Paleopedology of ferricrete horizons around Chennai, Tamil Nadu, India

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ABSTRACT

Some soils around Chennai, Tamil Nadu, are represented by ferricrete horizons, and these can be related to the underlying bedrock. In the present study, Red Soils and ferricretes have been studied from four different sites: Red Hills, Vaiyapur, Uttukkadu, and Pallavaram, which were formed from different parent rocks. Red Soils and ferricretes around Vaiyapur and Red Hills are formed from the Upper Gondwana sandstone and shale, while around Pallavaram they are formed from Precambrian charnockites. In this paper, morphology, micromorphology, and geochemistry of ferricretes and Red Soils are presented.

Microfabric elements in polished thin sections provide a basis for the interpretation of processes involved in Red Soil and ferricrete formation. Micromorphology of Red Soils and ferricretes reveals high content of the clay minerals gibbsite, smectite, halloysite, and kaolinite. Fe-oxide mineralogy is represented by hematite, limonite, goethite, and magnetite. Pedogenesis has produced iron segregation that has formed, both in external and internal forms, in a great variability of colors. Cracks and fractures are filled by either kaolinite or hematite. Some of the fractures are lined with black manganese oxide representing the final depositional phase. Based on geomorphology, the soils date to the late Neogene to early Quaternary period. Climatic conditions are interpreted to have been wetter than today.

Key words: ferricrete horizons, micromorphology, hematite, complex pedogenesis.

RESUMEN

Algunos suelos alrededor de Chennai, Tamil Nadu están representados por horizontes de ferricreta, que pueden estar relacionados con el lecho rocoso subyacente. En el presente estudio, los Suelos Rojos y las ferricretas han sido estudiados en cuatro diferentes sitios: Red Hills, Vaiyapur, Uttukkadu y Pallavaram, que fueron formados de diferente roca parental. Los Suelos Rojos y ferricretas cerca de Vaiyapur y Red Hills se formaron a partir de la arenisca y lutita Gondwana Superior, mientras que alrededor de Pallavaram se formaron a partir de charnockitas precámbricas. En este artículo se presentan la morfología, micromorfología y geoquímica de ferricretas y Suelos Rojos.

Los elementos de la microfábrica en secciones delgadas pulidas ofrecen una base para la interpretación de los procesos involucrados en la formación de Suelo Rojo y ferricreta. La micromorfología del suelo Rojo y la ferricreta revela un alto contenido de minerales de arcilla como gibsita, esmectita, haloisita y caolinita. La mineralogía de óxidos de Fe está representada por hematita, limonita, goethita y magnetita. La pedogénesis ha producido segregación de hierro, que se formó tanto interna como externamente en una gran variedad de colores. Las grietas y fracturas están rellenas de caolinita o hematita. Algunas de las fracturas se encuentran revestidas de óxido de manganeso negro, que representa la fase de depositación final. Con base en la geomorfología, se establece que los suelos datan del período Neógeno tardío al Cuaternario temprano. Se interpreta que las condiciones climáticas eran más húmedas que las actuales.

Palabras claves: horizontes de ferricreta, micromorfología, hematita, pedogénesis compleja.

INTRODUCTION

Deeply weathered terrains and thick regolith, including saprolite, are widespread, especially in the tropics and sub-tropical areas. These materials are of great importance because they provide a powerful tool for a variety of purposes, such as their significance to past terrestrial ecosystems, environments, and climates. Different facies of iron-cemented regolith materials (ferricretes) in the Chennai region, Tamil Nadu, occur in a variety of stratigraphic and soil settings, providing an opportunity to examine the different types of ferricretes and consider their stratigraphic and chronologic significance. The results from this study enable a re-examination and discussion of the concepts defining ferricretes as regional morpho-stratigraphic markers and of the related genetic associations with weathered, low-relief land surfaces and individual paleoenvironmental and chronological episodes.

In Chennai, Tamil Nadu, as in many other parts of the western and eastern India, studies of secondary ferruginous accumulations have been concerned with concepts associated with 'laterite'. The 'characteristic laterite profile' was seen as including an iron-rich cap over zones of iron depletion, and most research was interpreted within this context. The concept of 'laterite' and 'laterite profiles', however, contains some misleading genetic connotations and poorly defined terminology (see discussions by Ollier and Rajaguru, 1989 and Bourman, 1993a, 1993b). For this reason, I use the term *ferricrete* in preference to 'laterite'. Here I define ferricrete as an indurated crust cemented by iron oxides associated with weathering profile/horizons. The use of ferricrete as a geological marker is appealing, because it appears to enable the reconstruction of ancient land surfaces and to infer particular morphological and climatic processes that had shaped them. Initially, these ideas were an appealing combination of concepts originating from major strands of surficial geology, including the 'laterite concept', Davisian models of cyclic landscape evolution, and also climatic geomorphology.

The non-buried soil cover of central and south India consists mainly of Vertisols ('Black Soils') and Lixisols (Rhodustalfs or 'Red Soils'). These soils are non-buried paleosols because they formed in an earlier period of much more moist climate than the present (Bronger and Bruhn, 1989). The current distinct seasonal semihumid to semiarid conditions (<1,500 mm annual rainfall and very high evapotranspiration) do not support former soil-forming processes such as deep weathering and strong kaolinite formation; instead, secondary carbonate is accumulating in the saprolite (Cr) and lower parts of the Lixisol Bt horizons (Bronger *et al.*, 1994).

Duricrusts, such as ferricretes, have continued to be an attractive morphostratigraphic marker even though the model of surface formation was oversimplified. The reasons for this are based on a number of assumptions, including: (1) they reflect monogenetic events, for example climatic events, such as tropical conditions (Stephens, 1971), and 'mature' stages in landscape development (Woolnough, 1927); (2) they form on laterally continuous, 'flat' or extremely low-relief land surfaces, 30–35 m a.s.l., with gentle slope 5º to 8º (Woolnough, 1927; Wopfner and Twidale, 1967); (3) their morphology reflects age and stratigraphic equivalence (McFarlane, 1976, Firman, 1994); (4) they form in short time span (Woolnough, 1927, Bourman, 1993a, 1993b) and once formed undergo little modification. This is implicit in correlations between ferricretes and past climate and stages of landscape development, which dictate that ferricretes are relict features that achieved equilibrium with a particular paleoenvironment (Woolnough, 1927; Twidale, 1983); and (5) they are genetically associated with a deep weathering profile, and as a result they are assumed to have synchronous genetic histories (Stephens, 1971).

Field evidence from the Chennai-Red Hill region (Figures 1 and 2) enables the examination of many of the assumptions that provide the basis for the use of ferricretes as morphostratigraphic markers. Although no previous regional studies in the Red Hill area specifically dealt with models for ferricrete evolution, some of the studies from adjacent parts of central and northern Chennai provide a framework for comparison. Most references to ferricretes in the region tend to consider ferricretes in association with bedrock weathering presented by saprolites, either as equivalent materials or as exclusively post-dating apparent regional ferruginization phases. One of the more recent and extreme proponents of the use of ferricretes as morphostratigraphic markers is Firman (1994). He constructed a formal stratigraphic framework for these materials using colors, shapes, and sizes of ferruginous weathering features as a basis for stratigraphic and chronological correlations across vast areas of southeastern and central Australia. Little consideration is given to variations in the morphology of these accumulations due to other factors including parent lithology and local environmental conditions.

This study shows the age of ferricretes to be variable and that simple morphostratigraphic and many chronological assertions are not widely applicable to these materials in the Chennai region.

STUDY AREA

Red Hill (13º 12' 30" N, 80º 7' 45" E), Vaiyapur (12˚ 52' N, 80˚ E), Uttukkadu (12º 49' N, 79˚ 9'45" E), and Pallavaram (12º 58' N, 80º 3'40" E) are located in the north-northwestern region, ~45 km from Chennai (Figure 1). The bedrock in the region mostly consists of ferruginous sandstone and shale of Upper Gondwana age. Cenozoic sequences (up through the Miocene) form a thick cover surrounding the Chennai region, leaving it exposed as an inlier. The present climate is sub-tropical with annual rainfall

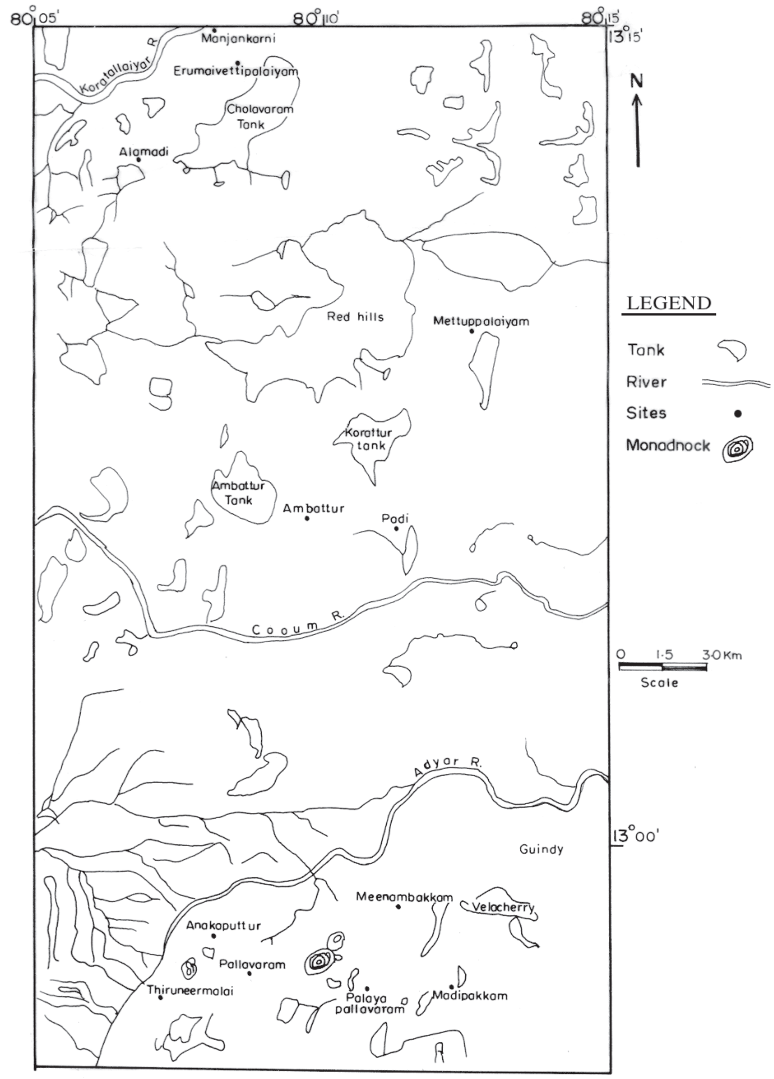

Figure 1. Location map.

averaging 1,200 mm and temperatures ranging from an average summer maximum of 42º–40º C and an average winter minimum of 16º C.

Tectonically, a north-south trending fault traverses through the coastal part of the area. Relative uplift has been occurring since the Proterozoic through to the late Cenozoic mainly along reactivated NNE–SSW, NNW–SSE, and N–S trending structures and lineaments, defining a series of tilted fault blocks. Uplifted parts of these blocks are dominated by charnockite, sandstone, and shale as bedrock exposures with a partial cover of alluvial sediments, mainly along present valleys. Bedrock exposure gradually decreases towards the east with down-tilted edge of the blocks beneath a cover of highly weathered bedrock, fluvial, alluvial, lacustrine and aeolian beach sediments, and duricrusts. Ferricretes are a common feature of the regolith-dominated parts of the landscape. In panchromatic imagery, ferricrete surfaces occur as dark tones. In false color composite (FCC) imagery, they are generally pink or pale brown. Such areas have little or no vegetation (Figure 2).

FERRICRETE STRATIGRAPHIC SETTING

A range of ferricrete facies with varying stratigraphic and bedrock settings occur in the Chennai region. The classification of the ferricrete facies presented here is similar to that of Bourman (1993b). Localities from the Chennai region referred to in the text are shown in Figure 1.

Ferricreted bedrock (saprolite)

The most diagnostic morphological feature of these ferricretes is the preservation of distinctive bedrock fabric and structures. These ferricretes most often take the form

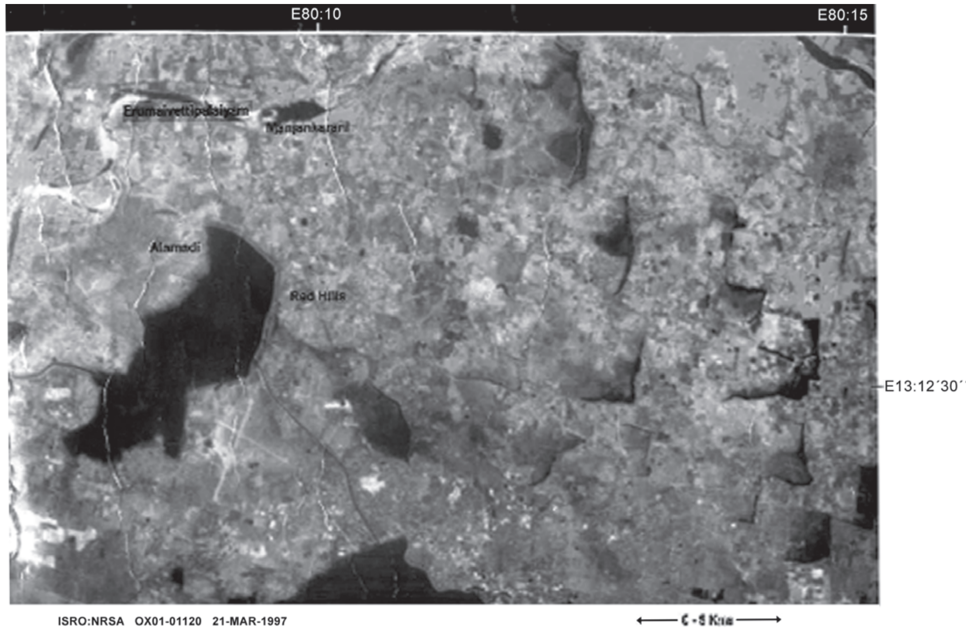

Figure 2. Satellite image of the area around Red Hills.

of a surficial concentration of dark purple, red, or brown mottles derived from the mottled zone of a weathering profile developed in the bedrock (as described by Bourman *et al.*, 1987). The kaolinitic material is eroded out leaving the hardened, iron cemented mottles to accumulate at the land surface during surface down wasting. The original mottles tend to vary in size and shape depending on characteristics of the original host bedrock lithology, such as foliation fabrics and fractures.

In the Red Hills areas (Figure 1), weathered bedrock containing ferricreted mottles are unconformably overlain by ferruginous conglomerate that are lithologically composed of quartzite and sandstone and are probably late–middle Pleistocene in age. Middle Paleolithic tools occur within this imbricate conglomerate. The truncation of many of these mottles and the incorporation of the eroded detritus into the fluvial sediments indicates that these ferricretes formed early (Figure 3). Goethite rims around many mottles and their proximity to younger ferricretes suggest they have continued to evolve since that time.

Charnockite, a quartz–alkali-feldspar–hypersthene–sillimanite–biotite–garnet rock, has weathered to form ferricretes and Red Soil. Spheroidal weathering of the bedrock is a common feature observed at the St. Thomas mound (Pallavaram) (Figure 4). Pisolithic ferricrete occurs as a lag above the Red Soil.

Ferricreted clastic sediments (ferruginous gravel)

This ferricrete facies consist of iron cemented clastic sediments, such as sands and gravels. They typically display the fabrics and the sedimentary structures of the original sediment, which include graded bedding, ripple laminations and cross bedding. At Red Hills, multiple ferricretes are mostly associated with the coarse sandy facies within a thick sequence of sandstone. This ferruginization results from the introduction of iron from groundwater, with sediment porosity and permeability differences influencing ferricrete formation and extent. Ferruginous accumulations are also common both within colluvial sediments and on the lateral margins of fluvial sediments. This area illustrate the great variety in ferricrete facies, host materials, and stratigraphic settings that may exist in one site, as well as the great range in the age of ferricrete formation.

Slabby ferricretes (petroplinthite)

Slabby ferricretes are characterized by ‘platy’ accumulations of secondary iron minerals and clay that typically form on valley sides, particularly at hydromorphic barriers such as unconformities (between weathered bedrock and ancient fluvial sediments). The profiles (2–3 m) at Padi and Ambattur (railway cutting) reveal slabby ferricretes overlain by a thin veneer of pisolitic and nodular iron oxides. The slabby ferricretes consist of horizontally disposed, plate-like masses of ferricrete up to several centimeters thick separated by iron-rich clays.

Detrital ferricretes

Iron cemented accumulations of ferruginous detritus

Figure 3. Red Soil profile exposed at Erumaivettipalaiyam.

provide a strong argument against monocyclic ferricretes in the Chennai region. They occur as a lag deposit, and consist of fragments of ferricreted bedrock, sediments, and slabby ferricrete that have been eroded, redeposited, and, in many cases, recemented. The ferruginous fragments usually have concentrically banded goethite overgrowths, which in some cases show a complex multi-layered genesis. The cores of the ferruginous detritus most often consist of ferricrete clasts, although, in some cases, they are formed by detrital quartz grains. The matrix material surrounding the detrital fragments usually contains hematite, goethite, and rounded quartz grains. All examples of this ferricrete type near Red Hills, *e.g.*, Alamadi and Manjankarani areas, either directly flank or are topographically higher than the ferricreted bedrock or sediments and are therefore younger in age.

MATERIALS AND METHODS

In this study, soil micromorphology has been used as a tool to understand Red Soil and ferricrete formation. Twenty-five thin sections, prepared by the resin impregnation method, were described following Bullock *et al.* (1985). The micromorphologic characteristics of ferricretes are presented in Table 1. Samples collected along the vertical profiles from different sites were analyzed for major oxide with a spectrophotometer following the procedure of Shapiro and Brannock (1962); the results are presented in Table 2. Clay minerals and fine fractions were identified with a X-ray diffractometer with CoK-alpha radiation, at the Indian Institute of Technology, Chennai.

RESULTS

Ferruginous Saprolite

The paleosols that developed from arkoses and lithic arenites have not been well documented until recently. The lowermost part of one of these paleosols is a 6–6.5 m-thick unit, consisting of a pallid zone, grading up into a red and white mottled zone, and capped by a hematite-rich zone. A buff-colored, one meter-thick, indurated, iron-rich quartz and kaolinite sandstone caps the lower unit. A two meter-thick mottled red and white zone, similar to the mottled zone in the lower unit, overlies the iron-rich sandstone. The mottled zone is capped by 5 m of white sandy iron-oxide clay stone composed entirely of quartz, hematite, goethite and kaolinite. Feldspars, biotite, and polycrystalline quartz grains present in the sandstone are mostly absent in all zones of the paleosols. Partially dissolved, etched, angular, and predominantly monocrystalline coarse quartz grains float in a hematite matrix throughout the paleosol (Figure 5). Hematite staining of the matrix and poorly defined iron nodules occur within the mottled and iron crust zones.

Slabby Ferricrete (petroplinthite)

The iron crust outcrops in Red Hills, Manjankarani, Vaiyapur, Uttukkadu, Pallavaram, and Chembarabakkam have similar textural organization and mineral composition, although they are associated to different rocks and located in different geologic settings. They are constituted basically by iron oxides and hydroxides (goethite), and quartz.

Well-rounded iron oxide nodules along with pore and fissure filling features composed mainly of iron hydroxides, aluminum hydroxides, and clays represent secondary development (Figure 6). In the four studied areas, the mineral composition, the textural organization, and the total and spot chemical composition of iron crusts indicate they originated through precipitation of iron oxide and hydroxide from the sedimentary host rocks. When compared with the iron crusts, the sedimentary rocks show only depletion in Fe_2O_3 content and slightly higher SiO_2, Al_2O_3, and alkaline element contents (Table 2). The higher SiO_2 contents are related to the occurrence of quartz, which is not present in the iron crusts.

Fe depletion is due to the eluviation of Fe and Mn giving rise to bleached E horizons. Micro-sampling and quantitative XRD analysis of concentric zones within individual slabs of ferricretes and pisoliths demonstrates variations in mineralogy. Analyses demonstrated a strong tendency for kaolinite and gibbsite to be concentrated in the rim of pisoliths while the cores tend to be richer in quartz.

Figure 4. Red Soil formed from the alteration of charnockites.

A hematite-rich band surrounding the core was observed in many pisoliths.

The sedimentary host rocks in Chembarabakkam, Red Hills, and Vaiyapur–Uttukkadu are comprised of altered material, clay, and sand+clay, respectively. The XRD-mineralogical analyses and the separation of heavy minerals indicate that the sedimentary rocks of the ferruginous sandstone outcrop are constituted predominantly of quartz, hematite and kaolinite. Biotite, ilmenite, tourmaline, zircon, and rutile occur as accessory minerals.

Iron-oxide pisoliths and nodules

The mineralogy of iron pisoliths from Red Hills was investigated to establish the processes responsible for pisolith evolution. Three types of nodules, Fe-rich (typic or annular morphology), Mn-rich (aggregate morphology), and Fe-Mn-rich (compound morphology), were encountered, all of which were formed *in situ*. The nodules were found to contain goethite, a low proportion (4–5%) of poorly crystallized Fe-oxides, and Mn-oxides (birnessite and vernadite), as identified from the XRD spectra. However, they contain no siderite or rhodochrosite. In the formation of compound nodules, Fe and Mn-rich nodules act as nucleating structures for subsequent accumulations in the form of coatings and/or matrix impregnation. Other phases present in pisoliths from Red Hills and Vaiyapur–Uttukkadu include gibbsite (~51 wt. %), kaolinite (~7 wt. %), hematite (~6 wt. %), anatase (~2 wt. %), quartz (~1 wt. %), and zircon (<1 wt. %).

Three different processes were found to be responsible for the development of pisoliths, namely spherulization, agglomeration and cortication. Spherulization is the development of aluminous spherules in kaolinitic plasma in response to the desilicification of kaolinite during ferruginization. Agglomeration is associated with the epigenetic replacement of kaolinite with hematite, resulting in the formation of ferruginous-kaolinite nodules (Federoff, 1979). The process of cortication, which is intrinsically linked to bauxitization, leads to the formation of concentrically banded cortices around spherules and nodules.

Common and nodular compound pisoliths are derived from the ferruginization of large ferruginous-kaolinite nodules. Reworked nodules are cemented in detritus iron matrix (Figure 7). The present-day distribution of compound pisoliths provides a valuable tool for reconstructing the appearance of the weathering profile at specific times in the past. The study revealed evidence for three major periods of ferruginization, each separated by a ferruginization-kaolinization phase associated with nodule development. Nowadays, the climatic and hydrological conditions do not favor the formation of mottled zones and nodular ferruginous-kaolinite layers.

Less common types include the root-like tubular and the ovate-type compound pisoliths. I consider the ovate compound pisoliths, similar in morphology to calcareous tubular compound pisoliths, to be the ferruginous remains of root concretions. Common compound pisoliths, on the other hand, are comparatively smoother and symmetrical in shape. Both common and nodular compound pisoliths are derived from the kaolinization of large ferruginous-kaolinite nodules. Tilley *et al.* (1994, 1995) made similar observations studying the Weipa Bauxites, North Queensland.

Pisolith thin-sections were mapped using techniques similar to geological field mapping. Textural and mineralogical maps were drawn on a photo-micrographic base. Mapping of the micro-sedimentological layering within pisoliths revealed the presence of unconformities, which are ascribed to periods of erosion or non-deposition.

Constituting a minor part in the Red Hills and in other sites, ferricretes are massive tubular structures composed of iron oxides, ranging in length from 2 to 5 cm, which I designate as compound pisoliths. The internal chamber of such structures usually contains ordinary pisoliths or oöliths, however, occasionally they are found to be completely barren. Four different types of compound pisoliths have been identified in the study area. The nodular form externally resembles the underlying ferruginous-kaolinite nodules. The present-day distribution of compound pisoliths provides a valuable tool for reconstructing the appearance of the weathering profile at specific times in the past. The

Table 1. Micromorphology of ferricretes.

Site No.	Ferricrete types	Coarse fraction mineralogy	C/F	Fine fraction mineralogy (XRD method)	G/M+H	Texture and structure	Features
1	Pisoliths	Quartz, feldspar, garnet, and mica	3/7	Kaolinite, Hematite, Limonite, Magnetite, Halloysite	3/7 to 4/6	Independent components with distinct boundaries and cortification, with multiple and complete rims	Transported and subsequently altered by pedogenesis
2	Nodular	Quartz, feldspar, garnet, rutile in traces	3/7 to 4/6	Kaolinite, Hematite. Gibbsite, Magnetite, Halloysite	6/4	Oolite, pisolitic sometimes diffused nodules present	Cracks, fractures, collform structures, less % of pores, voids between the grains
3	Slabby	Quartz, feldspar, mica, garnet	7/3 to 8/2	Hematite, Goethite, Gibbsite, Magnetite, Halloysite	5/5 to 4/6	Platy-thin layers, separated by iron-rich clays	Complex mobilization of clays through voids and pore spaces
4	Vermiform	Quartz, feldspar, mica, garnet	3/7	Hematite, Goethite, Gibbsite, Magnetite, Halloysite	4/6	Platy-thin layers, separated by iron-rich clays	Complex mobilization of clays through voids and pore spaces
5	Ferricreted bedrock	Quartz, feldspar, mica, garnet, hypersthene	7/3 to 4/6	Hematite, Goethite, Gibbsite, Magnetite, Halloysite	3/7 to 2/8	Platy-thin layers separated by iron-rich clays, papules of Fe-oxide impregnation	Complex mobilization of clays through voids and pore spaces

Note: C/F: Coarse fraction/fine fraction; G/M+H: Goethite/magnetite+hematite.

study reveals evidence for three major periods of ferricretization, each separated by a ferruginization-kaolinization phase associated with nodule development and erosion.

Red and yellow clays hosted by sandstone characterize the lithology in Manjankarani, Alamadi, and Red Hills outcrops. The XRD analyses indicate mainly iron clays, gibbsite, kaolinite group clays, and secondarily, quartz, biotite, and ilmenite as constituents of the sedimentary host rocks. They also occur constituted by lithorelict fragments of sandstone. The primary mineral composition indicate low amounts of easy weatherable minerals: around 5% feldspars and 5% phyllosilicates (mostly muscovite). Surprisingly, only little pedogenic clay mineral formation could be identified. Illite in the soils, as well as kaolinite, is predominantly of detrital origin and is ‘inherited’. The scarce non-regular mixed-layered minerals in the fine clay fraction (<0.2 μm) are regarded as a possible initial stage of the silicate weathering. In contrast, the hematite is of pedogenic origin. Therefore the rubefication is an autochthonous and recent process; rubefication of soils alone is not a reliable indicator for strong pedogenic weathering. The minerals identified by heavy minerals separation were tourmaline, zircon, rutile, and goethite.

Iron oxides and hydroxides formed by descending meteoric water and groundwater level oscillation, related to seasonal climatic variations, while quartz grains were partially etched and dissolved in response to intense leaching. Fractures in Red Hills outcrop are related to tectonic reactivation of regional lineaments (Quaternary), and were probably conditioned by water flow allowing the precipitation of iron oxides and hydroxides inside the fractures (Achyuthan, 1996). Grieves-type structures are formed by precipitation of iron oxides and hydroxides oblique to the fractures. Iron nodules, mottled red and white kaolinite zones, kaolinite rich intervals, and partially dissolved quartz grains are consistent with laterite development. Feldspars and other mineral constituents were altered to kaolinite. The iron crusts were formed from remobilization and concentration of iron oxides. The origin of pseudo-folded iron crusts is not directly related to tectonic processes. It was not possible to establish a correlation between the structural data of the studied areas and tectonic folding or regional deformation patterns.

In a climatic sequence from ten to one humid months per year, nine surface derived soils from saprolite of weathered charnockites, sandstone, and shale around Chennai indicate that, above a threshold of 2,000 mm (six humid months) in an Udic Rhodustalf, deep weathering is a recent process leading to the formation of kaolinite. Bronger *et al.* (1994) have shown that weathering of Typic Rhodudult and Typic Hapludox, formed above 900 m a.s.l. and receiving 2,500 mm of rainfall (ten humid months), leads to the formation of gibbsite. These soils are considered to be Vetusols, old non-buried soils that underwent the same or very similar processes of soil formation over at least several 100 ka under similar soil forming factors.

DISCUSSION

Age and stratigraphic significance

The ferricretes in the Chennai region have originated in a wide age range (Figure 8). Although absolute chronological controls are limited in the region, the chronological complexity and a series of ages relative to regional regolith and landscape features can still be appreciated from detailed field studies. Field relationships between different ferricrete types as well as with sedimentary and other regolith materials provide a general basis for the relative stratigraphy. Fluvial sediments are younger than these sediments and also have close field relationships with ferricretes.

Laterite soils are formed in moist, well-drained, tropical conditions (usually in areas with a significant dry season) on a variety of different types of rocks with high iron content. Initial stages of weathering leads to the formation of kaolinite and iron oxyhydroxides. Micro- and macro-level movements of iron and iron oxides through mineral pores in soil also begin to occur at this stage (Nahon, 1986). Next, mottled clay layers form, become more crystallized in the top horizons, and eventually form large iron-rich nodes. Yellow or white iron-depleted zones surround these nodes. The formation of the iron nodes occurs in a soil matrix made up of mostly weathered kaolinite and quartz and is called the ‘mottled clay layer’. The soil at this point contains large tubules and alveoles, formed during the creation of the bleached zones (Nahon, 1986). As weathering continues, these voids begin to fill with kaolinite and quartz grains. Further weathering leads to the ferruginization of these fill particles –kaolinite and quartz are replaced by Fe– and purple to red indurated facies are produced (Nahon, 1986). Often, ferruginous pebbly layers are formed in close association with the ferricrete horizon. Their formation is related to breakdown and down slope movement of pisolitic iron crusts. The end result is a ‘reddish matrix’ soil, constituted by kaolinite, goethite and

Table 2. Organic matter (OM) and major oxide content of ferricretes from different sites.

Site	Sample	Depth (cm)	OM (%)	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	Na_2O (%)	CaO (%)	MgO (%)	K_2O (%)	P_2O_5 (%)
Red Hills	$R_{II\,1}$	50	1.0	49.4	0.6	22.3	11.3	1.1	0.5	1.9	6.2	6.7
	$R_{II\,2}$	100	0.7	41.5	1.7	29.8	13.3	0.8	0.45	1.5	6.6	4.3
	$R_{II\,3}$	150	0.6	44.3	1.2	30.2	5.2	4.6	0.3	1.8	7.2	5.1
	$R_{II\,4}$	200	1.5	57.1	2.7	19.6	12.9	0.8	0.45	1.7	5.2	3.1
	R1	10	-	35.7	1.1	11.7	37.7	1.0	0.1	0.7	1.2	1.8
	R2	20	-	29.1	1.5	12.4	47.4	0.6	1.1	0.7	1.5	1.0
	R3	30	-	36.6	2.0	11.1	44.5	0.3	0.5	0.7	1.5	1.9
	R4	40	-	30.3	1.6	12.6	47.2	0.1	0.7	0.6	1.3	0.9
	R5	50	-	34.4	1.4	10.2	45.4	0.2	0.6	0.7	1.1	0.6
	R6	60	-	34.4	1.7	10.5	29.1	0.5	0.4	0.4	1.1	1.9
	R7	70	-	32.7	0.4	10.7	43.7	1.1	0.3	0.5	1.6	0.8
	R8	80	-	37.1	0.5	16.4	30.4	1.5	0.7	0.6	1.2	0.2
	R9	90	-	35.6	0.6	10.6	40.7	1.5	0.3	0.6	1.1	1.9
Vaiyapur	Va_1	10	1.1	47.6	2.4	25.5	12.3	0.4	0.4	2.2	4.1	5.1
	Va_2	20	1.1	50.1	2.3	30.1	5.4	0.6	0.4	0.7	5.4	4.9
	Va_3	30	0.8	45.2	2.0	33.2	12.2	0.4	1.1	1.6	3.6	3.8
	Va_4	40	0.7	42.7	3.7	28.02	15.4	0.4	0.3	1.1	3.8	4.4
	Va_5	50	0.8	41.7	3.1	30.1	13.3	0.6	0.2	1.5	4.8	4.5
	Va_6	60	0.5	39.9	3.0	25.3	17.0	0.6	0.4	1.2	7.6	4.8
Uttukkadu	U1	10	-	63.7	1.5	6.1	20.3	0.5	0.5	1.2	2.8	3.6
	U2	15	-	65.7	0.7	2.6	15.5	0.8	0.8	2.9	2.2	3.7
	U3	25	-	66.9	0.9	10.9	10.7	0.9	0.9	1.5	0.8	4.5
	U4	35	-	59.5	1.1	7.3	19.5	1.4	1.4	3.0	1.8	4.1
	U5	45	-	55.6	1.5	4.8	15.7	1.8	1.8	3.5	1.8	3.8
	U6	55	-	47.5	1.5	9.1	14.3	2.1	2.1	3.9	1.0	5.7
	U7	65	-	46.1	0.7	2.2	22.1	1.8	1.8	3.6	4.6	5.1
	U8	75	-	46.1	0.2	10.3	22.1	1.8	1.8	2.8	0.8	4.8
	U9	85	-	46.5	1.3	11.1	15.8	1.1	1.2	2.0	0.9	4.9

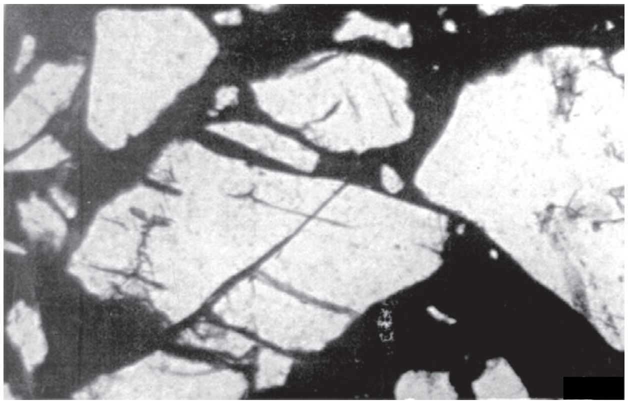

Figure 5. Photomicrograph showing coarse quartz with fractures and corroded margins. The fractures and cracks are filled with iron oxide. PPL, 60 X.

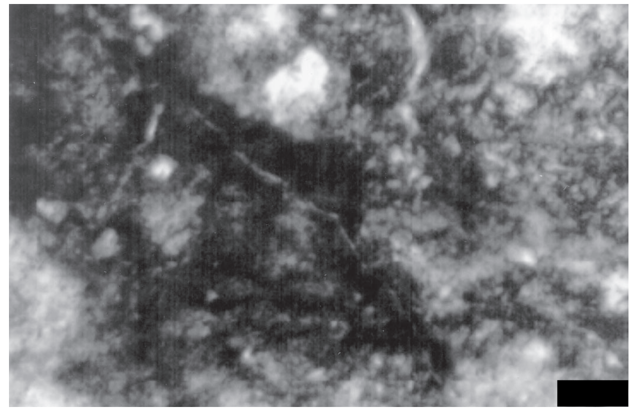

Figure 6. Photomicrograph showing iron oxide lining cracks and channels. Note the iron impregnation in the matrix. PPL, 60 X.

'fragments of the pisolitic iron crust' (Nahon, 1986).

The time span needed to create a fully developed ferricrete soil is still unknown, but estimates range from one to six million years. Factors influencing the required time are, among others, the parent material and the climatic changes during the time of formation. The deposited sandstone was subjected to intense weathering and alteration resulting from humid tropical climates. The climate has become more humid, leading to the dismantling of the ferricrete. The remnants of this former pedological system are the ferruginous nodules.

This continuous range of ferricrete ages supports a stratigraphic model of continual evolution and modification. The ferricretes have evolved throughout the evolution of the landscape since at least the Mesozoic. During this time, paleoclimatic and paleogeographical changes have led to ferricrete development and modification, which continues in the present semi-arid, moderate relief landscape. Many of the ferricretes account for landscape relief (slabby ferricretes or petroplinthites forming on valley sides, post-landscape incision); however, in some of the higher relief parts of the region their preservation potential has been low. Although ferricretes are frequently associated with highly weathered materials, they are not exclusive to deep weathering profiles and can form in a variety of materials and landscape settings. Ferricretes are best seen as a reflection of local environmental conditions that have continually changed and operated throughout the evolution of the landscape in the Chennai region. Their use as morphostratigraphic markers is therefore of limited regional value. Around Chennai, a single duricrusted peneplain is envisaged to have originated close to sea level and with a present expression as duricrusted remnants across the entire the coastal landscape (Woolnough, 1927). This surface is mainly assigned a late Neogene – early Quaternary age and is used along with associated duricrusts as a morphostratigraphic marker for Cenozoic geological and landscape studies. Under the actual drier conditions in Typic and especially Aridic Rhodustalfs, earlier soil-forming processes such as deep weathering and strong kaolinite formation have almost ceased; instead secondary carbonate is accumulating in the saprolite (Cr) and lower part of the Rhodustalf (Lixisol) Bt horizons. Most Alfisols (not only Ultisols) or Lixisols in now seasonal semiarid India are relict soils or non-buried paleosols formed in an earlier period of much more moist climate than the present.

Chronological model

A chronological model (an extension of Bourman, 1993b) of continual ferricrete evolution can be applied to the study region. Variations in local environmental conditions over the time of landscape development have a major impact on determining either ferricrete development or destruction. The presence or absence of ferricrete in many parts of the landscape may be seen as a balance between

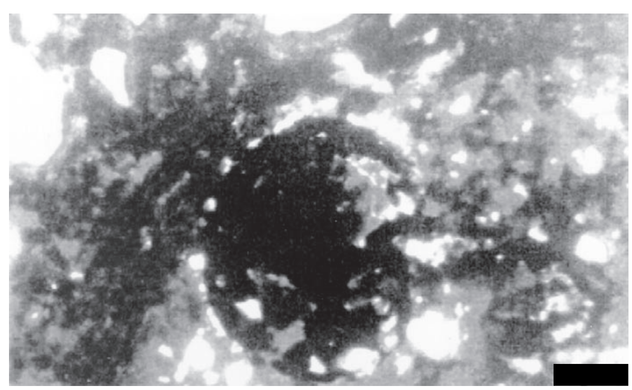

Figure 7. Pisolith exhibiting iron oxide nodule from an older/earlier horizon incorporated within the younger pisolith. Colloform bands are cementing the iron nodule. This structure is formed by complex processes of pedogenesis and groundwater action. PPL, 60 X.

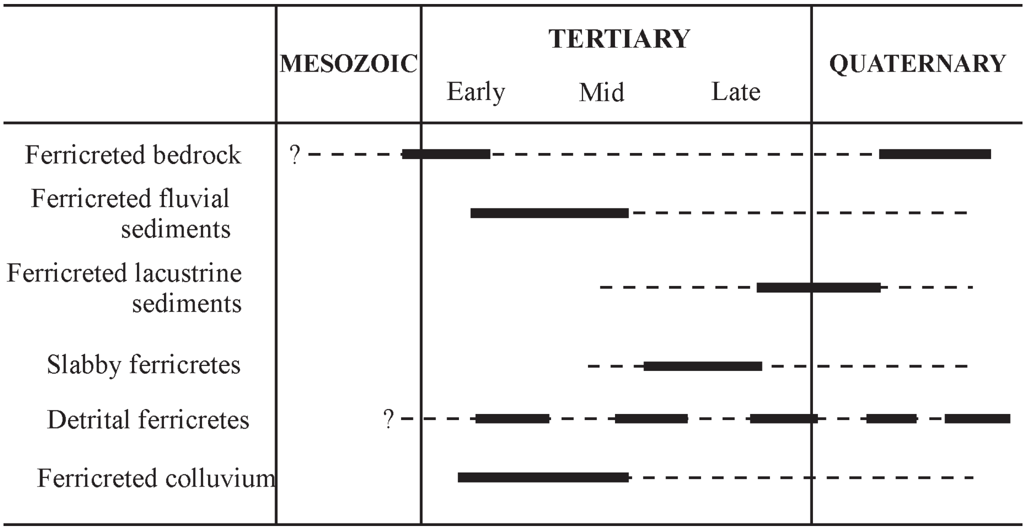

Figure 8. The general relative ages of ferricretes and associated ferruginous accumulations in the Chennai region. Solid lines represent well-constrained ages and dashed lines indicatie ages of greater uncertainty.

ferricrete forming processes (iron mobilization and precipitation, sedimentation, and weathering) and ferricrete destroying processes (erosion, chemical breakdown). Although these processes may be operating continually within an entire region, the rates of these processes will vary over time and landscape position. Ferricrete development may therefore be attributable not only to factors that would enhance ferricrete development but also to a reduction in processes leading to the destruction of ferricretes. Ferricrete formation in the Chennai region has been favored by minimal denudation, tectonic stability, an abundant source of iron (the weathering of mafic bedrock lithologies in preference to more felsic rocks), a climate favoring high rates of chemical reactions (warm and wet climates are the most ideal, but not essential), through flow of aqueous solutions, among many other factors that would contribute to a greater rate of ferricrete development than of destruction/erosion. Landscape setting is a major control on these factors explaining variations in the age and type of ferricrete across the landscape in a region. This model accounts for apparent 'peaks' in the age of ferricrete formation as well as for the occurrence of ferricretes in a range of climatic and landscape settings (tectonically stable, semi-arid, or cool climate regions). Local influences and certain weathering facies should not be misinterpreted as widespread events or processes.

CONCLUSIONS

Ferricretes in the Chennai region largely relate to local environmental conditions. Hematite is of pedogenic origin. Red Soils and ferricretes are widespread both in their lateral and vertical extent; they have complex structures, which take a significant amount of time to develop. Recession of the Miocene sea followed by high precipitation rates associated with subtropical/tropical climates resulted in intense weathering and alteration of the charnockites and sandstone. Iron nodules, mottled red and white zones, kaolinite-rich intervals and partially dissolved quartz grains are consistent with ferricrete and Red Soil development. Feldspars and other labile constituents were altered to kaolinite, while quartz grains were partially etched and dissolved as intense leaching occurred. The degree of feldspar alteration into kaolinite and of feldspar and quartz dissolution indicates that a humid and wet climate must have occurred since the late Neogene – early Quaternary period. Their age is best considered within the context of a model of continual formation and destruction operating over the course of landscape development.

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