bentonite. The boundary between the basalt and the overlying bentonite is transitional.

In most of the bentonite mines, basalt occurs as corestones which are either completely bentonitised or have an inner core of hard basalt followed outwards by more bentonitised rims. These

corestones represent relics of lava flows which had subsequently undergone spheroidal weathering. These corestones are mainly restricted to the bentonite zone.

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 or 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 iddingsite. 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 <sub>2</sub>	-	51.50 %
Al <sub>2</sub> O <sub>3</sub>	-	14.93 %
TiO <sub>2</sub>	-	1.77 %
Fe <sub>2</sub> O <sub>3</sub>	-	3.41 %
FeO	-	9.77 %
MnO	-	0.09 %
CaO	-	9.51 %
MgO	-	4.54 %
P <sub>2</sub> O <sub>5</sub>	-	0.22 %
Na <sub>2</sub> O	-	3.24 %
K <sub>2</sub> O	-	1.02 %

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### 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 irrevocable 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 the Deccan Trap basalt are calcic plagioclase (labradorite), olivine, augite and magnetite.

### Calcic Plagioclase Felspars

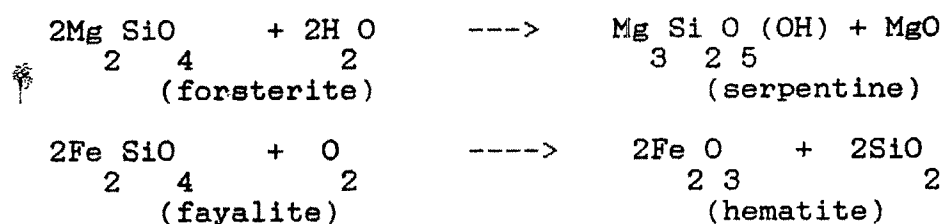
In the framework structure of the felspars, the tetrahedra are linked through all four oxygen atoms to yield a three-dimensional configuration. Aluminium substitution for silicon within the tetrahedra creates a net negative charge on the framework which is balanced by a calcium ion. Break down of the calcic felspars

proceeds through the loss of these calcium ions, but for their escape, the tetrahedral framework must be ruptured. In the calcic feldspars the aluminium - to silicon ratio is 1:1. Despite the similarities in structure of the alkali and the calcic feldspars, 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 the Al-O-Si bonds. With the loss of the metallic ions, the framework structure breaks down into chains which tend to polymerize 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 feldspars 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 the neither free silica nor free magnesia remains within the weathering zone. This and the ease 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 maghemite, or the hydroxide, goethite. However, much may persist in an extremely fine state and appear amorphous to X-ray radiation.



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 readily 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	: chlorite,	: Complete	: Kaolinite,
loss of	: Montmoril-	: loss of	: Ferric oxides
pyroxene $Mg^{++}$ ,	: lonite	: $Ca^{++}, Mg^{++}$	: Anatase
$Ca^{++} Fe^{++}$ , --->	: Calcite,	: Partial ----->	
Oxidation	: Ferric	: loss of $SiO_2$	
		2	
Of $Fe^{++}$	: 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,  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$  to boehmite,  
 $\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ .

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  $\text{CO}_2$  and at  $p\text{CO}_2$  at  $25^\circ\text{C}$ , when it is saturated with  $\text{CO}_2$ , the pH is approximately 5. Rainwater in clouds has a pH of 5.7, but this value varies according to the other cations that are present (Carroll, 1962). Not all rainwater is saturated with  $\text{CO}_2$ : there is a delicate equilibrium between the  $\text{CO}_2$ , the  $\text{H}_2\text{CO}_3$ , and the  $\text{HCO}_3^-$  content, which can be thermodynamically stated as:

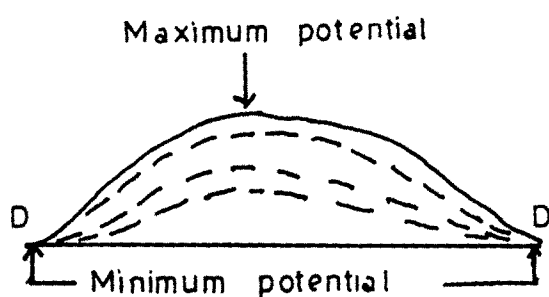
$$\frac{(\text{H}^+)(\text{HCO}_3^-)}{(\text{H}_2\text{CO}_3)} = K_{\text{H}_2\text{CO}_3} = 10^{-6.4} \text{ at } 25^\circ\text{C}.$$

This constant varies from 6.58 at  $0^\circ\text{C}$  to 6.33 at  $30^\circ\text{C}$  (Garrels and Christ, 1965, p.89), which is the pH range in which weathering takes place.

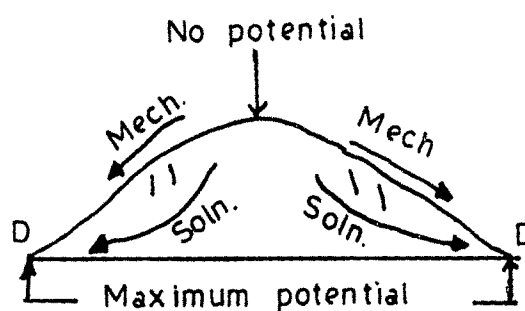
All water that comes in contact with rocks is slightly acidic. This is the most important fact of chemical weathering.

There now seems little doubt that laterites are essentially residual accumulations of chemically resistant minerals (McFarlane, 1983). From an overall point of view, the system of accumulation is entirely relative. Laterites 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

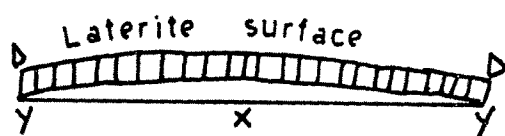
(a) Vertical surface movement



(b) Lateral enrichment



(c)



D - Drainage line

Y - Absolute accumulation predominates

X - Relative accumulation Predominates

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

FIG 108

between these two types of accumulation was stressed by d'Hooere (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.108). Interfluvial positions are areas where there is maximum potential for surface lowering (Fig 108 a and c). In Kutch, the palaeogeomorphology was controlled by the Deccan Trap flows. The residual relationship between basalt, bentonite, lithomarge and laterite 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. Chemical differentiation in the lateritic belt has resulted in the formation of two types of profiles :

- (a) Low Silica Type (LST) with a kaolinitic saprolite
- (b) High Silica Type (HST) with a bentonitic and kaolinitic saprolite.

These two sections are a manifestation of, mainly, the drainage intensity; with good drainage favouring the formation of LST sections and poor drainage the formation of HST sections.

#### Genetic Model :

The initial belt which underwent lateritization was, as discussed

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, with differential intensities on either ends of the width of the laterite belt. This is attributed to the slight slope, seaward ( $5-10^{\circ}$ ) of the Deccan basalt on the one hand, and the presence of intensely pillowed and jointed basalt seaward which would facilitate free drainage. Inland, near the contact of the Palaeocene lateritic belt and the Deccan Trap basalt, the drainage, near the weathering front (Fig.104) would be sluggish.

In fact, within a width of 1-2 km, two different types of drainages can be seen. This in turn, led to the evolution of two kinds of geochemical weathering environments viz., one with a free drainage and oxidising conditions, i.e., near the sea, and the second, with a sluggish drainage and reducing conditions, inland.

Hence, in this laterite belt, due to the differing geochemical environments on either side of the width, attributable to the topography, both relative and absolute accumulations have taken place. The inland positions are predominately sites of relative accumulation, as there is maximum potential for surface lowering.

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 in 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.

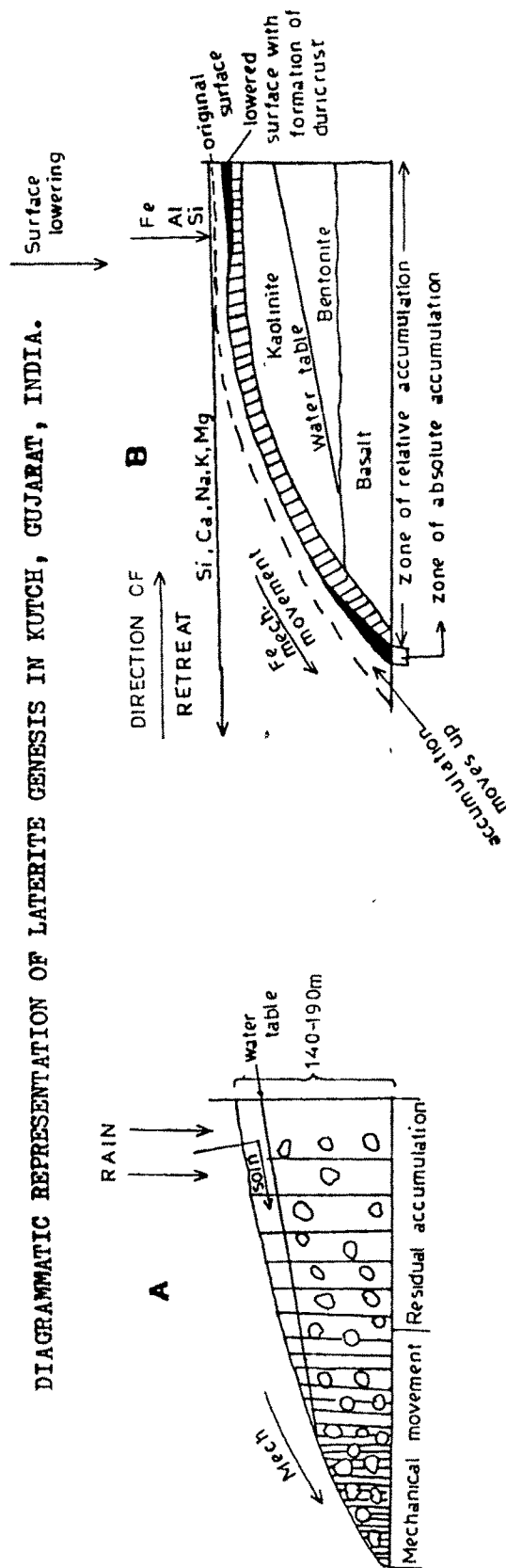
In short, within this narrow laterite belt, there are areas in which relative and absolute accumulation predominate and are identifiable.

Fig. 109 A represents the initiation of weathering of the edge Deccan Trap basalt having an elevation range between 140-190 m (Tables 4,15,22,32,34,38,41,43,45,60 ). The original elevations have been calculated from Cr-retained mass-balance models of the various complete LST and HST profiles in the area. 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 labradorite-olivine-augite below the water table. This produced Mg, Fe, Al, montmorillonite minerals (bentonite zone ) as alteration products (Fig. 65,83; Tables 23,24,25,26,27,61,62,63,64,65). The most mobile elements were evacuated by the seawards moving ground water (Fig. 109 b).

The bentonite zone occurred at progressively lower levels as the weathering front lowered below the ground water table level. The

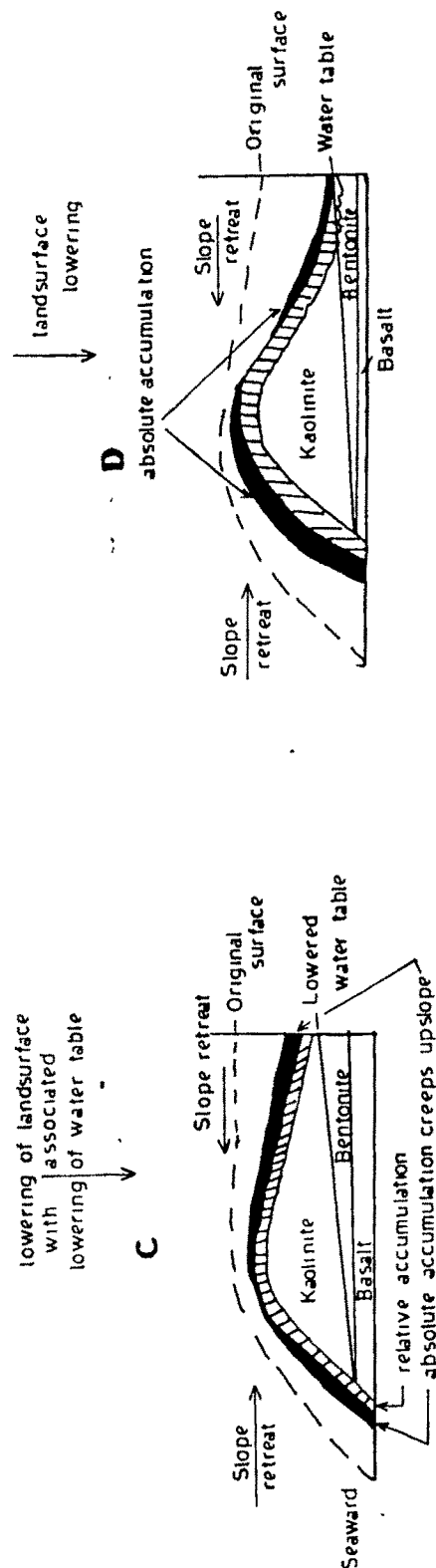
# DIAGRAMMATIC REPRESENTATION OF LATERITE GENESIS IN KUTCH, GUJARAT, INDIA.



Initiation of weathering of the edge of the Deccan Trap basalts. Residual accumulation predominates inland, while mechanical downslope movement pre-dominate sea-wards.

The early stages 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 ie. kaolinite and bentonite respectively, with bentonite occurring below the water table.

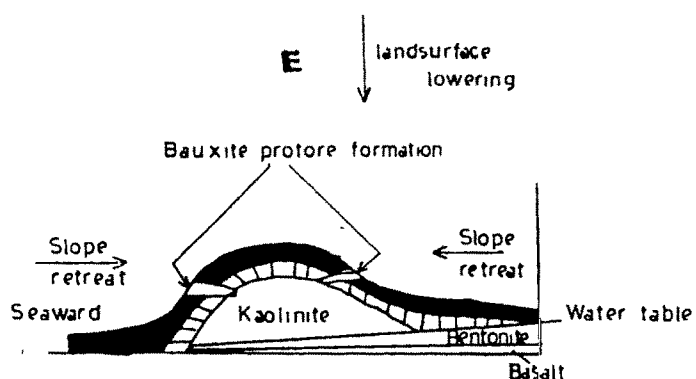
FIG 109



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

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

FIG. 110



Development of bauxite protore on both sides of the hillock giving rise to 2 different types of sections viz. LST seawards and HST landwards. The bauxite in the HST section is of the clayey type, while that in the LST section, it is of commercial grade. This can be attributed to better drainage conditions seawards. The development of the bauxite protore post-dates laterite formation, formed after the faulting depicted in Fig. . The removal of Fe can be attributed to microbial activity.

FIG III

other profile interfaces including the overlying kaolinite, laterite 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 Cr-retained mass balance studies of selected LST and HST 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.

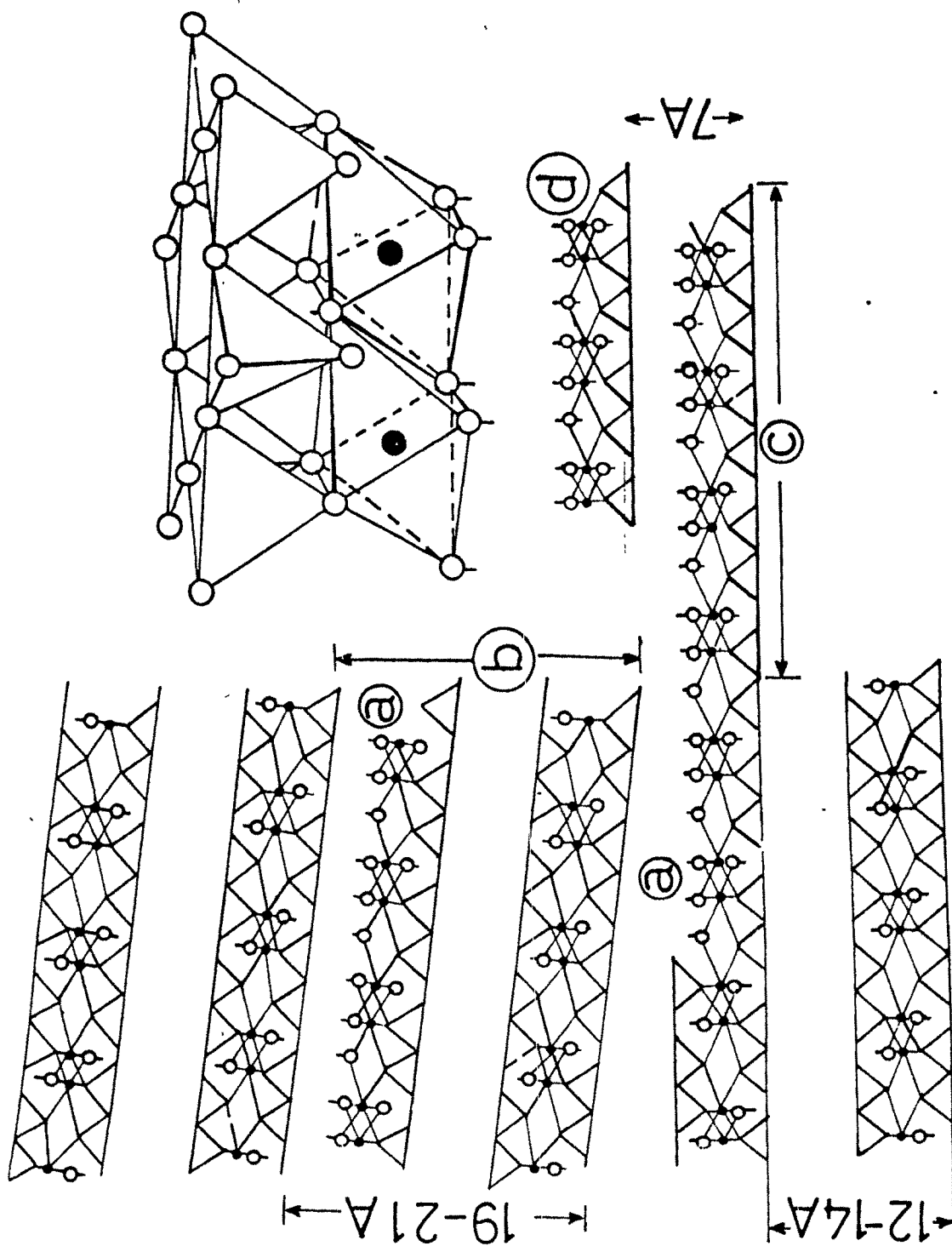
The bentonite, which occurred below the groundwater table level started decomposing into kaolinite above the water table due to freer drainage conditions, by intracrystalline leaching of interlayer cations and tetrahedral silica layers as has been suggested by Altschuler et.al. (1953). This consisted 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. 126 a).
- (2) Relapacement of vacant tetrahedral oxygen sites by hydroxyls to create a highly polar kaolin-like arrangement in the

residual 1 : 1 sheet (Fig. 112 a).

- (3) The highly charged outside layer of hydroxyl protons contracts the interlayer space of that of kaolinite by identical charge polarity (Fig. 112 b).
- (4) Extension of the kaolin-like sheet laterally by epitaxial growth of true kaolinite and development of hexagonal modification outgrowths at the edges of the montmorillonite flakes.
- (5) The primitive kaolinite crystals are nourished and enlarged (Fig. 112 c), as the montmorillonite continues to break down. New layers of kaolinite are added (Fig 112 d).

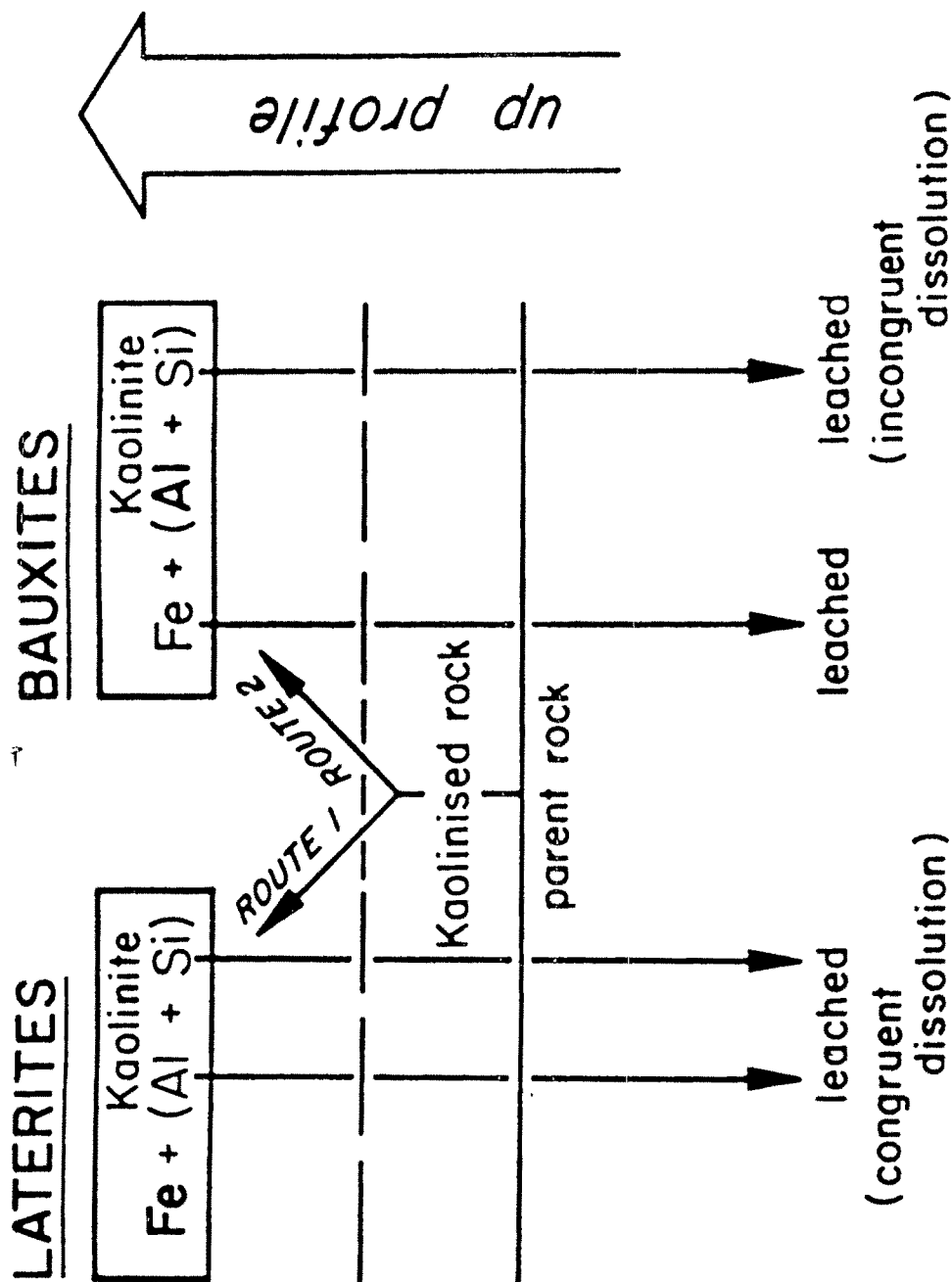
The formation of the kaolin belt marked the threshold for lateritization. The then kaolinized saprolite, must have been dominated by kaolinite, quartz, iron and aluminium minerals. This saprolite could only be lateritized if the kaolins broke down and quartz was leached out. McFarlane (1987), has stated 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. 113) 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.



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

AFTER ALTSCHULER, ET AL (1963)

FIG. 112



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. ( Mc FARLANE , 1987 )

FIG. 113

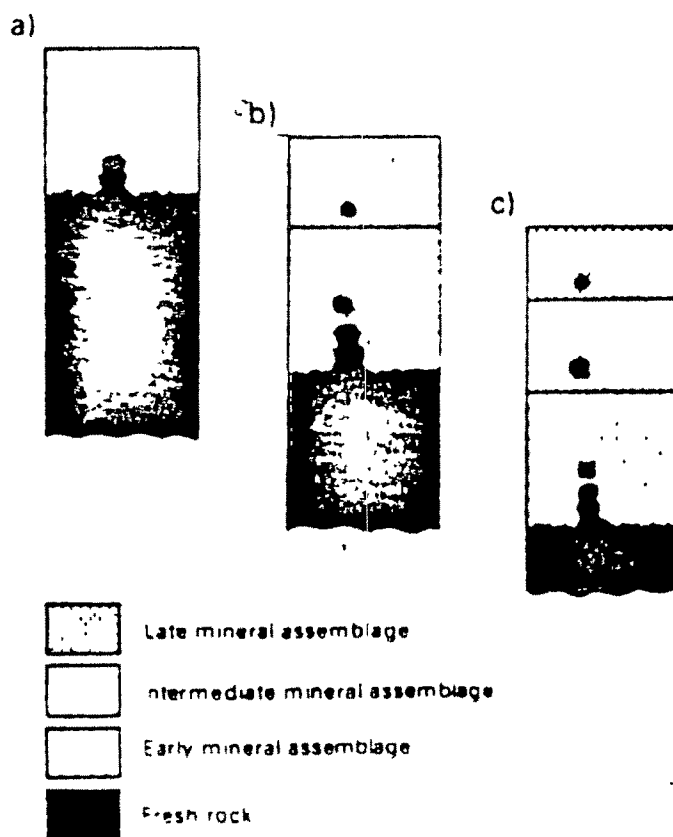
Although some extremely resistant primary minerals survive in the residuum, it is ultimately dominated by iron minerals (especially goethite and hematite) or aluminium minerals (especially gibbsite). The number of stages in the progression varies, apparently with leaching intensity, as is evident in Kutch with the HST profiles have an extra bentonite zone with the same missing in the LST profiles. The variation in the number of stages in the progression within one laterite belt can be attributed to leaching intensity (McFarlane, 1983 a).

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 (Okamoto et.al. 1957). In the case of bauxitization, although congruent kaolinite dissolution can be achieved, the removal of Fe with the Si can not. 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 is the case in Kutch. It is hypothesised that Fe enrichment (laterite protore formation) came first, followed later on by Al enrichment due to favourable environmental conditions.

All along, the process described in Fig 109 b was continuing, with further reduction of landsurface accompanied by retreat (Figs. 110, c&d; 111e). The slope bottom absolute Fe accumulation crept upslope to such an extent, that it covered the entire slope

and part of the crest also. That gave an apparent illusion that the Fe crest was residual in origin formed by the upward migration of Fe. Tables 32,34,38,41,43,45 reveal that there are top horizon gains of Fe with underlying horizons having less Fe, giving an illusion of upward migration. 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 Kutch in terms of pH and Eh have met with considerable frustration. Norton (1973), observed that the assemblages of minerals in many laterites do not conform 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 114 ) 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 both LST as well as HST profiles in Kutch, as revealed, by x-ray studies. There are no zones 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 bentonite zone with gradual destruction of the same upwards in the profile.



The inheritance effect. (a), (b) and (c) represent successive stages of profile development. Early and intermediate mineral assemblages survive to coexist with late mineral assemblages.

(after McFARLANE 1983)

FIG. 11.4

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 can not be explained in terms of a single set of hydrological history (McFarlane, 1983).

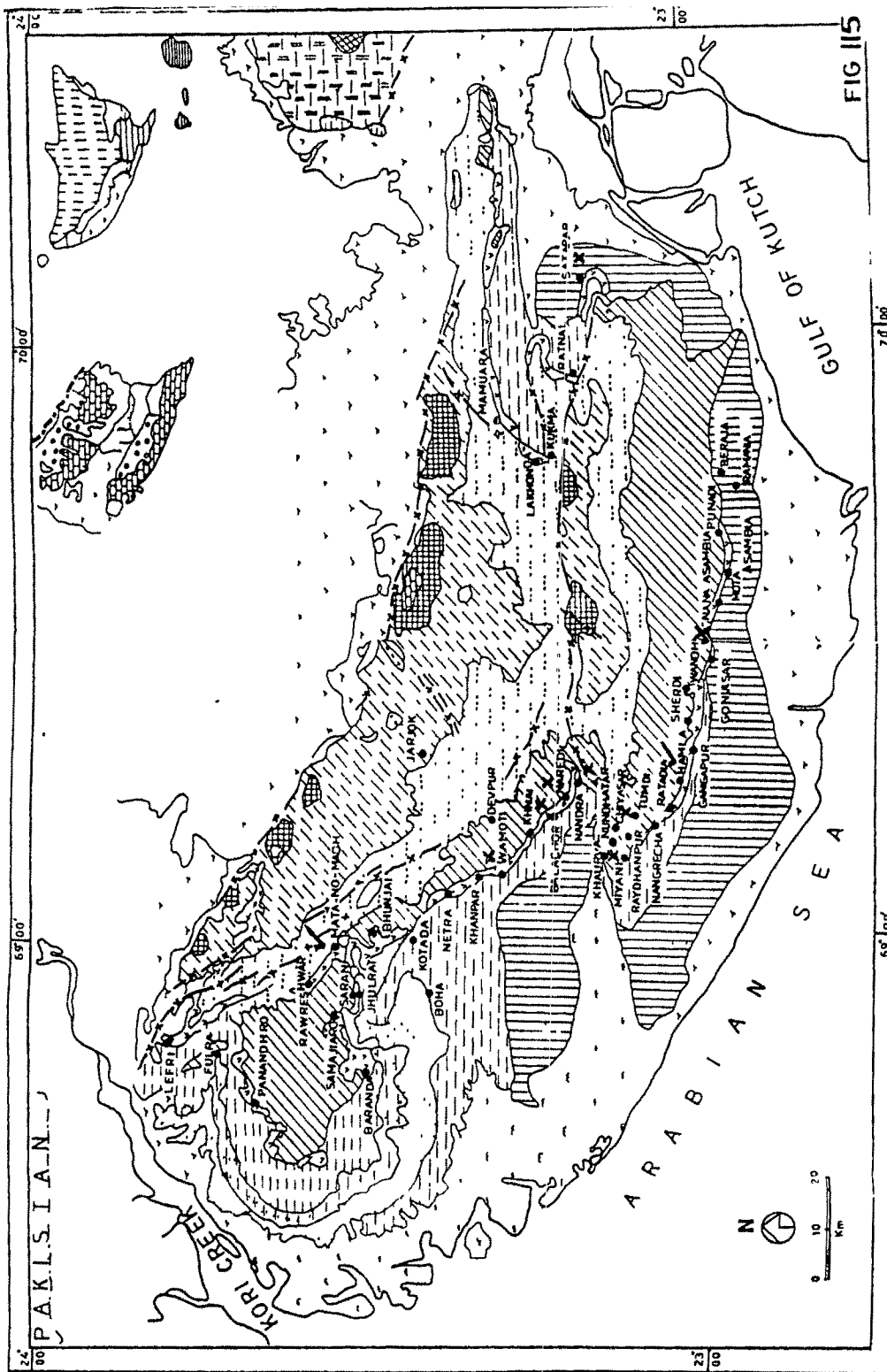
Failure of geochemical explanations for the varying mobilities in the LST and HST sections of Kutch for both Fe-enriched and Al-enriched residua following the above mentioned kaolinite dissolution leads one to point towards an important biological control (McFarlane, 1987). Geochemical constraints do 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 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 1 m, 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 1m (Button, 1981, Williams, 1981, Perviz, 1983).

As concerns the mobility of Fe in lateritic profiles microbiologists have long known that even where Fe is in abundance in soil profiles, the supply in 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 secretion 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 unconducive to mobilisation and micro-organisms which are capable of iron mobilisation exist there (McFarlane, 1987).

In Kutch 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. This is attributed to the fault (Fig115) which had displaced the entire Tertiary sequence, and resulted in the present topographical position of the Palaeocene belt. From (Fig



Geological map of Kutch showing the Fault which displaced the entire Tertiary sequence.

116). it can be seen that a majority of the HST profiles are located between the 60-80 m contours, while the LST profiles are found between 80-140 m contours. This elevational change of LST profiles could have been another cause of enhancement of bauxitization, but, during a much later period, when traditionally speaking, the conditions were inconducive for bauxite formation. This makes one wonder whether the genesis of LST profiles matured during the Quaternary time.



Contour map of Kutch showing present location map of various HST and LST profiles after faulting depicted in Fig 115, HST profiles are located between 60-80 m, while the LST profiles are found between 80-140 m contours.