Understanding the development of calcic and petrocalcic horizons is important for palaeoclimate reconstruction. The micromorphology and geochemistry of Quaternary calcic and petrocalcic horizons formed in the area around Coimbatore, Tamil Nadu are discussed. The calcic horizons represent the Bk horizons that occur as thick complex profiles (~300 cm thick) in the foothill regions while the laminar petrocalcic horizons representing the K horizon (80–100 cm thick) formed on hard rock in the topographic low-lying area. Calcic horizons are represented by powdery, nodular calcrete nodules and root casts with 95.2–64.5% of CaCO₃. Laminar petrocalcic horizons are compact with well rounded coalesced nodules and contain 56–64% CaCO₃. Micromorphological study of the calcic horizons show the occurrence of alveolar septal structures, calcified filaments, coated grains, spherulites, calcified root cells and calcispheres that indicate biogenic origins, mainly induced by plant root related microbial activity. The calcic nodules within the calcic horizons consist of quartz sand grains cemented by finely crystalline, grain-coating, often glaebular and pore-filling micrite. This development has taken place in phases of soil formation, erosion and reworking. The inter-relationships between these processes have caused variations in the phases of accretion of soil profiles developed in the foothill region.

Microfabrics of laminar petrocalcic horizons with detritus hosts show replacement, corrosion, displacement and shrinkage indicating that the laminar petrocalcic horizon formed under relatively semi-arid conditions. These characteristics indicate that the laminar petrocalcic horizons formed in a moderately near-surface environment with relatively high rates of evaporation and ground water action and are polygenetic in origin.

1. Introduction

Soils with calcic and petrocalcic horizons are widely distributed in arid and semi-arid lands of the world, and are good palaeoclimatic and palaeoecological indicators (Netterberg, 1971; Soil Survey Staff, 1975; Dhir 1995; Achyuthan and Rajaguru, 1997; Khadikkar et al., 2000). Calcic and petrocalcic horizon development is a characteristic feature in Quaternary hill slope deposits indicating very limited sedimentation rates or stable geomorphic surfaces (Goudie, 1973). The formation of calcic horizons on the hill slope surfaces also seems to be a genetic process, in which plant roots and associated microorganisms play an important role (Montenat, 1981; Vogt, 1984; Verrecchia, 1987; Wright, 1991; Sancho and Meledez, 1992; Alonsa-Zarza et al., 1998).

Understanding the formation of calcic and petrocalcic horizons in the Coimbatore area, in the southern peninsular region of India, is important as no detailed work has been carried out to understand their formation. The formation of Quaternary calcic horizons and laminar petrocalcic horizons formed over the preCambrian rocks raises several questions as to their formation, source of calcium carbonate, and palaeoclimate significance. Moreover, the study area is particularly interesting because of several morphological varieties of calcic and petrocalcic that have developed in different lithological and geomorphologic settings. Therefore, the purpose of this paper is to present the first study of calcic and petrocalcic horizon in this area, and to add new insights in the formation of calcic and petrocalcic horizons.
2. Study area

Calcic and petrocalcic horizons occur around the Coimbatore area, located in the southern peninsular region of India (Fig. 1). This region receives both the southwest and northeast monsoon rains because the Western Ghats form a major divide. The Western Ghats or Sahyadri mountains (as they are known in Maharashtra) run along the western edge of India’s Deccan Plateau, and separate the plateau from a narrow coastal plain along the Arabian Sea.

Coimbatore is a plateau region, which commands the eastern approach to the Palghat Gap and the major pass through the Western Ghats mountains (Fig. 1). In the west, the Palghat Gap is a wide depression in the Western Ghats, connecting the plains of Kerala and Tamil Nadu through a low pass. The plateau is bounded by the Nilgiri hills to the north and the Palani and Anaimalai hills to the south. The altitude decreases progressively to the east from a maximum of 409 m above sea level. The geology of the study area consists of PreCambrian crystalline rocks,
mainly represented by charnockite, gneisses rich in minerals such as hornblende, chlorite and biotite, and dolomite limestone. The gneisses and ultra basic rocks have invariably generated a wide pediment surface.

The main drainage basin is carved by the Noyil River. Denudation processes dominate over fluvial action in the study area. As a result, the area is marked by plateau land forms, structurally deformed and denuded residual hills of charnockites and gneisses with linear ridges of basic dykes. The various geomorphic units are residual hills, linear ridges, buried pediments, active pediments, shallow pediments, erosional plains, valley fills and uplands (Achyuthan and Shankar, 2005).

This region receives showers of the Indian summer southwest monsoon (June–August) and also the northeastern rains during October–December. The average annual rainfall received is 400–500 mm. The mean annual summer temperatures vary between 39 and 23°C while the winter temperatures fluctuate between 33 to 20°C. Coimbatore has mild winters and moderate summers. The general vegetation cover around Coimbatore belongs to the families of Artemisia, Acacia, and Chenopodiacea.

Calcic and petrocalcic horizons, classified following FAO (1998), cover nearly one-third of the study area and their occurrence has some bearing upon the proximity and the relief of the area. Calcic and petrocalcic deposit are locally known as “Chunambu kal” and “Odai kal” and are often used as a raw material for painting houses and laying temporary rough roads.

3. Materials and methods

Soil profiles associated with calcic and petrocalcic horizons were studied for their color, texture, structure and distribution pattern of calcic nodules within the profiles (Fig. 2). The classification schemes developed by World Reference Base for Soil Resources (Goudie, 1973; Gile et al., 1966, 1981; FAO, 1998) were the most useful because they covered all the basic forms of calcic and petrocalcic horizons in the study area.

Undisturbed soils and calcic and petrocalcic samples were collected for micromorphological studies. Twenty-eight thin sections were made on air-dried samples following the methods of Guillore (1985). Soil micromorphological features were described according to Bullock et al. (1985) and Federoff and Courty (1994).

Samples of calcic and petrocalcic horizons from different sites were collected for geochemical analyses to determine the major oxide content following the methods given by Shapiro and Brannock (1962). The mineralogy of carbonate nodules, coarse and fine fractions were identified by X-ray diffraction method using Cu Kα radiation at The Indian Institute of Technology, Chennai. Calcic carbonate nodules and petrocalcic carbonate samples were also studied using a scanning electron microscope (SEM): Model Leica Stereoscan No 430 I equipped with Oxford Link Pentafet, Leica Cambridge Ltd. for semi quantitative element analyses and surface morphological features of the calcrete nodules at the University of Trieste, Trieste, Italy.

4. Results

4.1. Field characteristics

Calcic horizons in the hill slopes around Marudanpatti, Nanjundapuram, Ramanathapuram and Vellakinur (Fig. 3a) commonly occur as nodules of irregular morphology with different size and shape in the distal end of a hill slope while the laminar petrocalcic horizons occur in the plains such as around Maillampatti (Fig. 1) and other low-lying areas. Calcic horizons are well exposed in the hill slope deposits along the gulley of the hills at Marudanpatti (Section A), Nanjundapuram (Section B) and Ramanathapuram (Section C), Vellakinur (Section D) (Fig. 2). Petrocalcic horizons are well exposed around Maillampatti (Section E) (Fig. 2).
Calcic horizons developed in colluvial units are ~250–300 cm thick. They exhibit a homogeneous yellowish brown (10 yr 5/3–5/4) color but generally are lighter in color down the profile due to the increased proportion of calcium carbonate nodules. The profiles can be divided into four kinds of horizons, based on the sediment texture and calcium carbonate nodule distribution in each profile. The horizons are:

- **Av horizon**, 0–50 cm thick, yellowish brown (10 yr 5/3–5/4) moderately sorted horizon with vesicles, rich in angular quartz and feldspar grains, contains mostly silt and clay and humus. It lacks coarse materials, even though small fragments of the pavement cover the Av horizon. Examination of the minerals contained in the Av horizon at Marudanpatti demonstrated that the materials in this horizon did not originate from the weathering of the rocky parent materials. Instead, dust deposited within the vesicles is the source of the silts and clays of the Av horizon.

- **Bw horizon**, 50–120 cm thick, with sand, silty sand and vertically oriented root casts of calcium carbonate. There is abundant occurrence of calcareous root casts that occur at a depth of 60–120 cm and below. The area around the root cast is generally brownish yellow (10 yr 5/8). The sediments are moderately sorted and fine grained.

- **Bk horizon**, 120–160 cm thick, contains a large number of carbonate nodules varying in size from 2 to 3 cm in diameter and shape from well rounded to spheroidal in nature. This horizon also contains powdery masses of carbonate with relatively low amounts of quartz and feldspar grains, with a higher proportion of mica flakes. Calcium carbonate generally masks the original sediment color. The proportion and hardness of the carbonate nodules increase with depth. This layer is also rich in manganese oxides in the form of small concretions and dendrites and around tubular pores. The sediments are fine grained and moderately sorted with lesser amounts of quartz and feldspar grains and a larger proportion of biotite and other mafic minerals.

- **160–215 cm horizon** consists of calcium carbonate nodules 3–5 cm in diameter distributed in poorly sorted, subangular–angular fine silt.

- **215–260 cm horizon** consists of small well rounded carbonate nodules (1–2 cm across) in the lowest horizon of this unit (240–260 cm). The soil has slightly higher clay and silt content of (6–7% clay and 8–9% silt).

- **Bt horizon**, 260–305 cm thick, is devoid of any carbonate nodules, and the soil is yellowish brown, with subangular–angular structure.

4.2. Profile description of laminar petrocalcic horizon

The laminar petrocalcic horizon (~80 cm thick) is exposed in the plains and low-lying areas over the Precambrian charnockites, dolomite limestone, gneiss and schistose rock at Maillampatti (Figs. 1 and 3b). The calcic horizons are formed in the upland region of the Coimbatore area. The individual exposures of the petrocalcic horizon (K Horizon) average 80 cm in thickness and can be divided into three horizons. Horizon I (Bkm1, 10–30 cm, rich in quartz and feldspar), Horizon II (Bkm2, 30–60 cm with a higher carbonate content) and Horizon III...
(Bkm3, 60–80 cm) with the highest carbonate content. The hardpan generally consists of cemented honeycomb calcrete, cemented calcareous powder and coalesced nodules giving rise to laminar petrocalcic horizons resting with a sharp contact with the hard rock (R Horizon).

4.3. Chemistry of calcic and laminar petrocalcic horizons

Chemical composition of the carbonate nodules within the calcic horizons shows that the concentration of calcium carbonate is very high compared to SiO₂. The concentration of calcium carbonate ranges from 75–85% whereas the silica makes up only 2–15%. There are also minor amounts of Fe₂O₃ and Al₂O₃.

In the calcic horizon, the ratio of SiO₂/CaCO₃ is not equal to the carbonate nodules as a result of calcite accumulation and void filling. Reeves (1976) made similar observations. Minor constituents include Al₂O₃ and Fe₂O₃ (Table 1). Low iron content in calcite is consistent with removal of available Fe²⁺ by hydrogen sulphide. The slight ferroan composition of calcite matrix in individual calcic nodules within the laminar petrocalcic horizon could have resulted from earlier and shallower precipitation during microbial reduction of Fe³⁺. CaCO₃ values vary between 80% and 90%. The relatively high oxide concentrations are indicative of the upper limit of fluctuation of a former water table level.

4.4. Coarse and fine grain mineralogy of calcic and laminar petrocalcic horizons

Coarse and the fine fraction mineralogy vary with depth in the sections studied. The coarse fraction from Marudanpatti, Nanjundapuram and Ramanathapuram (depth 10–30 cm), (40–60 cm), and (80–85 cm), respectively and Vellakinur (7–90 cm) is represented by quartz, chlorite, hornblende, garnet, hematite and calcite. The grains are angular to sub angular grains of quartz and feldspar. The fine fractions are montmorillonite, smectite, illite, vermiculite and traces of kaolinite. At Marudanpatti, (110–140, 160–170 cm), Vellakinur (230–250 and 300–320 cm), Nanjundapuram (60–80 cm) and Ramanathapuram

Table 1
Major oxide concentration of calcic nodules and laminar petrocalcic nodules

<table>
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<th>Sample No.</th>
<th>Depth (cm)</th>
<th>SiO₂ (%)</th>
<th>Al₂O₃ (%)</th>
<th>Fe₂O₃ (%)</th>
<th>CaCO₃ (%)</th>
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(90–110 cm), the coarse fractions are represented by quartz, biotite, calcite, chlorite, garnet, hematite, goethite and plagioclase. The fine fractions are montmorillonite, smectite, illite, vermiculite and traces of kaolinite with the grain shape varying from sub rounded to rounded quartz and angular to sub angular grains offeldspars. The base of the sections at Marudanpatti (180–195 cm and below), Vellakinur (270–280 cm) Ramanathapuram (115–120 cm) the coarse fraction includes quartz, biotite, hematite, magnetite, chlorite, calcite accompanied by fine fractions ofmontmorillonite, smectite, illite, vermiculite and traces of kaolinite. The quartz grains are subangular with sub-rounded calcite, flakes of biotite, prismatic and elongated grains of chlorite.

The coarse fractions are quartz, biotite, garnet, titanite, calcite, dolomite with graphite crystals, hematite and magnetite in the petrocalcic horizon at Maillampatti (1–10, 40–50, 80–85 cm). The clay fractions are smectite, illite, montmorillonite and vermiculite. Quartz and feldspar grains are angular to subangular. In these petrocalcic horizons, micrite spherulites occur within the calcic lamina.

Mineralogical analyses of the non-clay fine fraction (>2 μm fraction) of the calcic and petrocalcic horizons show low-magnesium calcite and small amount of quartz which are the two dominant minerals present within the pedogenic carbonate, with trace amounts of non-ferroan dolomite limestone with graphite crystals, feldspar, chlorite, limonite, titanite, hornblende, garnet, hematite and altered biotite. X-ray diffraction analyses of the powdered samples of the pedogenic carbonate and clay (fine fraction) indicate dominance of calcite and dolomite limestone over quartz, phyllosilicates and feldspar, montmorillonite, smectite, illite, vermiculite and traces of kaolinite. The quartz grains are subangular with sub-rounded calcite, flakes of biotite, prismatic and elongated grains of chlorite.

4.5. Micromorphology of calcic and laminar petrocalcic horizons

4.5.1. Groundmass

The groundmass/matrix of all the calcic nodules occurring in calcic and laminar petrocalcic horizons consist of calcite, which is the cementing medium. The size of the calcite crystals ranged from less than 2–15 μm. Three types of calcite cement occur in the matrix. They are broadly divided into:

- Micrite (2–4 μm) occurs as a cementing material between the skeletal grains and as clear rims around the grains within the groundmass (Fig. 4a). The rims are on an average 2–3 μm in size, which at places may or may not join the particles lying in the close proximity. Micrite also occurs as rims around micritic nodules. Micrite also occurs as needles (Fig. 4b). Easily weatherable minerals such as plagioclase, hornblende and biotite grains are replaced by micrite/microspar calcite (Fig. 4c–d).
- Subhedral crystals of microsparite and sparite (4–10 μm) occur. Microsparite and sparite also occur as drusy mosaic fillings between the micritic rimmed grains and rock fragments. They are also observed as: (a) hyypo-coatings around the voids and cavities (Fig. 5a); (b) the microsparite crystal size increases away from the walls of the grain/channels or cavities (Fig. 5b); (c) microsparite and sparite are generally elongated. The direction of elongation is perpendicular to the wall of the cavity/channel or grain boundary (Fig. 5c). The boundary between the micrite, microsparite, and sparite contact is serrate. Sparite (10 μm and above) generally occurs as infilling crystals within channels and voids (Fig. 5d).

4.5.2. Groundwater features

Groundwater features include recrystallized mottles consisting of ferruginous impregnations, cracks related to desiccation and fractures, clay mineral replacement such as illite, smectite, concretionary laminations and etched non-carbonate grains. The groundmass is microcrystalline to crystalline and strongly cemented with clear calcite. Coarse quartz grains are coated by clear microspar (Fig. 6a). Channels and voids within the nodules are filled with microsparite and sparite.

4.6. Biogenic features

Biotic features observed in the field and within thin sections are roots and rootlet filaments coated with powdery calcite (micrite) and are generally represented by root pores that are regular in shape, voids, channels and fractures. Voids are in filled with micrite or clear microsparite. Staining with Alizarin Red shows that the calcite within the voids is ferroan calcite. Larger voids are cavities filled at places with sparite. These are generally observed in the calcic carbonate nodules. In thin sections, the channels either have loose collapsing walls, or are lined with calcitic clay coatings. The channels are loosely filled by grains or partially to completely filled by microsparite/sparite. The shapes of the channels vary from tubular with rounded or tapering ends, to being bent at various angles, and cylindrical. Biological remains including root filaments and remains of animal excrement loosely fill the channels and voids. Fractures and shrinkage cracks are present in the calcic and petrocalcic nodules at Marudanpatti, Nanjundapuram and Ramanathapuram. In most cases, the fractures are filled by micrite or microsparite, or remain unfilled. Thin sections of the root casts reveal no occurrence of root cell pseudomorphs, which implies that calcitization of roots has occurred only outside of root cells. Callot et al. (1985) suggested that fungi and bacteria feed on the decaying root organic matter.

4.7. Calcitic features

Calcitic features are represented in the form of calcite coatings, hyypo coatings, and calcite nodules. Calcite nodules are mainly of three types.
4.7.1. Type I—calcic nodules

Type I calcic nodules are small (0.5 mm–2 cm across), well rounded to oval, and occur in strongly developed soils of the older members of the soil chronoassociation. The soils occur in the middle to upland interfluves of Marudanpatti over very gentle slopes and a deep groundwater table. Under the polarized microscope the fabric of the calcic nodules is defined by thick continuous to discontinuous micrite and diffused calcite needles mixed with soil matrix. It also occurs as coatings (4–5 μm) around coarse detrital grains of quartz and feldspar (Fig. 6a). Micromorphology observations reveal that intense weathering of feldspar and biotite has occurred in these calcic nodules during lime accumulation, and the margins of the grains are corroded and diffused.

4.7.2. Type II—calcic nodules with pedogenic features

Type II calcic nodules exhibit features such as alveolar septal structures, calcified filaments, micrite coated grains, micritic spherulites, micrite nodules indicating pedogenic processes (Fig. 6b). Irregular sesquioxidic impregnation in the calcitic cement also indicates pedogenesis (Fig. 6c).

4.7.3. Type III—calcic nodules with biogenic features

These calcic nodules are calcified root cells and calcispheres that are of biogenic origin, mainly induced by plant root related microbial activity. They consist of grains of quartzose sand cemented by fine crystalline, often glabular, grain-coating and pore-filling micrite (Fig. 6d). In thin section study, calcic nodules have been further subdivided based on the compactness into the following types:

- diffuse nodules that are microporous have a gradual boundary with the soil matrix. In the field these nodules are whitish, soft, and small as observed in Bk horizon. They are always associated with hypo coatings;
- compact nodules, that are gray or grayish and dense with a clear boundary with the adjacent soil matrix (Fig. 6b). Partially dissolved calcitic nodules have been

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Fig. 4. (a) Stereo photomicrographic showing micrite occurring as cementing material between the fine grains and as a clear rim around coarse grain X-50, (b) SEM image of micrite needles, (c) Photomicrograph showing plagioclase grain getting altered and getting replaced by micrite BXN. Magnification × 50, (d) Photomicrograph showing hornblende grain getting altered and getting replaced by micrite. BXN. Magnification × 50.
observed in the Marudanpatti, Nanjundapuram and Ramanathapuram litho profiles. The nodules show effects of biological activity in the form of fractures, root channels or pores. The soil matrix adjacent to the nodules appears clearly depleted of calcium carbonate in sandy silt horizons;

- highly compact nodules are grayish white in color and their groundmass is microcrystalline, but larger crystals are also present as infillings of channels and voids. Irregular sesquioxidic impregnation is present (Fig. 6c). Calcitic particles also occur as coatings around the fine silt grains. In the field these nodules are grayish, large and hard, irregular in shape and have been observed in deeper horizons of buried sediments that show signs of water logging. These can be best seen in Marudanpatti and Nanjundapuram area. Calcitic features are present in the form of compound nodules within the sandy matrix. Microsparitic calcites cement subangular to angular grains.

Features of dissolution and reprecipitation of microsparite are observed between the grains and the matrix. A gradual increase in size of calcite from micrite to sparite within the nodules is observed. As the calcium carbonate concentration increases with depth, the microstructure evolves to pellicular grain and to an intergrain micro-aggregate microstructure. The porosity is high and consists of loosely packed voids and a few channels that are sometimes lined by fine micritic calcite or fine clay fillings as passage features. Micromorphological studies of the nodules exhibit a distinct variation in the process of calcification, calcite mineral size, and also in fine calcitic particle content.

Fig. 5. (a) SEM image of microsparite occurring as hypocoatings around, (b) SEM photograph of calcite crystal size increases away fro, (c) Stereophotomicrograph of calcic rhizolith showing thick micrite coating around quartz material. Magnification × 50, (d) Photomicrograph showing channels filled by clear micrite and microspar. magnification × 50.
4.8. Micromorphology of laminar petrocalcic horizons

A relatively dense mosaic of microspar (Fig. 6d) along with some floating and etched detrital grains and some clay aggregates occur in the voids that form the horizon. Micromorphological analyses of the laminar petrocalcic horizon exhibit polycyclic and polyphase development of calcitic nodules. Calcite also cements detrital grains of quartz, feldspar, and rock fragments of amphibolite gneiss and charnockites. Micromorphology shows a variety of features such as meniscus cement, clay coatings (2–4 μm) around quartz and feldspar grains that occur within individual calcic nodules, alteration of mica, and iron oxide impregnation. These features can be interpreted as the result of groundwater action and exogenesis. Therefore, these petrocalcic are not singularly “alpha-type or beta type” carbonates but are a combination of the two (Wright, 1990).

Individual nodules consist of carbonate rims (0.3–0.5 μm thick) (1–2 in number) around the detrital grains and nodules of calcium carbonate (Fig. 7a). The alternate light and dark brown rims (10–15 μm thick) of microcrystalline calcite (Fig. 7b) were clearly visible on staining microcrystalline calcite with Alizarin red ‘S’. The dark laminate can be correlated to the Fe/Mg oxides and micrite and the lighter laminate to the pale pink microsparite. Darker laminations occur because of the breakdown of primary iron-bearing minerals from the PreCambrian gneiss and charnockite rocks. There is a direct correlation between the thickness of the lamina and the host grain size: coarser grain size results in thicker lamina (Fig. 7c). Alonso-Zarza (1999) also corroborates the same view. Wavy layers of dark colored micrite occur as rims all along the microsparitic and the sparitic nodules/iron oxide nodules (Fig. 7b). At places these types of nodules are dissolved at their edges. This is evidence of groundwater action, which is supported by features like loosely packed, single grain type of microstructures. Between the interface cement (micrite/microsparite) and the pore space meniscus, cement has formed at grain contacts.

The individual nodules within the laminar petrocalcic horizons (0.1–0.5 μm across) are spherical or ellipsoidal with one concentric rim (10–15 μm thick) of gray micrite (Fig. 7b). At the point contact, the cement consists of fine...
clear microspar or micrite. This is due to the process of freshwater films around the grains that dissolve the carbonate which allows original point contacts between the grains to become flatter (Knox, 1977). This cement is evidence of fluctuating ground water activity (Achyuthan, 2003).
Thin section examination of petrocalcic horizons shows quartz grains floating in calcite cement resulting in a floating texture. Exfoliation of biotite grains (Fig. 7d) often with iron oxide rim is observed within the individual nodules. Some of the intergranular fractures within the laminations are cemented with either micrite or sparite. These crystals are from 0.1 to 1 μm across and their morphology varies from anhedral to euhedral.

Petrocalcic horizons display calcified rootlets and filaments, which is indicative of some rooted vegetation during the formation. In a few voids acicular crystals of calcite were observed forming a mat on the nodule surface (Fig. 7e). SEM images (Fig. 7f) of calcified organic structure probably represent the cell walls of vascular tissues of roots. The pores are spherical and 1–5 μm in diameter and are lined by micrite crystals.

5. Discussion

No dates have been obtained on the calcic and petrocalcic horizons. However, the occurrence of Mesolithic–Upper Palaeolithic artifacts on the surface of these soil profiles can be used to estimate that the minimum age of the landscape dates back at least to the end of Late Pleistocene (~12 ka). Laminar petrocalcic horizons suggest much older age based on U/Th dating (Durand et al., 2006).

The types of plants that are presently growing on the hill slope surface since the late Pleistocene period correspond to a sparse cover of xerosclerophilous bushes and shrubs of Chenopodiaceae, Acacia and Artemisia. These plants are characterized by the development of extensive root systems. The roots systems expand over a broad horizon and also favor extensive carbonate precipitation, dissolution, restructuring and reworking. The present plant species in the semi-arid conditions probably were operating during calcic and petrocalcic horizon development. The geochemical analysis and the micromorphological studies of the soil sediments and the various types of calcic and petrocalcic horizons reveal that CaCO₃ is the predominant carbonate and the complex process of pedogenesis and groundwater action has formed these horizons.

Based on geomorphic observations, the Late Pleistocene hill slope surfaces reveal features of calcic nodules developed such as calcified filaments, coated grains, root casts, alveolar septal structures and peloids that are commonly recognized as biogenic or β-calcite nodules (Wright, 1991). The recognition of different horizons and the occurrence of root casts are indicative that most carbonate accumulation occurs in the soil (Gile et al., 1966; Esteban and Klappa, 1983; Machette, 1985; Mack and James, 1992), but it is mainly induced or accelerated by the activity of plant roots.

The occurrence of fine calcitic crystals as hypo coatings, and impregnated calcitic features could be the initial stages of pedogenic calcitic accumulation to form nodules. The source for the fine calcitic crystals could be the weathering of calcium rich minerals and also the dissolution of calcite grains from the upper layers being reprecipitated in lower horizons. The dissolution and reprecipitation of calcite also takes place in the form of needles within the intergrain voids and spaces. The process of dissolution and fast reprecipitation can explain the presence of distinct dull gray micritic envelopes occurring around the sparitic and microsparitic nodules. The process of the dissolution of calcite crystals forms fractures within the nodules.

The entire sequence is rich in calcite of different sizes and morphologies. Calcite is fine grained and predominant at the base of horizon Bk (~80–85% CaCO₃) forming carbonate nodules with chlorite, garnet, hornblende and titanite as accessory minerals. In horizon Bw and part of Bk CaCO₃ varies between 64.5–95.22%. In Bt horizon dolomite limestone is uniformly fine grained with specks of graphite (as identified under the microscope). In general, dolomite limestone is medium to coarse grained and abundant in the lower layers.

The mass fraction of carbonates in the calcic horizons gradually decreases downward and ceases around 160 cm below. Carbonates primarily appear as cements of quartz–grain boundaries, indicating precipitation under an evaporate condition. Carbonates in the lower calcic horizons are characteristically euhedral, and fine (50–60 μm) calcite-rich and Fe-poor grains (<3.5% Fe₂O₃; Table 1). Zoning texture is observed in coarse dolomite limestone grains from the top part of the horizon, suggesting that the dolomite limestone precipitated from repeatedly percolating fluids (either soil water or groundwater) with varying Mg/Ca ratios. This variation in the Mg/Ca ratio is due to the ion exchange reaction which takes place between the soil and the percolating waters (Durand et al., 2006). Some calcite nodules in the calcic horizons have small dolomite limestone cores, indicating that calcite formed later than dolomite limestone. The carbonates are pedogenic; they formed by utilizing Ca that leached from the upper soil section by downward flowing soil water (rainwater), CO₂ from the atmosphere (rainwater), and additional CO₂ generated by the oxidation of plant roots and soil organisms. Most of the carbonate minerals in the silicate-rich horizons (Sections A, B, C and D) of the Marudanpatti, Nanjundapuram, Ramanathapuram and Vellakinur paleosols are pedogenic.

Traces of hematite are indicative of an oxygenated environment (Jaynes and Chafetz, 1997). The quartz, feldspar, and biotite are interpreted as being lithogenic and/or detrital in origin. Quartz and feldspars are common to the dust and limestone residues within the region, and are locally derived.

Mg and Fe in the carbonates (Fe-rich dolomite limestone and Mg-rich calcite) of the paleosol sequence could have been supplied by alteration of the pyroxene and amphiboles that contain high amounts of Mg and Fe. Studies of modern laminar pedogenic carbonate horizons show that the primary source of Ca is generally eolian carbonate dust.
from regional sources rather than weathering of the parent material (Capo and Chadwick, 1999; Van der Hoven and Quade, 2002; Achyuthan, 2003). However research conducted by Durand et al. (2006) has shown, according to Sr isotopic analysis that the origin of calcretes in a region not far from the study area has shown that the provenance for Ca can be derived from a local source and only in some cases from dust.

The several stages of calcrete horizon formation are case and site specific. The main processes occurring at any precise stage are clearly seen at the macro scale from the hill slopes towards the plains (Fig. 8). The main stages are given in the following section.

5.1. Stage 1

Calcium carbonate which is dissolved from the upper horizons is transported downwards; fills up the voids and pores. CaCO$_3$ precipitation also takes place in the root zone. Clay illuviation takes place in Bt horizons as seen in the hill slope sections at Marudanpatti and Nanjundapuram.

5.2. Stage 2

Formation of transitional horizon begins with the Bk horizon of the previous soil that is overlain by detrital sediments varying from clays to medium gravels. Vegetation grew over the sediments and roots reached the Bk horizons. The soil fauna creates channels and voids through which solutions flow preferentially. Calcium carbonate that is dissolved and removed from the upper horizons of the soil accumulates lower in the soil matrix in voids. Excess of soil moisture causes calcium carbonate to precipitate as small micro calcite crystals or needles. This recrystallization particularly affects the walls of the channels and the voids, giving rise to hypocoatings and impregnative infillings. As in the colluvium area, it may be suggested that hypocoatings and impregnative infillings represent the first stages of calcite accumulation whereas evapotranspiration culminates in the precipitation of calcite crystals in a diffused form. Hypocoatings and impregnative infilling gradually coalesce and nodules become denser as simple packing voids and grain pores are in filled with secondary calcite crystals. These are observed in the lower horizons at Marudanpatti, Nanjundapuram, Ramanathapuram and Vellakinur.

5.3. Stage 3

Increased carbonate precipitation around roots results in the formation of carbonate nodules of variable size and morphology. The transition between the stage 1 and stage 2 (nodular horizon) is progressive. Subsequent growth of nodules is characterized by partial coalescence of nodules giving rise to a hardened but still friable, nodular horizon. Stages 1, 2 and 3 can be identified in the Marudanpatti, Nanjundapuram and Ramanathapuram and Vellakinur regions.
5.4. Stage 4

Carbonate precipitation is very intense and does not follow the root structures, but also occurs throughout the uppermost part of the Bk horizon. At this stage, the Bk horizon is progressively indurated and porosity is drastically reduced, leading to the occurrence of perched water table above it (Alonsa-Zarza et al., 1998). At this stage, plant roots looking for water have extended laterally promoting the development of sub-horizontal root networks. The laminar petrocalcic horizon forms in the still unconsolidated uppermost horizon. The degree of development and thickness of this horizon depends on the time that the root systems are able to be supported either in the upper soil horizon or by the new detrital deposits. As the accumulation of calcium carbonate increases, the porosity and permeability of the soil decreases. The original constituents of the host material are progressively replaced with increasing amounts of calcite. At this stage the CaCO$_3$ nodules may be counteracted by soil fauna or by colluvial transport causing local reworking. But in deeper horizons a rise in the level of groundwater dissolves and disrupts nodules that are eventually recemented. Thin carbonate laminae with detritus sediments indicate relatively short periods of stabilization probably followed by rapid sedimentation (Alonso-Zarza, 1999). Longer quiescent periods probably account for the formation of thicker carbonate laminar petrocalcic horizons (Machette, 1985; Sanz and Wright, 1994). Sesquioxidic features are characteristic of very dense nodules or nodules in deeper horizons. Their occurrence can be explained as the consequence of water logging in deep horizons generating reducing conditions that favor the mobility of ferrous iron. As accumulation of calcium carbonate increases, a point is reached when the soil fauna/organisms can no longer maintain viability. The intensity of soil forming processes due to biotic activity diminishes and eventually ceases to be important. This process is observed at Maillampatti.

5.5. Stage 5

Plant roots induce mechanical and chemical weathering, degradation and reworking of the topmost laminar horizon, which results in the development of calcic and petrocalcic rubble, progressively leading to the development of petrocalcic breccia. The size of the calcite crystals in the ground mass indicates that the first stage of calcium carbonate precipitation is not due to vertical leaching from top to bottom but is the result of a vadose crystallization of calcium carbonate transported by groundwater. This is amply supported by features such as meniscus cement, and laminar features. The nodules were then modified due to vertical leaching or reworking during erosional phases. Erosion or high sedimentation rates will inhibit both lamina formation and preservation. Repeated succession and combination of these various processes give rise to complex features, as observed at Maillampatti.

5.6. Stage 6

The erosion rate is higher than the sedimentation rate. The upper part of the petrocalic profile (B horizon or sediments) is removed and the laminar horizon is directly exposed to the atmosphere. Laminar brecciated horizons at surface indicate episodic runoff erosion that would have removed earlier overlying weathered materials (Alonsa-Zarza et al., 1998). Digeneric processes, mainly recementation, and replacement leads to the fossilization and indurations of the petrocalcic into paleocalciorthids (USDA 1998). The indurated petrocalcic profiles if they remain at the land surface are subjected to further processes, which disrupt and alter the calcitic nodules. Further pedoturbation along with carbonate dissolution and reprecipitation leads to the formation of reworked calcitic clasts and/or recemented petrocalcic breccia. This process of petrocalcic formation is commonly observed in the depression and calcrete nodules formed within aeolian and fluvio-aeolian sediments (Raghavan, 1987). Stages 4, 5 and 6 can be identified in the Maillampatti region.

Thus, laminar petrocalcic horizons reveal a complex process of development. Micromorphology characters such as the admixture of non-cemented coarse fragments in the calcium carbonate nodules suggest that some of the nodules could have been transported or reworked. Moreover, uncoated sand and well-rounded nodules also suggest reworking. The sequence of events in the laminar petrocalcic horizon formation can be summarized as follows:

(a) in the semi-arid landscape, water infiltrates through sand, thus raising the groundwater levels almost up to the surface of the soil in the depressions and above the surface in the deepest parts. Due to evaportranspiration during the dry seasons, calcium carbonate precipitates and accretion processes form carbonate nodules;
(b) during erosion phases, probably due to frequent flash floods, calcium carbonate nodules behave as coarse clasts and are transported by water. These nodules act as nuclei and are recemented by calcium carbonate. Rock fragments also get cemented along with the transported calcium carbonate nodules. Structures reported here, such as spherulites, have developed at the soil atmosphere surface. Calcitic spherulites that are relatively common in thick laminar petrocalcic profiles (Wright et al., 1996) have been interpreted to have been formed in desiccating surficial ponded waters (Verrecchia et al., 1995). The spherulites in the laminar carbonate are interpreted to have precipitated under air and/or water bodies (shallow pond) by locally discharged groundwater, rather than within soil (pedogenic) by downward-flowing soil water;
(c) the desiccation-like cracks and sparry calcite suggests the carbonates precipitated either under air or in a shallow water body before the accumulation of silicate-rich rocks. The carbonates have been mostly formed under air and they have been dissolved by the low-pH
(high $pCO_2$). Therefore, the laminar carbonates probably precipitated in a high-pH water body (shallow pond) by local discharged groundwater;

(d) the abundance of carbonate minerals changes abruptly from $\sim 50\%$ in the laminar carbonate to $\sim 10\%$ in the overlying silica-rich unit. This suggests that the silicate-rich horizon were not present during the formation of the laminar carbonate litho horizon. During more stabilized phases, the landscape is affected by pedological processes due to the growth of vegetation or increased density of vegetation thus altering the original fabric. Micronodules within the laminar petrocalcic horizon have been interpreted as being formed by either cyanobacteria or bacteria (Verrecchia et al., 1995; Wright et al., 1996). The increase in the carbonate content in the laminar carbonate may be due to substitution.

Frequent repetition of this cycle and the succession of micro phases within it have given rise to laminar petrocalcic horizon in low-lying areas. Fluvial actions of streams having their catchments in nearby Western Ghats were responsible for the disruption of laminar petrocalcic horizon into fragments or boulders, cobbles and gravels. As the succession of these phases can vary, the laminar petrocalcic horizon has been formed by groundwater, from runoff, subsurface lateral movement beneath the impermeable layers and pedological processes forming compound profiles on hard rock substrates.

6. Paleoclimate inference

Lack of intense leaching by rainfall often leads to the formation of laterally extensive pedogenic carbonate in layers (Capo and Chadwick, 1999). In this study, the presence of clays such as smectite, montmorillonite, illite, vermiculite and iron oxide such as hematite and absence of sepiolite-palygorskite associated with low magnesium calcite indicate that the petrocalcic formed under semiarid climate (mean annual rainfall between 300 and 500 mm) similar to the present climate of the area. Formation of hematite requires very high temperatures or environments wherein the activity of water is considerably reduced. Moreover, sepiolite and palygorskite are generally present in soils of drier climates (arid, mean annual rainfall 50–100 mm) (Verrecchia and Verrecchia, 1994; Jimenez Espinosa and Jimenez-Millan, 2003). The clay mineralogy in the hill slope deposits does not indicate significant changes in the climatic regime before and after the calcic horizon formation. Calcic horizon formation appears to have been controlled by slope stability. Plant colonization of the colluvial surface deposit leading to the formation of calcic carbonate horizons has taken place under relatively stable conditions in a semi arid environment.

In warm arid and semi-arid environments, the accumulation of clay minerals produces increasingly well developed soil horizons with the passage of time. Differences in the strength of development of two prominent soil horizons, silt- and clay-rich surface vesicular (Av), and clay-enriched subsurface argillic (Bt), has strongly influenced the amount and seasonal continuity of plants, available water and the physiological activity of long-lived plants. Our study shows that subsurface, surficial soil horizon and calcrete development has taken place in phases. The Bt horizon is fine sandy loam or sandy clay loam. They have developed in strongly acid through neutral sandy or loamy sediments. The Bt horizon developed in a subhumid, mesothermal climate probably wetter than today, with hot dry summers and cool moist winters. The runoff was slow and permeability was moderate.

7. Conclusions

No dates have been obtained on these paleosols. Micromorphology studies reveal that calcic horizon development was initially nucleated along the hill slope deposit, supported by root decomposing activity that controlled the morphology of carbonate accumulation within the soil during early stages of development.

The occurrence of micro-spar calcium carbonate crystals, adhesion of clays and silt-sized detritus grains in the micrite, spherulites either in thick lamina or within the petrocalcic and brecciated laminar horizons, indicate that these petrocalcic horizons do not represent a unique and continuous stage of soil formation, but that degradation, reworking and exposure of some previously formed horizons (mainly the laminar horizon) occurred throughout the development, especially in distal areas of the hill slope. The formation of the thick petrocalcic profiles took place in different more or less well differentiated stages that were repeated over time. Laminar petrocalcic horizons can be used as signatures of periods of relative stability, with a thin soil cover that allowed the growth of vegetation followed by events of groundwater action and sedimentation thus giving rise to composite, polygenetic profiles in a semi arid environment.

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