GEOMORPHOLOGICAL AND PEDOLOGICAL EVOLUTION OF PARTS OF LOWER GANGETIC PLAINS IN WEST BENGAL

A THESIS

submitted in fulfilment of the
requirements for the award of the degree
of
DOCTOR OF PHILOSOPHY
in
APPLIED GEOLOGY

By

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Gratis

CANDIDATE'S DECLARATION

I hereby certify that the work, which is being presented in the thesis entitled **"GEOMORPHOLOGICAL AND PEDOLOGICAL EVOLUTION OF PARTS OF THE LOWER GANGETIC PLAINS IN WEST BENGAL"** in fulfilment of the requirement for the award of the degree of **Doctor of Philosophy**, submitted in the Department of Earth Sciences of the University, is an authentic record of my own work carried out during a period from May 1989 to January 1995 under the supervision of **Dr. B. Parkash** and **Dr. A. K. Singhvi.**

The matter embodied in this thesis has not been submitted by me for the award of any other Degree.

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Lalan Prasad Singh

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Abstract

The Lower Gangetic Plains form one of the most extensive fluvio-deltaic plains of the world. Quaternary climatic and sea level changes and tectonics have influenced significantly the development of landforms and soils of these plains. The present study aims to decipher the roles of these factors on morphogenesis and pedogenesis of the area during the Quaternary Period, using soil-geomorphic approach.

On the basis of field observations and laboratory analyses the degree of soil profile development in different soil-geomorphic units were determined. Based on relative degree of development, the soils of the area were divided into five members of a soil-chronoassociation (Mohindra et al., 1992) and have been given the names QGWB1 to QGWB5. Various soil-geomorphic units units included in different members are: QGWB1 - Ganga Floodplain; QGWB2 - Bhagirathi Plain and Old Ganga Plain; QGWB3 - Barind Tract (Lower Level) and Damodar Terminal Fan; QGWB4 - Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain and Ajay-Silai Plain and QGWB5 - Lateritic Upland.

Soils of QGWB1 member are least developed and A/C type of horizonation is observed in these soils. The thickness of B horizon increases in general from QGWB2 (40-50 cm) to QGWB4 (80-110 cm) soils. Soils of QGWB4 member are poorly drained, fine textured, vertic intergrade soils with vertical cracks occurring on the gently sloping plains. The soils of the Lateritic Upland occur on an undulating region and they consist of two distinct units. The lower autochthonous unit starts with a lithomarge at the base grading up into pisolitic laterite (200-300 cm thick). The pisolitic concretions have been cemented by iron oxide. The upper allochthonous unit with a maximum thickness of 50-150 cm is comprised of gravelly sand at the top followed by lateritic mudstone which consists of detrital lateritic particles bound by iron oxide. The lower unit occurs only on the lower slopes of the unit.

The preliminary Thermoluminescence ages of QGWB1 to QGWB4 members are 500 yr, 1-1.5 ka, 3-4 ka and 5-6 ka respectively. Lateritic soils of QGWBB member have been assigned a tentative maximum age of 125 ka. The minimum age is 22 ka that marks the beginning of the Last Glacial Stage. Another unit named the Raghunathganj Surface/Soil has been recognized. It has an undulating surface with a minor surface exposure in the Bhagirathi-Brahmani Plain and occurring at a depth of 1.5 to 3 m under the Brahmani-Ajay and Ajay-Silai Plains. It has a petrocalcic horizon with calcretes developed to stage IV of carbonate morphology of Gile et al. (1966). It has not been considered in the construction of soil-chronoassociation, as it was not studied in detail. A radiocarbon age of 23 ka has been obtained from a calcrete sample from this unit.

The pedogenic processes occurring in the lower autochthonous unit of Lateritic Upland (QGWB5) soils represent intense weathering of ferralitisation stage of Duchaufour (1982). The upper allochthonous unit of lateritic soils represents eroded lateritic material from the hinterland and its emplacement in the topographically lower regions due to lowering of the msl as discussed below. This can be called as Laterite-Derived-Facies (LDF) after Valeton and Wilke (1993).

The moderately developed soils of the Bhagirathi-Brahmani, Brahmani-Ajay and Ajay-Silai Plains are marked by clay illuviation and transformation of smectite and illite into interstratified clay minerals on a large scale. Additionally they are marked by pedoturbation in the upper part and swelling and shrinking leading to formation of slickensides and stress-oriented coatings. The presence of illuviation features and high amount of 2:1 swelling clays in these soils suggests fersialitisation stage of weathering of Duchaufour (1982).

Formation of small amounts of chlorite and illite-chlorite in the surface horizons of QGWB3 soils together with common occurrence of gleyans and flood coatings suggest that illite is being transformed to chlorite through illite-chlorite (e.g. in Barind Tract) and chlorite-smectite (in Damodar Terminal Fan) by ferrolysis in a manner suggested by Brinkman (1969/1970, 1977).

The poorly developed soils of the young fluvial plains such as the Bhagirathi Plain and Old Ganga Plain are marked by hydromorphism and slight clay illuviation

The paleoclimatic and sea level changes seem to have played a significant role in the development of landforms and soils of the study area. Three major phases of sea level and climatic changes since Mid Pleistocene can be recognized from eastern coast of India. The transgression of first phase at ca. 125 ka led to the deposition of the parent material for the Lateritic soils (QGWB5). Lateritization started with regression of the sea of this stage on the upland areas with a good drainage under a warm and humid climate. The low msl in the later part of this phase must have caused the formation of the LDF. In the second phase a small transgression at ca. 30 ka with associated rising groundwater must have accelerated lateritization of the autochthonous Lateritic soils in a manner suggested by Valeton and Wilke (1993). Regression at the end of this phase probably led to erosion and formation of Raghunathganj Surface/Soil with petrocalcic horizon during an arid phase. The third phase of transgression at 7-6 ka led to the deposition of sediments of the QGWB3 (Damodar Terminal Fan) and QGWB4 members. As the sea regressed during this phase, freshly deposited sediments were exposed on which pedogenic processes started, as a result soils are younger from west to east in the region east of the Lateritic Upland. This regression has also contributed at least partly to entrenchment of the courses of the Ganga, Damodar, Ajay and Brahmani rivers due to reduced msl.

The above discussion also implies the existence of another Quaternary cycle of lateritization different from the Early Tertiary 'Indian Cycle' identified by Valeton and Wilke (1993).

The present region lies in one of the most seismically active zones of the world. Most of the study area overlies the Bengal Basin. Its contact with the Peninsular rocks is along the Chotanagpur Foothill Fault. Within the Basin, three major tectonic units are: Tectonic Shelf in the western part, Barind Tract Horst in the north and the Ganga Fluvio-deltaic Plain (GFDP) Graben in the eastern part. The Tectonic Shelf and Barind Tract Horst are separated by the Ganga-Padma Fault and the Damodar Fault separates the Tectonic Shelf and GFDP Graben. The Medinipur-Farakka Fault within the Tectonic Shelf separates the Lateritic Upland in the west from QGWB4 soils in the east. The Chotanagpur Foothill, Medinipur-Farakka and Damodar Faults are roughly N-S trending with significant reliefs of 250 m, 25 m and 6 m across them respectively and form step faults with eastern sides in each case being downthrown side. The Lateritic soils (QGWB5) and the QGWB4 soils are presently 120-30 m and 50-20 m asl but the sea level rose to +25 m and +6 to 10 m above sea level during 125 ka and 7 ka transgressions respectively, suggesting that the Tectonic Shelf has been uplifted significantly more on the western side and less on the eastern side since 125 ka. The total uplift is probably accounted partly by throw across the faults and partly by steep easterly slopes of the plains.

The Barind Tract Horst has at least three erosional levels (with varying reliefs of 5 to 20 m) soils developed on each of them. These indicate tectonic uplift in at least three stages and these levels are similar to river terraces.

The western boundaries of the (i) Lateritic Upland, (ii) BBP, BAP, ASP Plains and (iii) DTF units are marked by Chotanagpur Foothill, Medinipur-Farakka and Damodar Faults respectively and these faults were the areal limits of sediments deposited at different times indicating their activity at those times. Thus the activity along faults affected sedimentation directly and pedogenesis indirectly.

All the easterly flowing rivers in the Tectonic Shelf zone have shifted their courses towards the south within their floodplains indicating southerly tilting of the Shelf in the last 100's of years. The Dwarkeshwar, Silai and Kasai rivers show annular drainage pattern indicating activity of some basal dome in this zone. Also, the courses of the rivers Ganga, Damodar and partly Bhagirithi are confined to faults.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The Lower Gangetic Plains form one of the most extensive fluvio-deltaic plains of the world. A large proportion of the agriculturally productive land of India supporting 1/10 th of the population of the country is occupied by these plains. Any understanding of the landforms and soils of these plains is imperative for the development and management of these important resources.

The Lower Gangetic Plains conceal the Bengal Basin which has been continuously affected by tectonism since its inception (Sengupta, 1966; Roybarman, 1983). The effect of tectonism has been manifested in the form of violent earthquakes causing much loss of human life and property. Quaternary climatic changes have been witnessed in other parts of the Gangetic Plain (Singh, 1971; Singh et al., 1974) and hence the possibility of such climatic vicissitudes affecting the Lower Gangetic Plains is high. Also, the proximity of coastline suggests that these plains must bear the imprints of Quaternary sea level changes. The soils represent episodes of land surface stability with little or no deposition and thus record Quaternary environments in areas where there is no depositional or erosional evidence of subaerial Quaternary history (Catt, 1992). Hence the study of soils is essential in deciphering the history of landform evolution and climatic changes.

Keeping the above mentioned points in view, detailed investigations of the landforms and soils of the Lower Gangetic Plains in parts of West Bengal (Fig. 1.1) was carried out. Mapping of landforms and soil-geomorphic units (Fig. 2.2) was done using remote sensing techniques and field checks. The degree of soil profile development was determined on the basis of field morphology and laboratory analyses of soils. Using these data, a soil-chronoassociation was prepared for the study area. This has helped to work out the roles of sea level and paleoclimatic changes and tectonics on the development of landforms and soils of the study area during the Quaternary Period.

1.2 Regional Geology and Tectonic Setting

The sub-surface geology and tectonic framework of the Lower Gangetic Plains have been described in detail by Wadia (1966), Sengupta (1966) and Roybarman (1983). Here only a brief account is attempted.

The Bengal Basin is bordered by the Precambrian Peninsular Shield in the west, Arakan-Yoma Uplift in the east and Shillong Massif in the north and opens up in the Bay of Bengal towards the south. It is a pericratonic basin and its evolution is intertwined with the sequential developments of the Himalayas and the Indo-Burmese Ranges as a result of collision of the Indian, Chinese and Burmese Continental Plates.

The western margin of the Bengal Basin is marked by two significant features: (1) A series of basement ridges buried under the alluvium bordering the eastern margin of the Precambrian Shield area, and (2) a series of normal faults and fault-line scarps along the eastern margin of this zone. Seismic evidences suggest that at least some of these basin margin faults were active contemporaneously with sedimentation (Sengupta, 1966). Five structural and depositional zones of the foreland shelf of the Bengal Basin (within West Bengal) have been recognized from west to east: (a) shield area, (b) basin margin fault zone, (c) stable shelf, (d) hinge zone with associated structures, and (e) basin deep (Sengupta, 1966).

Roybarman (1983) recognized four main stages of evolution of the Bengal Basin from the available seismological data: (i) **Pre Rift Stage**. During the Permocarboniferous and Early Mesozoic times, the western fringes of the West Bengal Basin were believed to be the part of the Gondwanaland, (ii)**Rift Stage Associated with volcanism.** The breakup or the rifting of the Gondwanaland coincided with the timing of the Rajmahal Volcanism during the Late Jurassic-Early Cretaceous time, (iii) **Post-Rift Carbonate Platform Stage.** During the Paleocene-Eocene time, thick carbonate sediments were deposited in the shelf and this shelf facies changed to shaly facies in the deeper part of the basin. At this stage open marine

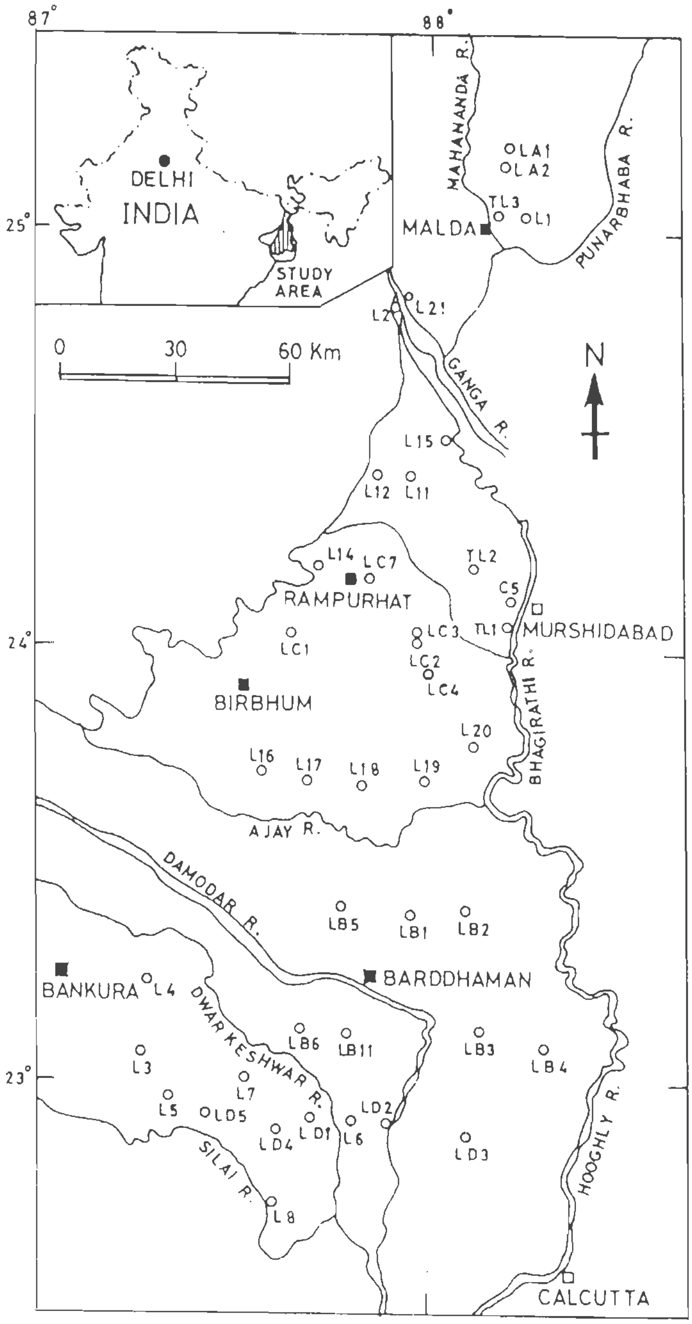

Fig. 1.1 Location and extent of the study area showing sampling sites of the soil profiles.

conditions prevailed with clear differentiation of the basin, shelf, slope and continental rise, which could not be recognized in the previous stages. (iv) **Late Tertiary Deltaic Stage.** Clastic sediments were deposited under the deltaic environment during the Early Miocene-Pliocene time.

A number of workers (Fergusson, 1863; Hirst, 1916; Morgan and McIntire, 1959; Coleman, 1969; Nandy, 1980; Sesoren, 1984) have referred to the neotectonic aspects of the region. According to Morgan and McIntire (1959), the eastern and northern parts of the Bengal Basin have been subjected to more structural modifications than have the western and southern parts. Nearly all faults and folds they mapped are north of the Ganges River. A similar distribution is observed in respect of epicenters of recorded earthquakes (Morgan and McIntire, 1959). The Barind area in the northern West Bengal and Bangladesh exemplify the neotectonics of a significant part of the Bengal Basin (Khandoker, 1987). The elevated areas of Pleistocene sediments of Barind-Madhupur are outlined by well defined faults: the Karatoya-Banar Fault on the northeast, the Padma Fault on the southwest, the Malda-Kishanganj Fault on the northwest and the Meghna Fault Zone on the southeast (Khandoker, 1987, Fig. 2).

1.3 Physiography and Climate

Physiographically the study area consists of three major units; steep easterly sloping plains in the western part, fluvio-deltaic plains of the Bhagirathi in the east and the Barind Tract in the north. All the major rivers of the northern part flow in a generally southerly direction (Fig. 1.2). The rivers draining the easterly sloping plains originate in the west in the Peninsular Shield and flow in an easterly direction following the regional slopes of the plains. The Bhagirathi river flows in a southerly direction along a structurally controlled course.

The region experiences a hot and humid monsoonal climate. The proximity to the Bay of Bengal in the south, alignment of the Himalaya in the north and Meghalaya Plateau in the northeast determine largely the climatic character, i.e., the distribution of weather elements with respect to time and space. The spatial and seasonal distribution of the elements such as temperature, rainfall and relative humidity are too uneven.

January invariably appears as the coldest month, the temperature ranging between 17°C and 21°C and increasing southward (Sagar Islands 20.4°C). The temperature starts rising gradually throughout the region from February but the rise is well marked (4°C to 6°C) in March and it continues till the end of May; the rise in the temperature is checked by early June due to the outburst of monsoon. May records the maximum average temperature (29°C - 33°C). The temperature starts declining gradually from June onwards and it becomes well marked between October and November when it falls by 3°C to 5°C. This marks the start of the winter season. The winter season is characterized by the sweep of northerly or northwesterly winds. The weather changes are associated with the occasional western disturbances causing some rainfall, but cold waves are rare.

The average relative humidity is generally high (over 50%) throughout the region except in the western fringes where for about two months - March and April, it is less than 40%. During July, August and September the average relative humidity becomes over 80% which decreases westward.

The rainfall (1200 mm to >4000 mm) is fairly widespread in the region though with uneven seasonal and spatial distribution characteristic of the monsoonal climate. Nearly 80% of the total annual precipitation is concentrated during the four months of monsoon (June to September). There are four sources of rainfall in the region; i.e., the westerly disturbances of winter, the convectional overturning of air resulting in the local depression during March-May causing pre-monsoonal showers, the cyclonic disturbances of the monsoon and post-monsoon periods and the monsoon currents occurring along the convergence lines of the sea-level monsoonal troughs (Singh and Singh, 1971). The northern and southern parts of the area, owing to the proximity of the Himalaya and the Bay respectively, experience relatively more annual rains than the central and the western parts. In the northern part, in the districts of Malda and

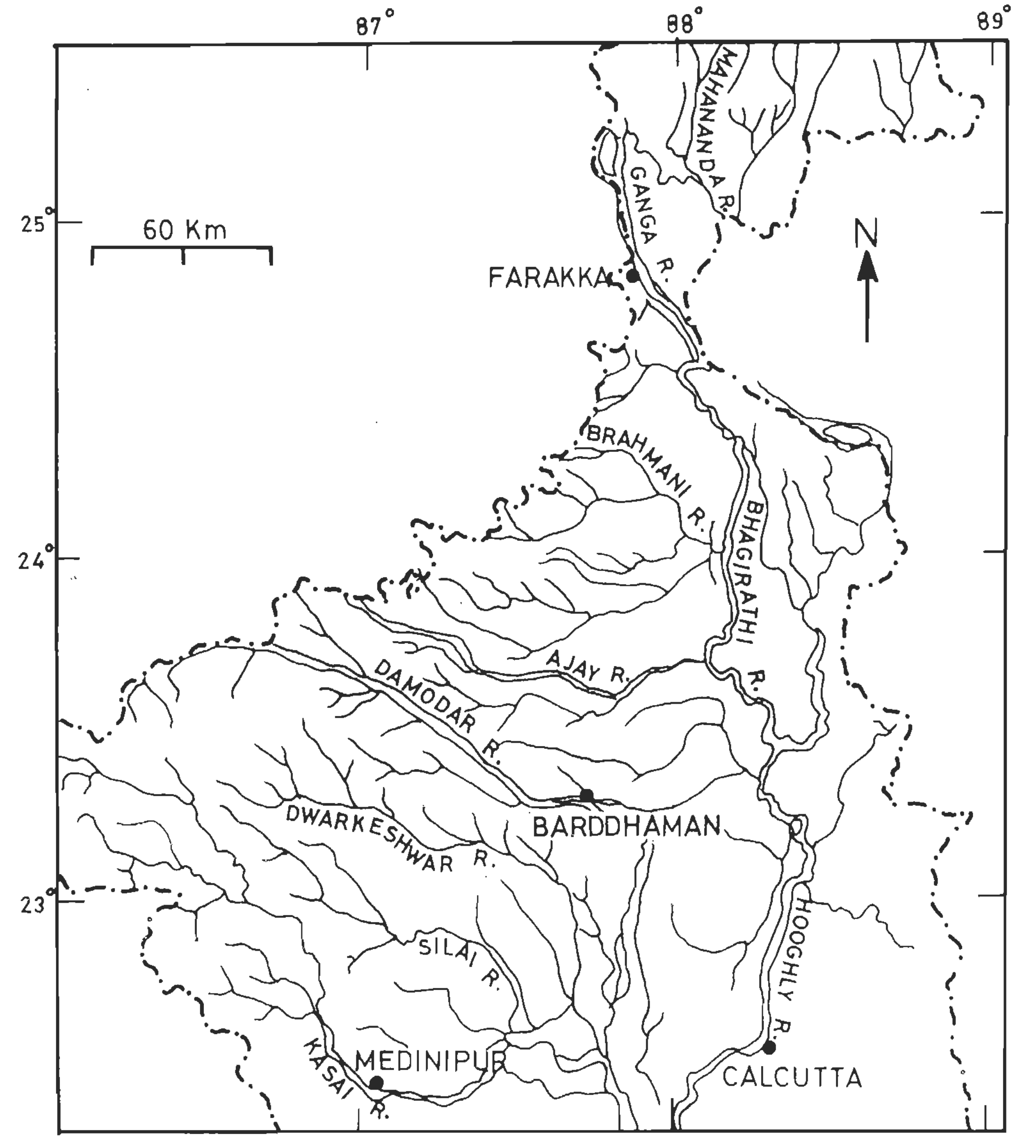

Fig. 1.2 Drainage Map of the study area and adjoining areas.

West Dinajpur the rainfall ranges between 1400 mm to 2400 mm. In the region south of the Ganges the annual rainfall increases from 1400 mm in the west to 1600 mm in the east.

1.4 Groundwater

The mode of occurrence of groundwater in the Lower Gangetic Plains is intimately related to the physiographic features and the meteorological factors. The northern part of the area is characterized by extensive near surface aquifers which have groundwater in unconfined condition.

In the upper floodplains of the Bhagirathi and in narrow sector of the Damodar Basin groundwater occurs in unconfined condition with depth of water table ranging from 3 to 6 m below ground surface. Ground water occurrence in the western fringe of the Bengal Basin is restricted to localized zones which are both under confined and unconfined conditions.

Groundwater together with surface water conditions in the region has greatly affected the physico-chemical properties of soils. Recurrent floods, frequent droughts and widespread waterlogging are characteristics of the region. Except the northern and western part, major portion of the area is low lying. Also, the soils are clayey and hence imperfectly drained. They are subjected to overflow and stagnation of water during rainy season. The clayey soils of low lying areas of floodplains of Damodar and Hooghly are often subject to hydromorphic conditions due to waterlogging.

1.5 Background

Previous studies concerning the Quaternary landscape evolution of the Lower Gangetic Plains have concentrated on the broad subdivisions of the Quaternary deposits without any critical assessment of soil and landform relationships. Ball (1877) divided the Quaternary sequence in parts of West Bengal into Older and Newer Alluvium, though the basis of classification was not clearly defined. Mukerji (1955, 1958 in Randhawa, 1982) described the morphological characteristics of the soils of West Bengal occurring on different physiographic regions as Ganga riverine alluvium, Ganga flats, Ganga uplands, Ganga lowlands, Vindhyan riverine lands, Vindhyan flat lands, Vindhyan Highlands and coastal soils. Niyogi, et al. (1968) and Mallick (1971) broadly mapped and classified the Quaternary alluvium in the area. Bhattacharya and Banerjee (1979) divided the area around Ajay-Bhagirathi valley into four geomorphic plains from west to east - Lateritic Upland, Older Deltaic Plain, Younger Deltaic Plain and Recent River Terrace sediments (Fig. 1.3) and assigned them ages from Pleistocene to Recent. Morgan and McIntire (1959) did some reconnaissance studies on the Quaternary geology and alluvial morphology of the Bengal Basin including the Ganges Delta. They suggested that "Older Alluvium" of Bengal consisted of multiple Pleistocene terraces similar to those in the Mississippi Alluvial Valley and called them as the "Barind" and the "Madhupur Jungle". More recently Umitsu (1993) divided the Late Pleistocene and Holocene sediments in the Ganges Delta and its surrounding region into five units. According to him all these units have been deposited since the maximum epoch of the last glacial age. His studies were based on the analysis of bore hole samples and a few radiocarbon dates from fossil woods, organic matter, shell fragments and peat samples.

Excellent reviews on the morphology, clay mineralogy, micromorphology and genesis of soils of the country including West Bengal were published in the proceedings of the 12th International Congress of Soil Science (Randhawa, 1982). Shankaranarayana (1982) presented reviews on the morphology and genesis of soils and Digar and Barde (1982) on the morphology and genesis of red and lateritic soils of West Bengal. A selective overview of the work done on some important aspects of soils of the region is attempted here.

(a) Soil Mapping

Niyogi (1975) and his co-workers published the detailed map showing Lateritic Upland Plain, Older Deltaic Plain, Younger Deltaic Plain and Recent Floodplain in the coastal belts of

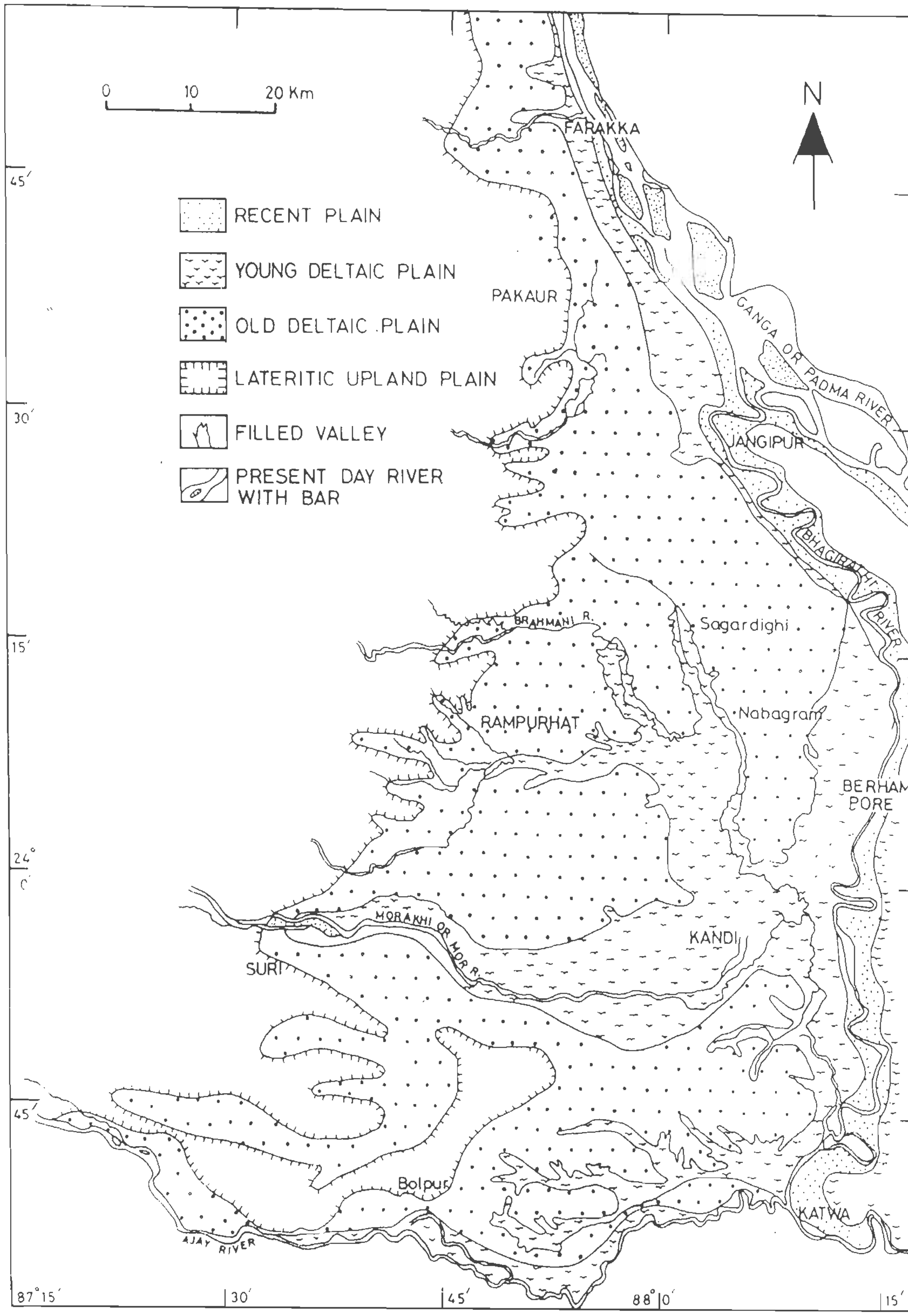

Fig. 1.3 Quaternary Geomorphological Map of Ajay-Bhagirathi Valley (Modified after Bhattacharya and Banerjee, 1979).

West Bengal. Later on Bhattacharya and Banerjee (1979) published the map showing similar subdivisions for Ajay-Bhagirathi valley. A more comprehensive soil resource map of West Bengal has been brought out recently (Nat. Bur. Soil Surv. Landuse Plan., 1991).

(b) Clay Mineral Studies

Clay mineralogy of soils of West Bengal has been studied by several workers (Bagchi, 1951; Adhikari, 1957, 1958; Sarkar and Chatterjee, 1964; Anjaneyulu et al., 1965). Most of them aimed primarily in the identification of clay minerals from surface soils (<50 cm depth) from small areas. Detailed and systematic studies pertaining to the variation of clay mineral assemblages with depth in a profile and in different soils are lacking.

Ghosh and Datta (1974) and Ghosh et al. (1976a) studied the clay mineralogy of surface horizons (0-23 cm depth) of some alluvial soils of West Bengal. Their studies revealed the dominance of mica (10%-40%), smectite (30-60%) and kaolinite (6%-10%), with occasional presence of mixed-layer minerals (10%-38%) and chlorite (7%-18%) in the clay fractions. The Lateritic soils of Bankura and Medinipur districts in West Bengal contained mainly kaolinite together with appreciable quantity of illite and mixed layer minerals.

(c) Micromorphological Studies

Micromorphological studies of soils of the Lower Gangetic Plains are very limited. Kooistra (1982) has provided the micromorphological descriptions of six soil series from West Bengal. She noted the remains of sedimentary lamination and sesquioxide accumulations in fluvaquents of the floodplains of the Hooghly river. Also, the occurrence of pedogenic carbonates, sesquioxide nodules and hydromorphic conditions were observed in the Fluventic Eutrochrepts of the Bhagirathi Floodplain. In some Vertic Ochraqualfs, the presence of deformed infillings of clay and silt sized materials were observed (Kooistra, 1982).

From the foregoing background, it is evident that no detailed work concerning the evolution of landforms in relation to soils have been done in the lower Gangetic Plains.

1.6 Objectives

The main objective of the present study has been to work out the history of Quaternary landform evolution and pedogenesis in parts of the Lower Gangetic Plains. The various components of the objective are as follows.

(1) identification and mapping of different landforms and soil-geomorphic units,

(2) study of soil properties (e.g. morphology, chemical analysis, clay mineralogy and micromorphology) and preparation of a soil-chronoassociation for the study area,

(3) To elucidate the roles of paleoclimatic and sea level changes and tectonics on the geomorphological and pedological evolution of the region during the Quaternary Period.

1.7 Plan of Work

The work was started with the analysis of Landsat satellite images (black and white as well as False Colour Composites) and topographic maps in order to distinguish the major landforms and geomorphic units on the basis of their photo-characters and topographical expressions. These units were further verified in the field by direct observation of geomorphic features and soils. This was followed by the preparation of a soil-geomorphic map. The specific objectives of the field work were as follows.

(1) study of morphology of soils developed on different geomorphic units along the pre-decided traverses (Fig. 1.1). Traverses were selected such that these crossed through all the soil-geomorphic units enabling to identify variability of soil properties within units

and between units.

(2) systematic bulk sampling of soils from different horizons of a pedon for detailed texural, chemical, and clay mineralogical analyses.

(3) sampling of soil materials for thermoluminescence and radiocarbon dating.

(4) collecting undisturbed samples for micromorphological studies.

The best sites for studying soil horizons were found to be the brick kiln sections. Where brick kilns were not available pits were dug. Special care was taken in selecting the site to avoid human interference of the section.

1.8 Organization of Chapters

The thesis has been organized into six chapters. Chapter 2 describes the identification and mapping of major landforms and geomorphic units and study of morphology of soils of each geomorphic unit with particular reference to the description of soil profiles and variation of their field characteristics. Chapter 3 deals with textural, chemical and clay mineralogical characteristics of the soils of different units. Variations of texture, clay mineralogy and oxides of major elements in soils of different units have been discussed in detail. Micromorphological studies have been dealt with in chapter 4. Chapter 5 consists of thermoluminescence studies of soils of the region. Finally, chapter 6 summarizes the morphology, texture, micromorphology and clay mineralogy of soils of different units. A synthesis of data in terms of soil-chronoassociation and the roles of paleoclimatic and sea level and tectonics in the evolution of landforms and soils of the area is given. Significant conclusions drawn from the study are also included in this chapter.

CHAPTER 2

LANDFORMS AND SOIL MORPHOLOGY OF THE AREA

2.1 Introduction

The close relationship between geomorphology and soils has been widely recognized (Birkeland, 1984, 1990; Catt, 1986; Gerrard, 1992; Mohindra et al., 1992; Srivastava et al., 1994). It has been well established that the soils are the products of the same natural processes and conditions that sculpture the landform they exist in. Therefore, integrated identification and mapping of different landforms and soils is essential for proper understanding of geomorphic history of an area.

2.2 Identification and Field Investigation of Major Landforms and Soil-Geomorphic Units

Multispectral remote sensing techniques are being extensively used to map soils and landforms on regional scale with a reasonable degree of accuracy (Hilwig, 1976). In the present study, Landsat black and white images of band 1, 2 and 4 at 1:10,00000 scale (Fig. 2.1) as well as False Colour Composite (FCC) at 1:250,000 scale of Landsat Thematic Mapper (TM) have been used. In addition, topographic sheets of Survey of India at 1:250,000 scale were used as base map.

Various criteria used for image interpretation were colour, tone, texture, landforms, vegetation cover, drainage pattern, drainage density and erosion pattern. The overall red colour of the FCC represents the vegetation cover over the area; the intensity of red tone is directly related to the density of vegetation cover. The active channels appear as blue, whereas the abandoned channels or lakes with stagnant bodies of water appear as black lines/patches because of lower reflectance values. The dry channels with sandy beds as well as scattered sandy patches are identified by high reflectance and appear as light yellow lines/patches. The highest reflectance is produced by fresh sand along the active channel belts, and this appears as bright white patches, and hence is clearly distinguishable from weathered sand along the paleochannels. The channels of the major streams and their older courses define, in a general way, the location of their floodplains. In the case of smaller channels, the floodplain areas are less extensive and are typically restricted to narrow patches alongside the channels generally limited by the adjoining river banks or by the natural levees.

Using the above mentioned criteria of image-interpretation three major landforms were recognized and mapped in the study area. These include (i) Upland Areas, (ii) Old Fluvial/Deltaic Plains and (iii) Young Fluvial Plains. Within each landform, a number of soil-geomorphic units with their characteristic soils were recognized which have been discussed later. The boundaries of different soil-geomorphic units were confirmed later by direct observation in the field and a soil-geomorphic map showing different units was prepared (Fig. 2.2). Also, different tectonic features of the study area were recognized and have been discussed later in this chapter.

The field investigation involved augering at a number of points before selecting a specific site for detailed study of soil characteristics of a particular unit. At a selected site, an excavation, approximately 1.5m x 1.0 m, was made with at least one smooth vertical wall. The excavation was oriented such that one vertical wall was properly illuminated, to allow an examination of the complete profile and to facilitate taking a photograph. A total number of 40 pedons were studied in the field and soil properties of horizons were recorded. The profile at each site was divided into different horizons and each horizon was described in terms of depth, thickness, colour, texture, mottling, structure, consistency, carbonates, coarse fragments, pores and roots using the scheme of Soil Survey Staff (1966).

After recording various soil characteristics systematically, samples from different horizons of each soil profile were collected for laboratory analyses. For micromorphological studies undisturbed samples were collected in tin boxes of approximately 7 cm x 5 cm x 5 cm size, as described by Kemp (1985).

Various landforms and morphology of soils of the study area have been described below.

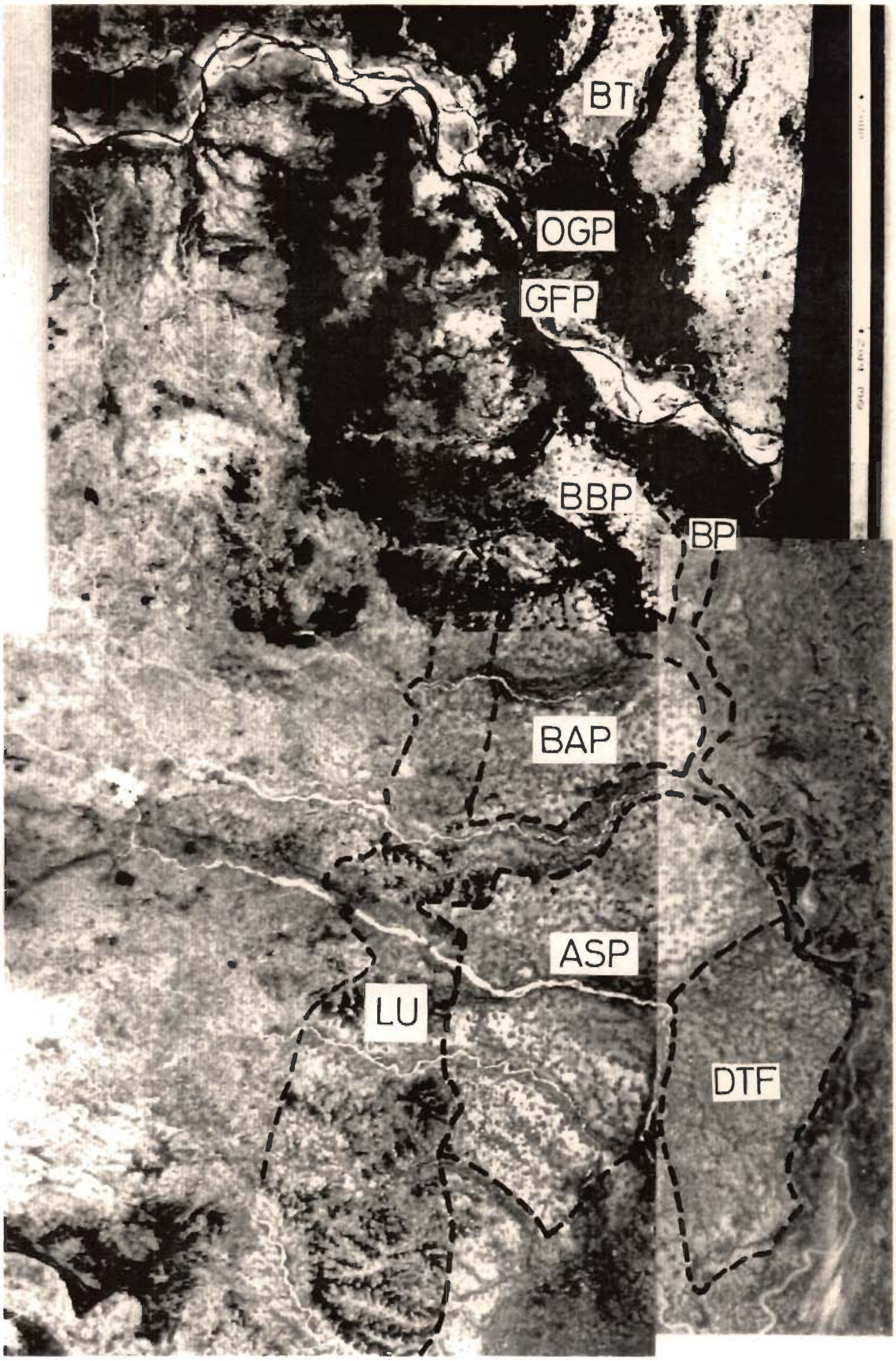

Fig. 2.1 Mosaic of Landsat (TM) Black & White images showing the study area. Abbreviations are same as in text.

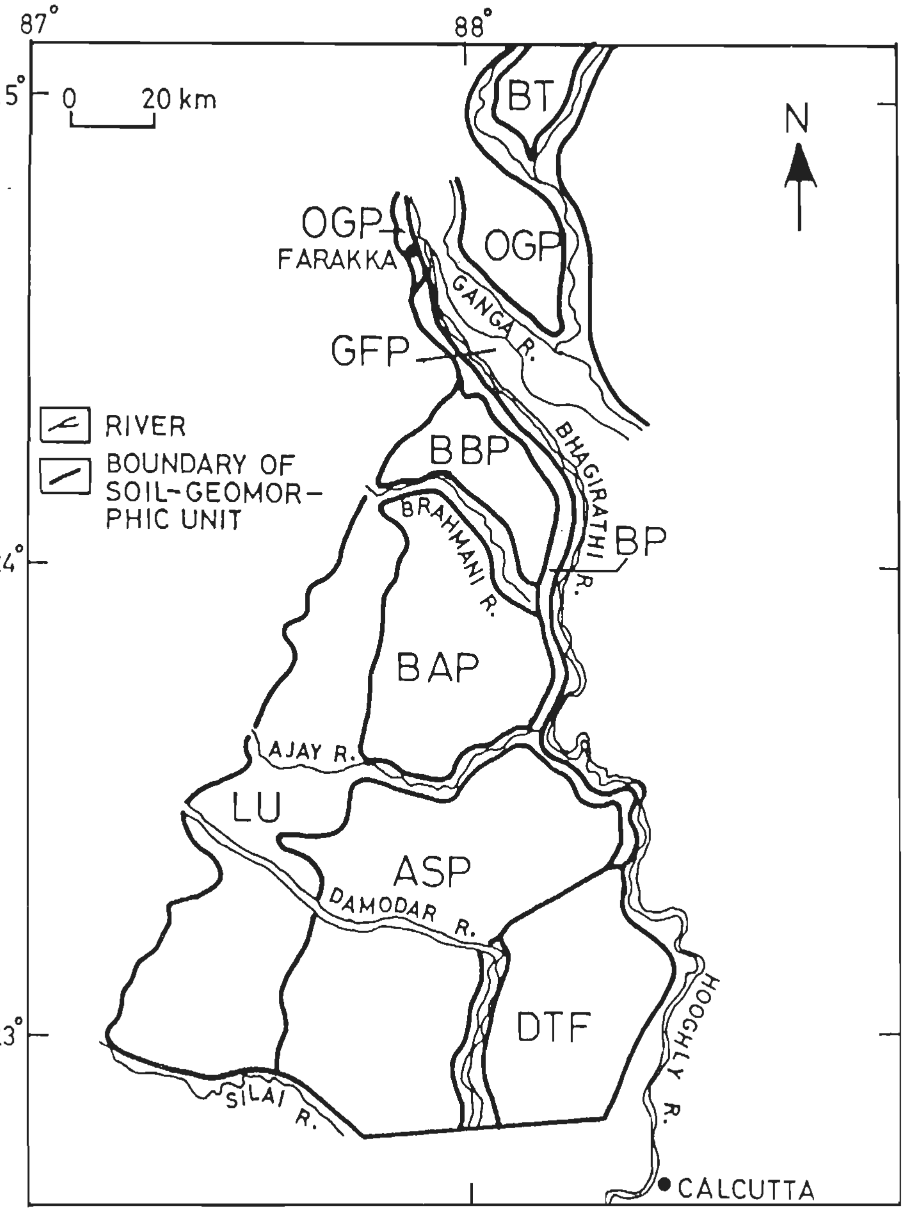

Fig.2.2 Soil-geomorphic Map of the study area showing nine soil-geomorphic units indentified from remotely sensed data.

2.3 Major Landforms and Soil-Geomorphic Units

As mentioned above three major landforms (i.e. Upland Areas, Old Fluvial/Deltaic Plains and Young Fluvial Plains) were recognized and mapped in the study area. The Upland Areas occur at the highest elevation in the study area and are characterized by their dissected topography and distinct levels. The heighest levels are overlain by strongly developed polygenetic soils. These include (i) Lateritic Upland in the western part and (ii) Barind Tract in the northern part of the study area. The Old Fluvial/Deltaic Plains are gently sloping plains lying to the east of the Lateritic Upland. These are overlain by moderately developed soils. They include (i) Bhagirathi-Brahmani Plain, (ii) Brahmani-Ajay Plain, (iii) Ajay-Silai Plain and (iv) Damodar Terminal Fan. The Young Fluvial Plains lie to the north and east of the Old Fluvial/Deltaic Plains and are identified in the satellite images by their clear association with some rivers. These include (i) Old Ganga Plain, (ii) Ganga Floodplain and (iii) Bhagirathi Plain.

The different constituent soil-geomorphic units of each landform as given above have characteristic soils developed on each of them and they have been called soil-geomorphic units (Table 2.1). Important characteristics of different units as interpreted from the images and toposheets are given in Table 2.2.

Table 2.1 Major Landforms and Soil-Geomorphic Units

Landform	Soil-Geomorphic Unit	Abbreviations Used
Upland Areas		
	Lateritic Upland	LU
	Barind Tract	BT
Old Fluvial/Deltaic Plains		
	Bhagirathi-Brahmani Plain	BBP
	Brahmani-Ajay Plain	BAP
	Ajay-Silai Plain	ASP
	Damodar Terminal Fan	DTF
Young Fluvial Plains		
	Bhagirathi Plain	BP
	Old Ganga Plain	OGP
	Ganga Floodplain	GFP

Table 2.2 Characteristics of different soil-geomorphic units as interpreted from remotely sensed images.

Soil-geomorphic units	Physiography	Landsat (TM) FCC Image Characteristics
Barind Tract	High relief, dendritic drainage, imperfectly drained, courses of rivers incised in nature	Grayish brown with strong red mottles in some parts, fine to medium texture
Lateritic Upland	High relief with rolling topography, excessively drained, dendritic in general, annular in southern part, highly disected, valley cuts and fills	Reddish brown, smooth texture, dull red in forested parts
Bhagirathi-Brahmani Plain	Moderate relief, poorly drained, parallel and secondary dendritic	Light grey with fine texture and very faint red mottles
Brahmani-Ajay Plain	Moderate relief, poorly drained, parallel in general with secondary yazoo and dendritic	Light grey in general with fine txture, red mottles where moisture, drainage density high
Ajay-Silai Plain	Moderate to low relief, gently sloping, imperfectly drained, parallel with low to medium sinuosity streams	Light grey with fine texture, red mottles where moisture, drainage density high, paleochannels show uniform dark brown colour
Damodar Terminal Fan	Low relief, imperfectly drained, anastomosing drainage pattern	Uniform red colour with dark patches along distributaries
Bhagirathi Plain	Low relief, moderately drained, straight to meandering pattern, yazoo in some parts	Uniform red colour with a few bluish grey and dark grey patches, uniform dark grey in ox-bows and abandoned channels filled with water
Old Ganga Plain	Moderate to low relief, meandering pattern with numerous paleochannels, ox-bow lakes and meander scars, moderately well drained	Red and dark brown interwoven, dark grey in ox-bows and paleochannels
Ganga Floodplain	Low relief, meandering channels, ox-bow lakes, point bars	Bluish grey in general with red patches at places, bright white in sand deposits along active channels

2.3.1 Lateritic Upland

The Lateritic Upland is a dissected belt of laterites lying to the east of the Chotanagpur-Rajmaha highlands. The slope of this plain ranges from 1.2 to 1.8 m/km and it lies at the highest elevation (35 to 120 m) in the study area. This plain is characterized by reddish brown smooth texture and pittec appearance in FCCs. Drainage is coarse textured and floodplains are wider than those in the neighbouring highlands. Several patches of laterites are covered by forest. A great degree of dissectior is clearly observed in the field and in the images. In general, the region shows a dendritic pattern bu in the southern part (south of the Damodar River), an annular pattern is observed. A number of valley-fills, with active meandering streams are distinguished in the images and in the field. The valley-fills are characterized by a grayish white tone with medium texture.

The soils of the Lateritic Upland consist of two distinct units (i.e. the lower unit and the upper unit). The description of two typical profiles (Fig. 2.3 and 2.4 a,b) constituting the two units are as follows.

PEDON # LC1

Classification	: Typic Haplustalf
Location	: Ganpur canal cutting, 2.5 km from Mallarpur on Suri-Rampurhat road, Birbhum District
Date of examination	: 14-3-91
Parent material	: Sedimentary
Erosion	: Moderate to strong
Slope	: >5%
Drainage class	: Very well drained;
Moisture condition	: Dry
Depth of water table	: Not recorded
Physiography	: Undulating
Landuse	: Canal Bank
Climate	: Sub-tropical monsoonic

UPPER UNIT

Sub-unit	Hori-zon	Depth (cm)	
Gravelly Sand	C	0-45	Brown (7.5YR5/4) moist, sandy gravel intermixed with clay, many medium to coarse vesicular pores, slightly hard, firm, slightly plastic, very weakly cemented, a few fine roots, gravelly quartz embedded in the clayey sand matrix, abrupt boundary.

Lateritic	II B	45-220	Yellowish red (5YR5/7) when moist, prominent yellowish red (5YR5/6) mottles, Mudstone crumby and breaks into irregular pieces, many medium to coarse vesicular pores, moderately cemented in the ferruginous clay matrix, strong subangular blocky structure, slightly plastic and sticky, clay coatings, firm and slightly hard, sesquioxide coatings, many hard, rounded ferro-manganese concretions and angular lateritic pieces, abrupt smooth boundary.

LOWER UNIT

Sub-units	Hori-zon	Depth (cm)	
Laterite	$IIIBox_1$	220-300	Yellowish red (5YR5/7) moist, dominant medium to coarse prominent yellowish red (5YR5/6) mottles, crumby and breaks into irregular pieces, strong subangular blocky structure, many medium to coarse vesicular pores, firm, hard and indurated, strongly cemented with sesquioxide, many large hard irregular, ferro-manganese concretions embedded in ferruginous matrix, gradual smooth boundary.
Plinthite	$IIIBox_2$	300-340	Yellowish red (5YR5/7) moist, highly mottled with yellowish red (5YR5/6) colour mottles, vermicular with subangular blocky structure, firm, soft when fresh but hardens after exposure, strongly cemented with sesquioxide, hard irregular, ferro-manganese concretions embedded in kaolin, diffuse boundary.
Lithomarge	$IIIBox_3$	340-440	Reddish yellow (7.5YR6/7) moist, highly mottled with mottle colours varying from reddish yellow (7.5YR6/7) to yellow and light grey (7.5YR7/0), vermicular with subangular blocky structure, firm, soft, slightly plastic and sticky, small quartz grains (1-2 mm size) and rock fragments in the kaolinitic matrix, a few hard, irregular, ferro-manganese concretions of <2 mm size, clay coatings around concretions, calcareous nodules in the lower part.

PEDON # LB5

Classification	: Typic Haplustalf
Location	: 2 km east of Oregram from a moram quarry near Bhatar, Barddhaman District
Date of examination	: 25-3-91
Parent material	: Sedimentary
Erosion	: Moderate to strong
Slope	: $>5\%$
Drainage class	: Very well drained;
Moisture condition	: Dry
Depth of water table	: Not recorded
Physiography	: Undulating
Landuse	: Quarry
Climate	: Sub-tropical monsoonic

have incised natures. The Bansloi river which flows towards east in its upper reaches, takes a north easterly turn before meeting the Bhagirathi river. From the courses of all the major rivers defining the boundary of this unit it seems that the unit is bounded by faults from all the sides (Fig. 2.1 and Fig. 2.2). A typical soil profile (Fig. 2.5 b) of this unit is described as below.

PEDON # L12

Classification	: Vertic Haplaquept
Location	: Murarai; 100 m west of railway line, 100 m east of road to Rajgram; Birbhum District
Date of examination	: 20-4-90
Parent material	: Alluvium
Slope	: < 2 %
Drainage class	: Poorly drained
Moisture condition	: Dry
Depth of water table	: 6 m
Physiography	: Plain with gentle slopes
Landuse	: Paddy and gram
Climate	: Sub-tropical monsoonic
Remarks	: Hexagonal cracks 3-4 mm wide and vertical cracks of 1 cm width up to a depth of 40 cm

Hori-zon	Depth (cm)	
Ap	0-10	Dark brown (2.5Y4/3) dry, silt loam, strong massive, common fine prominent reddish yellow (7.5YR6/6) mottles, hard, firm, slightly plastic, very fine ktubular pores, many very fine roots, clear smooth boundary.
A1	10-22	Brown (2.5Y5/3) dry, loam, strongly developed medium subangular blocky, many medium prominent reddish yellow (7.5YR6/6) mottles, many fine tubular pores, very hard, firm, plastic, abundant very fine roots, clear smooth boundary.
B1	22-33	Olive brown (2.5Y4/4) dry, common medium distinct (7.5YR6/8) mottles, clay loam, strong coarse subangular blocky, very fine irregular pores, very hard, firm, plastic, many patchy thin clay cutans, very few very fine roots, gradual smooth boundary.
B21t	33-61	Olive brown (2.5Y4/4) dry, common medium distinct brownish yellow (10YR6/8) mottles, clay loam, strong coarse subangular blocky, many very fine irregular pores, very hard, firm, very plastic, patchy moderately thick clay cutans, very few very fine roots, diffuse smooth boundary.
B22t	61-118	Olive brown (2.5Y4/4) dry, clay loam, many medium distinct brownish yellow (10 YR 6/8) mottles, strong coarse subangular blocky, very hard, plastic, moderately thick clay cutans.
C1	18-130	Strong brown (7.5YR5/6) dry, sandy loam, many medium vesicles, soft very friable, nonplastic.

The soils of Bhagirathi-Brahmani Plain are poorly drained, fine cracking soils. The thickness of solum (A+B horizon) ranges from 110-120 cm. Vertical cracks of 3-4 mm width (Fig. 2.5a) extend up to a depth of 40 cm from the surface.

Thickness of A horizon varies from 20 to 25 cm. Soils of this horizon have dark brown to brownish gray colour in 2.5 Y hue with values 4 to 7 and chromas 2 to 3. The soils have moderately developed subangular blocky structures. Soils are hard to very hard when dry, firm when moist and sticky and plastic when wet. Semi-hard ferro-manganese concretions are common in these soils. These soils show a clear smooth boundary with the underlying horizons.

The thickness of B horizon varies from 85 to 100 cm. The soils are silty clay loam to clay in texture and have moderately developed structure. The colour varies from olive brown to dark grayish brown in hue 2.5 Y with values 4 to 7 and chromas 2 to 6. These soils are very hard, firm and plastic. Semi-hard ferro-manganese concretions of 2 to 3 mm size are quite common in the lower part of the horizon. Silty and patchy thin clay coatings and slickensided pressure faces are quite common.

2.3.4 Brahmani-Ajay Plain

This unit lies in the south of the Bhagirathi-Brahmani plain. The main rivers draining through this plain are the Ajay, Morakhi and Dwarka. The Ajay river meets Bhagirathi almost perpendicularly. The Dwaraka flows as a yazoo tributary of the Bhagirathi river in the eastern part of the plain due to the presence of a series of natural levees along the course of the Bhagirathi. As observed in the images (Fig. 2.1), the Ajay and Morakhi rivers appear to have shifted southward from their previous course within their floodplains. In the FCC a number of paleochannels are observed on the northern side of both the rivers. Two typical profiles of this plain are described below.

PEDON # LC2

Classification	: Vertic Haplaquept
Location	: Between Khargram and Kanduri; 300 m northwest of Khargram, 300 m southeast of Kanduri; 100 m north of Khargram-Aroali road, Murshidabad District
Date of examination	: 15-3-91

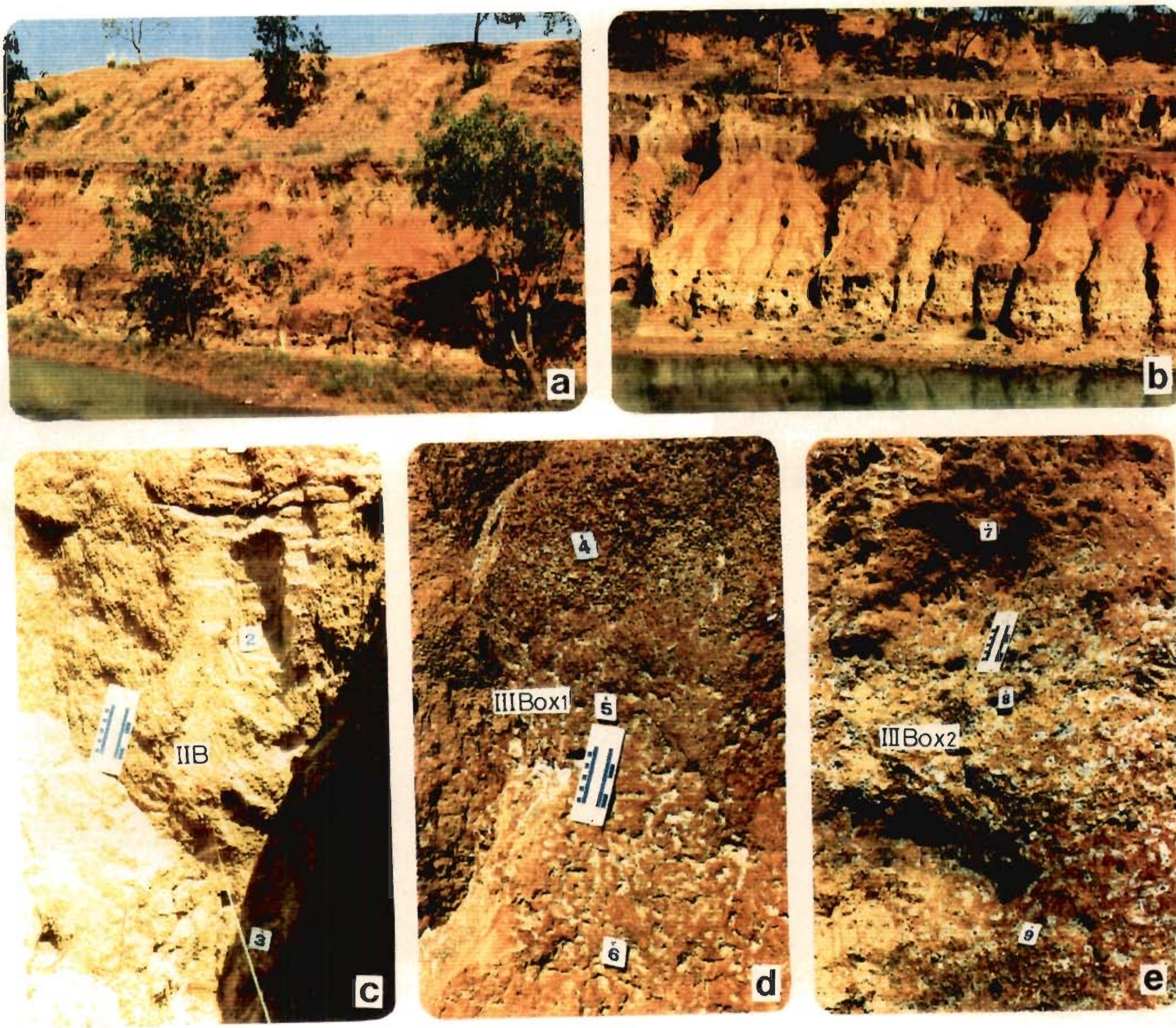

Fig. 2.3 Photographs showing (a) and (b) Field view of laterite, (c) Laterite Mudstone, (d) Laterite Crust and (e) Plinthite from a typical pedon (LC1) from the Lateritic Upland.

UPPER UNIT

Sub-unit	Hori-zon	Depth (cm)	
Gravelly Sand	C	0-37	Brown (7.5YR5/4) moist, sandy gravel intermixed with clay, few fine faint mottles, structureless, many medium to coarse vesicular pores, slightly hard, firm, slightly plastic, common medium roots, a few rounded hard black and red ferro-manganese concretions (<2 mm) and pieces of laterites, abrupt smooth boundary.

LOWER UNIT

Laterite Crust (1)	$IIBox_1$	37-150	Light grey (7.5YR7/0) dry, common coarse prominent red (10R4/6) mottles, many medium to coarse vesicular pores, slightly hard, firm, slightly plastic, strongly cemented, a some quartz grains (1-2 mm size) embedded in the matrix, many hard black and red ferro-manganese concretions (<2 mm), abrupt smooth boundary.
Laterite Crust (2)	$IIBox_2$	150-320	Red (10R4/8), with some light grey (7.5YR7/0) patches, crumby and breaks into irregularpieces, irregularly mottled, many medium to coarse vesicular pores, hard and indurated, firm, plastic, strongly cemented, small quartz grains (1-2 mm size) embedded in the ferruginous matrix, many hard irregular black and red ferro-manganese concretions (<2 mm), clay coatings around concretions, gradual smooth boundary.
Lithomarge	$IIBox_3$	320-360	Varying colours of red (10R4/8), reddish brown (2.5YR4/8) and yellow (10YR7/6), many medium to coarse vesicular pores, soft, plastic, small quartz grains (1-2 mm size) embedded in the kaolinitic matrix, a few hard irregular ferro-manganese concretions (<2 mm), clay coatings around concretions.

The lower unit starts with a lithomarge at the base and grades upwards into plinthite and pisolitic lateritic crust. Its thickness varies from 200 to 300 cm at different locations. The soils of lower unit are yellowish red (5YR5/7) to red (10R4/8) colour. At places light grey colour (7.5YR7/0) are also observed. They are highly mottled and the mottle colours vary from red (10R4/6), yellowish red (5YR5/6) to light grey (7.5YR7/0). The lateritic crust is crumby and breaks into irregular pieces. They are strongly indurated with iron oxide. They are hard when dry, firm when moist and slightly plastic and sticky when wet. Continuous sesquioxide coatings are common. Quartz grains and large, hard, irregular, ferro-manganese concretions are strongly cemented with sesquioxide matrix. The plinthite lying below the lateritic crust is soft when fresh but hardens on exposure. the lithomarge is mottled and has a vermicular subangular blocky structure. It is sticky, firm, hardens on exposure but crumbles on wetting or under pressure. It consists of kaolinitic clay with iron-rich accumulations. Rock fragments embedded in the matrix are also observed occasionally. Further below, calcrete nodules embedded in the clay matrix are frequently observed.

The upper layer with a maximum thickness of 50 to 200 cm is comprised of gravelly sand at the top and underlain by a lateritic mudstone (Fig. 2.3). The lateritic mudstone consists of pieces of laterites bound by a fine-grained ferruginous clay matrix and are seen only on the lower slopes of the Lateritic Upland unit. They have sharp boundary against the lower unit. At the places where lateritic mudstone is not present, the gravelly sand directly overlies the lower unit (Fig. 2.4 b).

2.3.2 Barind Tract

The Barind Tract is an uplifted region in the northern part of the study area. A number of Himalayan rivers flowing southwards cut across this tract and divide it into four units trending almost N-S. At least three topographic levels with their height varying from 5 to 20 m can be recognized on this tract, with degree of soil development decreasing from highest to lowest levels (Hossain, 1994). The major portion of the tract falls in Bangladesh. In the study area mainly the lowest level is present and has been studied. In general, the river beds of the tract are well below the level of surrounding country. Descriptions of two typical soil profiles (Fig. 2.4 c, d) of this unit are as follows.

PEDON # LA1

Classification	: Fluventic Ustochrept
Location	: Brick-pit in Ramkrishnapalli village, Malda
Date of examination	: 29-2-91
Parent material	: Alluvium
Erosion	: Moderate to strong
Slope	: $< 1\%$
Drainage class	: Imperfectly drained; rain water stagnates for a month
Moisture condition	: Moist
Depth of water table	: 10 m
Physiography	: Moderately undulating land having elevation range of 50 m to 100 m
Landuse	: Paddy
Climate	: Sub-tropical monsoonic

Hori-zon	Depth (cm)	
Ap	0-26	Light Brownish gray (2.5Y6/2) moist, sandy loam weakly developed subangular blocky, slightly hard (dry), many fine tubular pores, abundant medium roots, abrupt smooth boundary.
B1	26-52	Gray (5Y5/1) moist, loam, moderately developed medium subangular blocky, many fine tubular pores, firm(moist), plastic(wet), strongly cemented, abundant fine roots, about 5% ferro-manganese concretions of 2 mm size, gradual smooth boundary,
B21	52-72	Olive (5Y5/4) moist, few fine faint mottles, silty loam, moderately developed medium subangular blocky,many cutans, many fine roots, gradual smooth boundary, moderate lime effervescence.
B22	72-103	Olive gray (5Y5/2) moist, few fine faint mottles, silty clay loam, moderately developed medium subangular blocky, many very fine tubular pores, very firm (moist), plastic (wet), strongly cemented,few thin clay cutans, many fine roots, gradual smooth boundary, moderate lime effervescence, many Fe-Mn concretions of 3 mm size.
C1	103-144	Dark grayish brown (2.5Y4/2) moist, few fine faint mottles, silty loam, moderately developed medium plastic(wet), strongly cemented, few thin clay cutans, common fine roots, clear smooth boundary, many Fe-Mn concretions of 3 mm size.
C2	144-167	Grayish brown (2.5Y5/2) moist, few fine faint mottles of red colour (2.5Y5/8), silty loam, moderately developed medium subangular blocky, many very fine tubular pores, firm (moist), plastic (wet), strongly cemented, few thin clay cutans, common fine roots, gradual smooth boundary, many Fe-Mn concretions of 1 mm size.

PEDON # L1

Classification	: Fluventic Ustochrept
Location	: Jalanga; 60 m west of National Highway-34; 0.5 km south of BSF Camp, Malda
Date of examination	: 09-11-91
Parent material	: Old Alluvium
Erosion	: Moderate
Slope	: < 1 %
Drainage class	: Imperfectly drained
Moisture condition	: Moist
Depth of water table	: 10 m
Physiography	: Plain
Landuse	: Paddy
Climate	: Sub-tropical monsoonic

Hori-zon	Depth (cm)	
Ap	0-15	Grayish brown (2.5Y5/2) moist, silty loam, weakly developed subangular blocky, firm (moist), many fine tubular pores, abundant fine roots, clear smooth boundary.

A1	15-35	Grayish brown (2.5Y5/2) moist, silty loam, weakly developed coarse subangular blocky, many fine tubular pores, firm (moist), slightly plastic (wet), common medium faint mottles, common fine roots, gradual smooth boundary.
B1	35-65	Gray (5Y5/1) moist, few fine faint mottles, silty loam, moderately developed medium subangular blocky, many very fine tubular pores, firm (moist), slightly plastic (wet), patchy thin clay cutans, many fine roots, gradual smooth boundary.
B2	65-92	Grayish brown (2.5Y5/2) moist, few fine faint mottles, silt loam, moderately developed medium subangular blocky, many very fine tubular pores, firm (moist), plastic (wet), patchy thin clay cutans, common very fine roots, gradual smooth boundary
C1	92-120	Grayish brown (2.5Y5/2) moist, few fine faint mottles, silt, weakly developed subangular blocky, common very fine tubular pores, firm (moist), plastic (wet), patchy thin clay cutans, common fine roots, clear smooth boundary.

The soils of this unit are in general medium textured silt loam. The solum (A + B horizon) thickness ranges from 100 cm to 110 cm. The colour of soils of A horizon varies from grayish brown to light brownish gray in hue 2.5 Y with values 5 to 6 and chromas 2 and less. The texture ranges from sandy loam to silt loam with puddled to weak subangular blocky structure. They are usually firm when moist and slightly sticky and plastic when wet. The boundary between A and B horizon is clear smooth to gradual smooth.

The thickness of B horizon ranges from 60-80 cm. The colour of soils of this horizon ranges from olive gray to grayish brown in 2.5 Y to 5 Y hue with value 5 and chromas 2 to 4. Their texture varies from silt loam to silty clay loam and structure from weak to moderate subangular blocky. Silt coatings are observed in these horizons. Soils of this horizon are variably mottled with mottles of red (2.5 YR 5/8) colour. Ferro-manganese concretions are present throughout the B horizon. Traces of lime concretions are observed in a few pedons. The B horizon grades into the C horizon which has a grayish brown to dark grayish brown colour in 2.5 Y hue with value 4 to 5 and chroma 2. Small (less than 1 mm) ferro-manganese nodules are common.

2.3.3 Bhagirathi-Brahmani Plain

This soil-geomorphic unit lies to the east of the Lateritic Upland (Fig. 2.2). The major rivers of this plain are the Bhagirathi,Brahmani, Dwarka and Bansloi. The Bhagirathi and Brahmani rivers

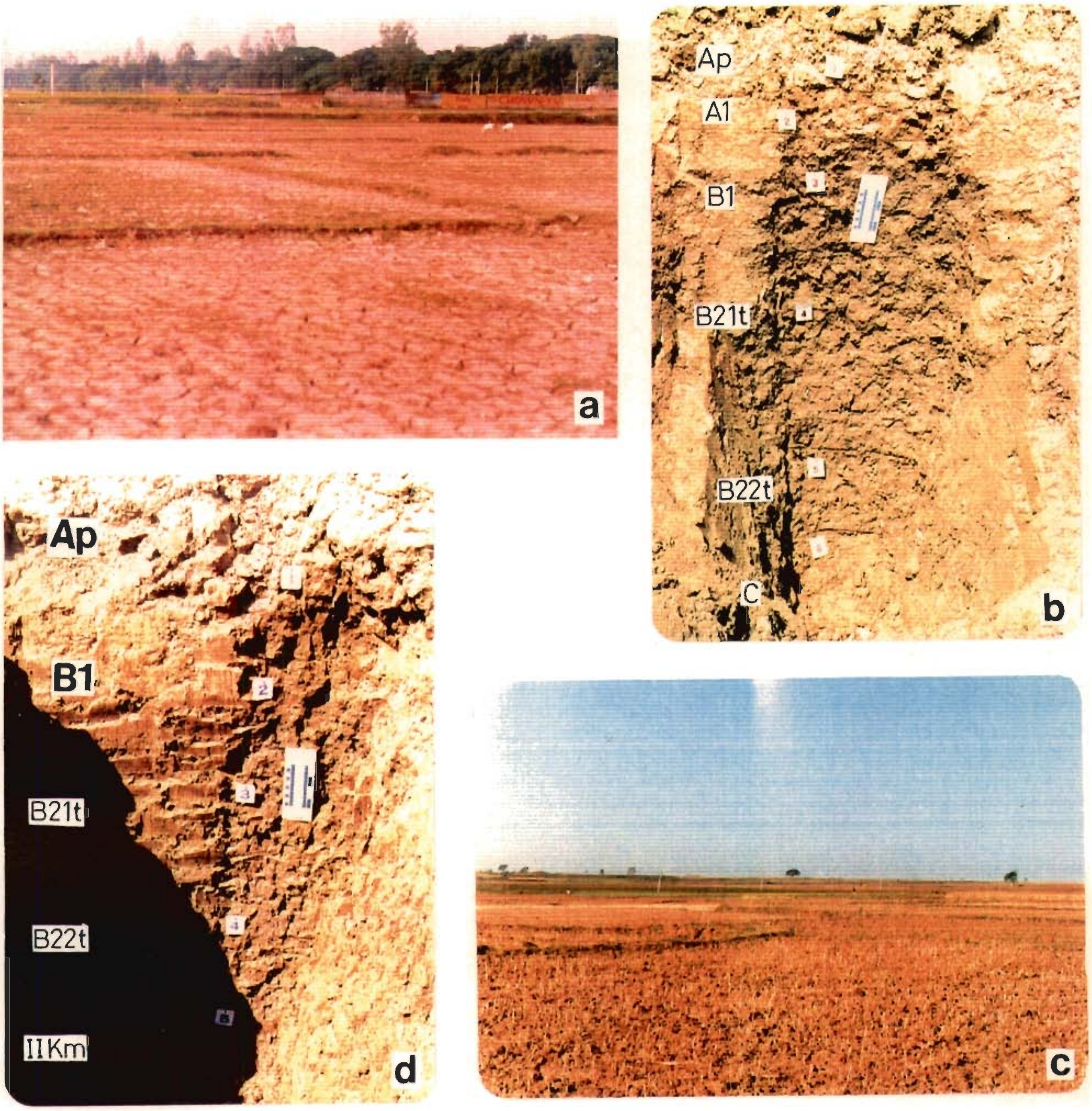

Fig. 2.5 Photographs showing (a) Field view and (b) A typical pedon (L12) from poorly drained soil of the Bhagirathi-Brahmani Plain; (c) Field view and (d) A typical pedon (LC4) with a buried petrocalcic horizon (II Km) from the Brahmani-Ajay Plain showing calcrete nodules (white patches).

Parent material	: Alluvium
Slope	: 2 %
Drainage class	: Imperfectly drained
Moisture condition	: Dry
Depth of water table	: 10 m
Physiography	: Plain with minor undulations
Landuse	: Paddy and mustard
Climate	: Sub-tropical monsoonic
Remarks	: Profile location is at the highest level of the area.

Horizon	Depth (cm)	
Ap	0-20	Light gray (2.5Y7/2) dry, silt loam, common fine distinct reddish yellow (7.5YR6/8) mottles, loose, nonplastic, many very fine tubular pores, abundant very fine roots, clear smooth boundary, iron stains along root channels.
A1	20-29	Grayish brown (2.5Y5/2) dry, silt loam, weak medium subangular blocky, many medium prominent reddish yellow (7.5YR6/8) mottles, many very fine tubular pores, very hard, firm, plastic, abundant very fine roots, gradual smooth boundary, a few ferro-manganese concretions, white silty specks.
B1	29-44	Light gray (10 YR7/1) dry, abundant medium prominent reddish yellow (7.5YR6/8) mottles, loam, strong coarse subangular blocky, very fine irregular pores, very hard, firm, plastic, patchy thin clay cutans, few very fine roots, gradual smooth boundary, ferro-manganese concretions more prominent than in A1, silty coating.
B21t	44-58	Light brownish gray (2.5Y6/2) dry, common medium distinct strong brown (7.5YR5/6) mottles, silt loam, strong coarse subangular blocky, common very fine tubular pores, very hard, firm, very plastic, patchy thin clay cutans along pores, common very few very fine roots, gradual smooth boundary, concretions 1-3 mm in size are very common, prismatic columns of silt/clay.
B22t	58-85	Light brownish gray (2.5Y6/2) dry, clay loam, many medium distinct strong brown (7.5YR5/6) mottles, strong coarse subangular blocky, extremely firm very plastic, common very fine tubular pores, few very fine roots, diffuse smooth boundary, often breaks along plain which consists mainly of clay/silty material, ferro-manganese concretions (1-2 mm) common.
B23t	85-104	Light brownish gray (2.5Y6/2) dry, clay loam, common medium distinct brownish yellow (10YR6/6) mottles, strong coarse subangular blocky, common very fine tubular pores, extremely firm, very plastic, continuous thin clay cutans, diffuse smooth boundary, silty/clayey coatings along ped surfaces very common.
B3	104-140	Light brownish gray (2.5Y6/2) dry,clay loam, common medium distinct brownish yellow (10YR6/6) mottles, strong coarse subangular blocky, common very fine tubular pores, extremely firm very plastic, common thin clay cutans.
C	140-160	Light yellowish brown (2.5 Y6/4) dry, clay loam, medium distinct brownish yellow (10YR6/6) mottles, massive, extremely firm and very plastic.

PEDON # LC4

Classification	: Vertic Haplaquept
Location	: Khorsha, 0.5 Km west of Kandi, 100 m south of Kandi-Kulee road
Date of examination	: 15-3-91
Parent material	: Alluvium
Slope	: 2 %
Drainage class	: Imperfectly drained
Moisture condition	: Dry
Depth of water table	: 2 m
Physiography	: Plain with minor undulations
Landuse	: Paddy and mustard
Climate	: Sub-tropical monsoonic

Hori-zon	Depth (cm)	
Ap	0-20	Light yellowish brown (2.5Y6/4) dry, silt loam, common medium distinct reddish yellow (7.5YR6/8) mottles, strong coarse massive, common very fine tubular pores, very hard plastic, common fine roots, a few ferro-manganese concretions, clear smooth boundary.
B1	20-58	Light yellowish brown (2.5Y6/4) dry, silt loam, weak moderate subangular blocky, common medium distinct strong brown (7.5YR5/6) mottles, common very fine tubular pores, slightly hard, slightly plastic, common fine roots, gradual smooth boundary, ferro-manganese concretions common.
B21t	58-82	Olive (5Y5/3) dry, common medium distinct yellowish brown (10YR5/6) mottles,clay loam,strong coarse subangular blocky,common very fine tubular pores, very hard, very plastic, patchy thin clay cutans, few fine roots, diffuse smooth boundary, ferro-manganese concretions common.
B22t	82-113	Olive (5Y5/3) dry,few fine faint yellowish brown mottles, clay loam, strong coarse subangular blocky, common very fine tubular pores, very hard, very plastic, continuous thin clay cutans, diffuse smooth boundary.
IIKm	113-150	Pale olive (5Y6/4) dry, loam, few fine faint mottles, strong coarse subangular blocky, few very fine tubular pores extremely hard, ferro-manganese concretions, lower part is strongly cemented and contains many hard calcareous nodules of various size (i.e. 2 mm to 3 cm).

The soils of the Brahmani-Ajay Plain occur on nearly level to very gently sloping lands with less than 2 percent slopes. The thickness of the solum (A + B horizon) ranges from 120 to 140 cm. Vertical cracks of 3-4 mm width extend up to a depth of 25-30 cm from the surface.

The thickness of A horizon varies from 30 to 35 cm. The colour of soils of this horizon varies from light gray to grayish brown in 2.5 Y hue with values 5 to 7 and chroma 2. Soils are hard when dry, firm when moist, and sticky and plastic when wet. They have silt loam texture. Few semi-hard ferro-manganese concretions are present. They show a clear smooth boundary with the underlying horizons.

The thickness of the B horizon varies generally from 90 cm to more than 110 cm. The soils of this horizon have loam to silty clay loam textures and moderately developed subangular blocky structures. Their colour varies from light gray to light brownish gray in hue 2.5 Y with value 6 and chromas 1 to 2. They have prominent yellowish brown (10YR6/6) to strong brown (7.5YR5/6) mottles. Soils are hard to very hard when dry, firm when moist and sticky and plastic to very plastic when wet. Small hard to semi-hard ferro-manganese concretions, clay and silt coatings and slickensided pressure faces are common in these soils.

Calcrete nodules of various sizes (2 mm to 2 cm) are observed in the II Km horizon of pedon # LC4 (Fig. 2.5 d).

2.3.5 Ajay-Silai Plain

This plain lies to the south of the Brahmani-Ajay Plain. Most of the rivers of this unit have medium to low sinuosity except the Damodar, which has a fairly straight channel. Striking feature of the region between the Damodar and Silai rivers is the stream pattern. The Damodar river flowing in an easterly direction takes a sharp turn of 90° and acquires an almost north-south course with low sinuosity. The north-south course of the Damodar river limits the extent of the plain in the east. The Dwarkeshwar, Silai and Kasai rivers show annular pattern. Some typical profiles (Fig. 2.6) of this unit are described as below.

PEDON # LB1

Classification	: Vertic Haplaquept
Location	: 200 m southeast of Kullugarh village from a shallow well, 100 m north of road to Manteshwar; Bardhaman District
Date of examination	: 3-3-91
Parent material	: Alluvium
Slope	: 1 %
Drainage class	: Imperfectly drained

Moisture condition : Dry
Depth of water table : 7 m
Physiography : Plain
Landuse : Paddy
Climate : Sub-tropical monsoonic
Remarks : Ferro-manganese concretions are present throughout the profile; cracks during summer

Hori-zon	Depth (cm)	
Ap	0-20	Gray (7.5YR6/0) dry, clay loam, paddled, common medium prominent strong brown (7.5YR5/8) mottles, many fine tubular pores, slightly hard, sticky, abundant fine roots, clear smooth boundary, brown colour stains along root channels.
B1	20-36	Gray (5Y6.5/1) dry, clay loam, common medium prominent strong brown (7.5YR5/8) mottles, moderate fine subangular blocky, many medium tubular pores, hard, firm, plastic, abundant fine roots, abrupt strong lime effervescence, ferro-manganese concretions (2 mm size) and calcrete nodules of a few mm to 1.5 cm size.
B21t	36-58	Gray (5Y6/1) moist, common medium distinct mottles, silty clay loam, moderate medium subangular blocky, common fine tubular pores, hard, plastic, common moderately thick clay cutans, abundant fine roots, gradual smooth boundary.
B22t	58-87	Gray (5Y6/1) moist, clay loam, few fine faint mottles, moderate medium subangular blocky, common fine tubular pores, firm, plastic, common moderately thick clay cutans, gradual smooth boundary, ferro-manganese concretions (< 2 mm size) common.
B23	87-127	Gray (5Y6/1) moist, clay, few fine faint mottles, moderate medium subangular blocky, few very fine tubular pores, very firm, very plastic, continuous thick clay cutans, ferro-manganese concretions (< 2 mm size) common.
C	127-150	Gray (5Y6/1) moist, silt loam, few fine faint mottles, weak to moderate medium subangular blocky, firm, plastic.

PEDON # LB2

Classification : Vertic Ochraqualf
Location : Kharpur, 50 m west of Maldanga-Bhatar road; Bardhaman District
Date of examination : 3-3-91
Parent material : Alluvium
Slope : 1 %
Drainage class : Imperfectly drained
Moisture condition : Dry
Depth of water table : 7 m
Physiography : Plain
Landuse : Paddy, Potato
Climate : Sub-tropical monsoonic

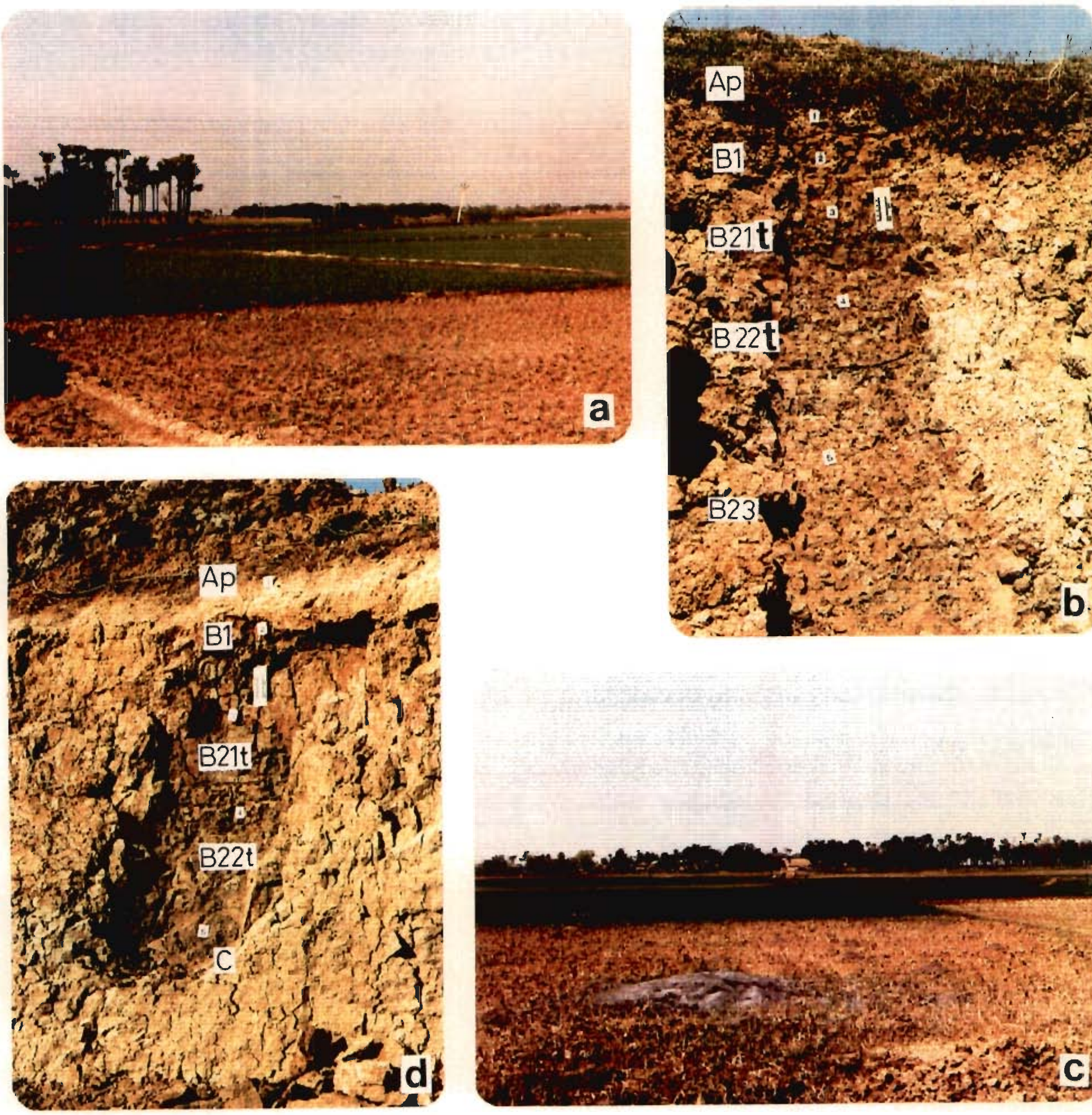

Fig. 2.6 Photographs showing (a) Field view and (b) A typical pedon (LB1) from the Ajay-Silai Plain; (c) Field view and (d) A pedon (LB2) from the same unit showing vertical cracks.

Hori-zon	Depth (cm)	
Ap	0-18	Light gray (10YR7/1) moist, silt loam, many fine tubular pores, soft, abundant fine roots, abrupt smooth boundary.
B1	18-34	White (10YR8/2) dry, silt loam, common medium prominent yellow (10YR7/8) mottles, moderate medium subangular blocky, many fine tubular pores, soft, abundant fine roots, a few ferro-manganese concretions (2 mm size).
B21t	34-88	Light brownish gray (2.5Y6/2) moist, abundant medium distinct mottles, clay loam, moderate medium to coarse subangular blocky, common fine tubular pores, firm, very plastic, patchy thin clay cutans, many ferro-manganese concretions (2 mm size) gradual smooth boundary.
B22t	88-126	Gray (5Y6/1) moist, clay common medium distinct olive brown (2.5Y5/4) mottles, moderate medium subangular blocky, many very fine tubular pores, firm, very plastic, patchy moderately thick clay cutans, gradual smooth boundary, ferro-manganese concretions (< 2 mm size) many.
C	126+	Gray (5Y6/1) moist, silt loam, few fine distinct olive brown (2.5Y5/4) mottles, moderate medium subangular blocky, many very fine tubular pores, firm, plastic, ferro-manganese concretions (< 2 mm size) common similar to that in the overlying horizon.

PEDON # LB 11

Classification	: Vertic Haplaquept
Location	: 200 m west of Sehara Bazar, 500 m south railway line to Sahaspur road; Barddhaman District.
Date of examination	: 10-3-91
Parent material	: Alluvium
Slope	: <2 %
Drainage class	: poorly drained
Moisture condition	: Moist
Depth of water table	: 6 m
Physiography	: Plain with gentle slope
Landuse	: Paddy, Potato, mustard
Climate	: Sub-tropical monsoonic
Remarks	: cracks are present up to 25 cm depth.

Hori-zon	Depth (cm)	
Ap	0-20	Olive gray (5Y5/2) moist, clay, few fine distinct dark brown (7.5 YR4/4) mottles, weak medium subangular blocky, many fine tubular pores, firm, plastic, abundant medium to fine roots, some ferro-manganese concretions (<2 mm), abrupt smooth boundary.
A1	20-38	Olive gray (5Y5/2) moist, silty clay loam, few medium distinct dark brown (7.5 YR4/4) mottles, moderate medium subangular blocky, many very fine tubular pores, firm, plastic, abundant medium to fine roots, some ferro-manganese concretions (<2 mm), silt grains of gray colour along ped surfaces, clear smooth boundary.

B1	38-57	Light brownish gray (2.5Y6/2) moist, clay, common medium distinct dark brown (7.5 YR4/4) mottles, moderate medium to coarse subangular blocky, common very fine tubular pores, extremely firm, very plastic, few fine roots, very common ferro- manganese concretions (2-3 mm), gradual smooth boundary.
B21t	57-83	Light brownish gray (2.5Y6/2) moist, silty clay, common medium prominent strong brown (7.5 YR5/6) mottles, moderate medium subangular blocky, common very fine tubular pores, firm, very plastic, patchy thin clay cutans, very few very fine roots, few ferro-manganese concretions (2-3 mm), gradual smooth boundary.
B22t	83-117	Light brownish gray (2.5Y6/2) moist, clay, few fine faint mottles, moderate medium subangular blocky, common very fine tubular pores, extremely firm, very plastic, many fine to coarse hard and semi-hard ferro-manganese concretions, diffuse smooth boundary.
C	117-151	Gray (2.5Y6/0) wet, clay, few fine faint mottles, moderate medium subangular blocky, common very fine tubular pores, extremely firm, very plastic, many fine to coarse hard and semi-hard ferro- manganese concretions.

PEDON # LD1

Classification	: Vertic Haplaquept
Location road	: Uttar Balrampur, 100 m east of Goghat Registry office near Arambagh-Kamarpukur, Hooghly District.
Date of examination	: 8-3-91
Parent material	: Alluvium
Slope	: <1 %
Drainage class	: Imperfectly drained
Moisture condition	: Moist
Depth of water table	: 7 m
Physiography	: Plain with some undulations
Landuse	: Paddy, potato and mustard
Climate	: Sub-tropical monsoonic

Hori-zon	Depth (cm)	
Ap	0-14	Light gray (7.5YR7/0) dry, loam, common medium distinct reddish yellow (7.5YR7/8) mottles, structureless, many fine tubular pores, loose non plastic, abundant very fine roots, abrupt smooth boundary.
A1	14-29	Light gray (7.5YR7/0) dry, sandy loam, common fine distinct reddish yellow (7.5YR7/8) mottles, structureless, many fine tubular pores, loose non plastic, many very fine roots, gradual smooth boundary.
B	129-52	Light brownish gray (2.5Y6/2) dry, loam, many medium distinct dark brown (7.5YR4/4) mottles, weak medium subangular blocky, many very fine tubular pores, firm slightly plastic, many fine roots, clay coatings along ped faces, a few medium (2 mm) size ferro-manganese concretions, diffuse smooth boundary.
B21t	52-99	Light brownish gray (2.5Y6/2) moist, loam, many medium prominent reddish yellow (7.5YR6/8) mottles, moderate medium subangular blocky, common very fine tubular pores, firm slightly plastic, many fine roots, clay coatings along ped faces, common medium (2-4 mm) size ferro-manganese concretions, diffuse smooth boundary.

B22t 99-120 Light brownish gray (2.5Y6/2) moist, loam, many medium prominent reddish yellow (7.5YR6/8) mottles, moderate medium subangular blocky, common very fine tubular pores, firm slightly plastic, common fine roots, clay coatings along ped faces more common, common medium (2-4 mm) size ferro- manganese concretions, diffuse smooth boundary.

C 120-198+ Light yellowish brown gray (2.5Y6/4) moist, sandy loam, many medium prominent reddish yellow (7.5YR6/8) mottles, moderate medium subangular blocky, common very fine tubular pores, nonplastic, common fine roots.

Soils of this geomorphic unit are moderately developed. The solum thickness ranges from 100 to 140 cm. The A horizon is silt loam to clay loam and its thickness ranges from 15 to 30 cm and rarely up to 40 cm. The colour of this horizon varies from light gray to olive gray in 2.5Y to 5Y hues with values 5 to 7 and chromas 0 to 2. The structure is weak to moderate subangular blocky. A few semi-hard ferro-manganese concretions of less than 2 mm size are present in these soils. Iron stains are present along the root channels. The boundary between A and B horizon is clear and smooth.

The thickness of the B horizon varies from 80 to 110 cm. The soils of this horizon show gray to light brownish gray colours in 2.5Y to 5Y hue with values 5 to 6 and chromas 2 or less. Their texture vary from silty clay to clay loam and they show moderately developed medium subangular to angular blocky structures. Clay coatings and ferro-manganese concretions are common. Some patchy thin silt/clay accumulations are seen along the pores. Distinct mottles of strong brown to olive brown colour are present. Soils are hard when dry, firm when moist and plastic to very plastic when wet. The B horizon grades into the C horizon.

2.3.6 Damodar Terminal Fan

It is a low gradient fan dominated by low sinuosity streams confined between the Damodar river in the west and the Hooghly river in the east. Its maximum N-S extent is about 70 km and maximum E-W extent is about 40 km. The fan tapers down towards south (Fig. 2.1). The fan is characterized by a network of abandoned channels and natural levees of the ancient Damodar and swamps. A number of distributary channels, chute cut offs and anastomosing paleodrainage pattern are observed in the FCC of the area. The Damodar river has a braided channel in its upper reaches and acquires a low sinuosity after entering the fan. The fan may be called a "Terminal Fan" as it forms at the terminal stage of the river. The field characteristics of some typical pedons of this unit described below.

PEDON # LB3

Classification	: Aeric Haplaquept
Location	: 3 km south of Debipur from Birsimul village, south of GT Road; Bardhaman District
Date of examination	: 4-3-91
Parent material	: Alluvium
Slope	: <1 %
Drainage class	: Imperfectly drained
Moisture condition	: Moist
Depth of water table	: 0-3 m
Physiography	: Plain
Landuse	: Paddy, Potato
Climate	: Sub-tropical monsoonic
Remarks	: Hydromorphic soil with gleyed horizon, the profile remains saturated for some period every year due to presence of high water table

Hori-zon	Depth (cm)	
Ap	0-12	Light brownish gray (2.5Y6/2) moist, loam, apedal, many medium tubular pores, hard, loose, friable, abundant medium roots, abrupt smooth boundary.
A1	12-23	Light brownish gray (2.5Y6/2) moist, loam, apedal massive, many medium tubular pores, loose, friable, common medium roots, abrupt smooth boundary, ferro-manganese concretions common.
B1	23-33	Light brownish gray (2.5Y6/2) moist, loam, common medium distinct strong brown (7.5YR5/6) mottles, massive, many medium tubular pores, soft, friable, patchy thin clay cutans, common fine roots, gradual smooth boundary, ferro-manganese concretions common, silty material along root channels.
B21g	33-70	Light brownish gray (2.5Y6/2) moist, silt loam, massive, many fine distinct strong brown (7.5YR5/6) mottles, many fine tubular pores, firm, slightly plastic, common fine roots, ferro-manganese concretions more common as compared to B1, gradual smooth boundary, gray colour gleyans.
B22g	70-93	Light brownish gray (2.5 Y6/2) moist, loam, massive, many fine distinct strong brown (7.5YR5/6) mottles, many fine tubular pores, loose, friable, common fine roots, ferro-manganese concretions common, gradual smooth boundary, gray colour gleyans.
C	93-120+	Gray, moist, sandy loam, massive, loose, friable.

PEDON # LB4

Classification	: Aeric Haplaquept
Location	: Tinagram, 3 km west of Pandua, 200 m north of GT Road ; Hooghly District

Date of examination	: 4-3-91
Parent material	: Alluvium
Slope	: <1 %
Drainage class	: Imperfectly drained
Moisture condition	: Moist
Depth of water table	: 0-3 m
Physiography	: Plain
Landuse	: Paddy, Potato
Climate	: Sub-tropical monsoonic
Remarks	: Hydromorphic soil with gleyed horizons;

Hori-zon	Depth (cm)	
Ap	0-17	Light brownish gray (2.5Y6/2) moist, loam, massive, many medium tubular pores, very friable,abundant medium roots, gradual smooth boundary.
A1	17-31	Light brownish gray (2.5Y6/2) moist,silt loam, many medium distinct strong brown (7.5YR5/8) mottles, weak subangular blocky, many medium tubular pores, slightly hard, friable, many medium roots, diffuse smooth boundary, a few ferro- manganese concretions.
B1	31-47	Gray (5Y5/1) moist, silty clay loam, common medium distinct yellowish red (7.5YR6/8) mottles, strong subangular blocky, many medium tubular pores, hard, firm, plastic, patchy thin clay cutans, few fine roots, ferro-manganese concretions (2 mm size) common, gradual smooth boundary.
B21g	47-72	Light brownish gray (2.5 Y6/2) moist, silty clay loam, many medium prominent yellowish red (5YR5/6) mottles, weak to moderate subangular blocky, many fine tubular pores, hard,firm, plastic, continuous moderately thick clay cutans, very few fine roots, ferro-manganese concretions (2-5 mm size) more common than in B1, gradual smooth boundary, gleyans common.
B22g	72-98	Light brownish gray (2.5Y6/2) moist, loam, many medium prominent yellowish red (5YR5/6) mottles, moderate subangular blocky, many fine tubular pores, slightly hard, firm, plastic, no roots, ferro-manganese concretions less common, gradual smooth boundary, gleyans common.
C	98-120+	Grayish brown (2.5Y5/2), moist, loam, common medium distinct yellowish red (5YR5/6) mottles, apedal, soft, very friable, no concretions.

PEDON # LD3

Classification	: Aeric Haplaquept
Location	: 200 m south of Haripal railway station in Chak Chandinagar village; 13 km from Tarkeshwar on Tarkeshwar-Sheoraphuli Rail route; Hooghly District
Date of examination	: 9-3-91
Parent material	: Alluvium
Slope	: <1 %
Drainage class	: Imperfectly drained
Moisture condition	: Moist
Depth of water table	: 1-3 m
Physiography	: Plain
Landuse	: Paddy, Potato

Climate : Sub-tropical monsoonic
Remarks : Hydromorphic soil

Hori-zon	Depth (cm)	
Ap	0-20	Light brownish gray (2.5Y6/2) dry, silt loam, few fine faint mottles, weak medium granular, many fine tubular pores, hard, slightly plastic, abundant medium roots, abrupt smooth boundary.
A1	20-40	Light brownish gray (2.5Y6/2) dry, silt, common fine distinct mottles, weak, granular, many fine tubular pores, hard, slightly plastic, abundant fine roots, animal activity, gradual smooth boundary.
B1	40-61	Light gryish brown (2.5Y6/4) dry,silt loam, common faint mottles, weak medium granular, many fine tubular pores, slightly hard, slightly plastic, patchy thin clay cutans, abundant fine roots, gradual smooth boundary.
B21g	61-80	Light graish brown (2.5Y6/4) moist, silt loam, many fine distinct mottles, weak medium granular, many fine tubular pores, slightly hard, slightly plastic, moderately thick clay cutans, gleyans common, many fine roots, gradual smooth boundary.
B22g	80-94	Light grayish brown (2.5Y6/4) moist, silty clay loam, weak medium granular, many medium prominent dark reddish brown (5YR3/3) mottles, abundant fine tubular pores, slightly hard, firm, slightly plastic, continuous moderately thick clay cutans, common fine roots, ferro- manganese concretions less common, clear smooth boundary, gleyed horizon.
C1	94-117	Very dark grayish brown (2.5Y3/2), moist, silt loam, many medium distinct reddish yellow (7.5YR6/8) mottles, weak medium granular, common fine tubular pores, firm slightly plastic, continuously moderately thick cutans, few very fine roots, gradual smooth boundary.
C2	117-151	Dark grayish brown (2.5Y4/2), moist, silt loam, many medium distinct reddish yellow (7.5YR6/8) mottles, weak medium subangular blocky, common fine tubular pores, friable nonplastic, no roots.

Soils of this unit are weakly to moderately developed (Fig. 2.7) and show hydromorphic conditions as they remain saturated with water for some period every year. The thickness of solum varies from 90 to 100 cm. The soils of A horizon have light brownish gray (2.5Y6/2) to light yellowish brown (2.5Y 6/4) colours and distinct strong brown (7.5YR5/8) mottles. They have silty loam to loamy texture. A few small (<2 mm) soft ferro-manganese nodules are present. Animal activity is quite common.

The thickness of B horizon varies from 55 to 70 cm. Soils have silt loam to silty clay loam texture and weak to moderately developed subangular blocky structure. Their colour varies from light brownish gray (2.5Y6/2) to dark grayish brown (2.5Y4/2) with distinct yellowish red (5 YR5/6) to dark

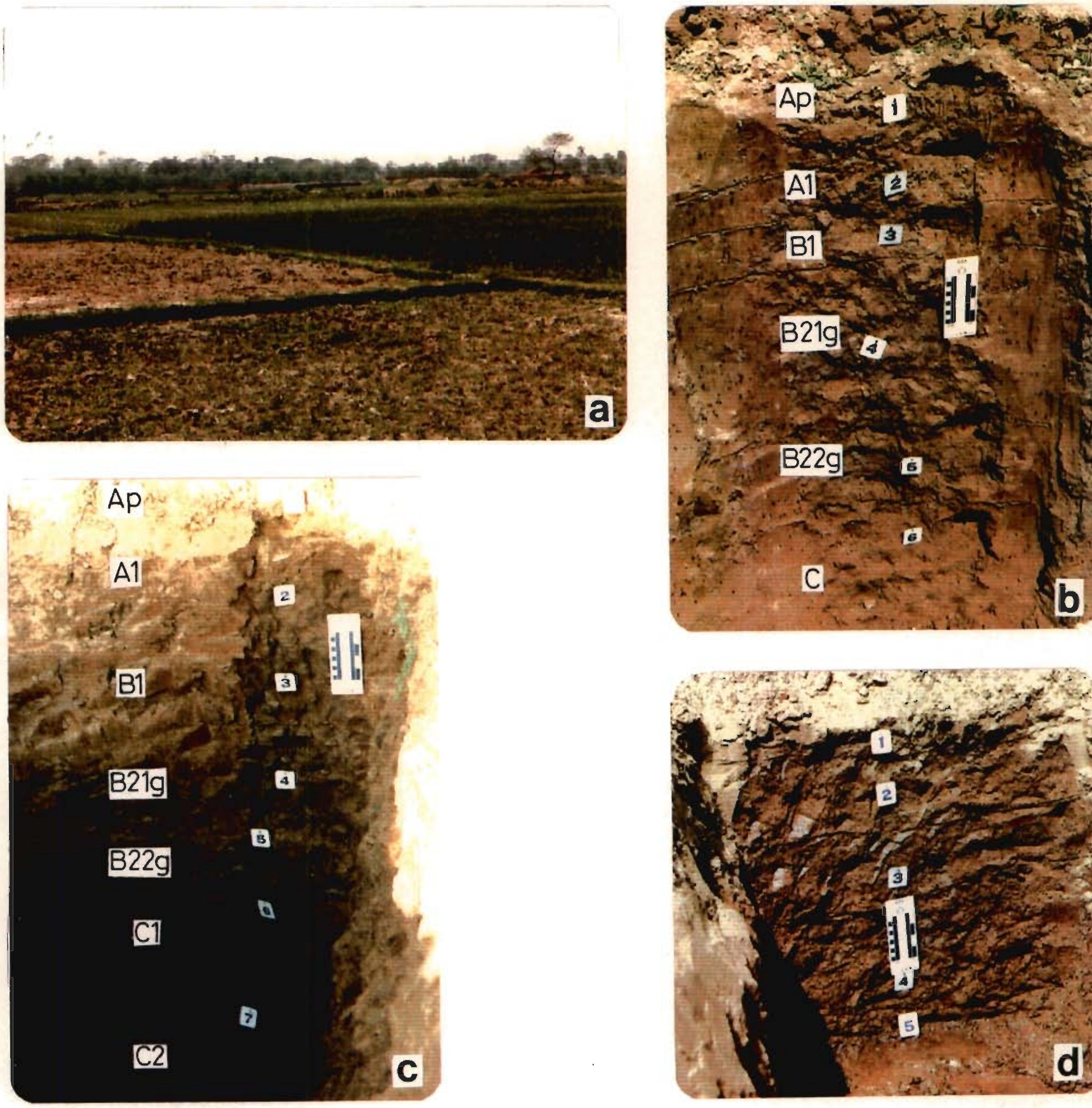

Fig. 2.7 Photographs showing (a) Field view and (b) A typical pedon (LB3) from the hydromorphic soil of the Damodar Terminal Fan; (c) Another pedon (LD3) from the same unit showing bleached A1 horizon and (d) A profile with high water table.

reddish brown (5 YR3/3) mottles. The B horizon soils grade into the C horizons along a gradual smooth boundary.

Soils of the C horizon have grayish brown (2.5Y5/2) to light brownish gray (2.5Y6/2) colour and silty loam texture. Mottles are quite common but ferro-manganese concretions are very few.

2.3.7 Bhagirathi Plain

This plain lies to the east of the Old Fluvial/Deltaic Plains. The Bhagirathi river, a distributary of the Ganges defines its eastern limit. This unit lies at an elevation of 10-20 m and its slope is less than 0.8 m/km. The Bhagirathi takes off from the Ganges about 15 km north of Jangipur (West Bengal) and flows in a southerly direction. In the southern part the Bhagirathi is known as the Hooghly river. Its course is guided by faults. All through its course in the floodplain, it flows in a number of straight stretches punctuated by sharp and acute meanders at places. In this unit well preserved meander scars, cut offs, abandoned channels and levees are observed in the Landsat images. One typical profile is described below (Fig. 2.8a-b).

PEDON # L15

Classification	: Typic Ustifluvent
Location	: 100 m east of Raghunathganj City, Murshidabad District
Date of examination	: 24-4-90
Parent material	: Alluvium
Slope	: <1 %
Drainage class	: Moderately well drained
Moisture condition	: Dry
Depth of water table	: 3 m
Physiography	: Plain
Landuse	: Paddy,
Climate	: Sub-tropical monsoonic

Hori-zon	Depth (cm)	
Ap	0-18	Light brownish gray (10YR6/2) dry,loam, many fine tubular pores, hard, firm, very weakly developed, slightly plastic, many very fine roots, clear smooth boundary.

B1	18-31	Light brownish gray (10YR6/2) dry, loam, few fine faint yellowish brown (10YR5/6) mottles, weak medium subangular blocky, many fine tubular pores, hard, firm, slightly plastic, common very fine roots, gradual smooth boundary.
B21	31-43	Grayish brown (10YR5/2) moist, silt loam, few fine faint yellowish brown (10YR5/6) mottles,weak medium subangular blocky, many fine tubular pores, hard, firm, plastic, few very fine roots, gradual smooth boundary.
B22	43-64	Dark grayish brown (10YR4/2) moist, silt loam, few fine faint mottles, strong medium subangular blocky, many fine tubular pores, hard, firm, plastic, few very fine roots, gradual smooth boundary.
C1	64-105	Dark grayish brown (10YR4/3) moist, silt loam, common fine distinct mottles, strong medium subangular blocky, common very fine tubular pores, hard, firm, plastic, clear smooth boundary.
C2	105-130	Grayish brown (10YR5/2) moist, loam, apedal, common very fine tubular pores, very few very fine roots.

The soils of this unit are weakly developed. A horizon thickness ranges from 15 to 20 cm. The colour of soils of this horizon varies from light brownish gray to gray in hue 10 YR with value 6 and chroma 2. The texture ranges from silt loam to loam with a very weak subangular blocky structure. Soils are hard when dry, firm when moist and sticky and slightly plastic when wet and often show reddish yellow to yellowish brown mottles. The boundary between A and B horizon is clear smooth.

The thickness of B horizon ranges from 40 to 50 cm. The colour of soils of B horizon ranges from grayish brown to dark grayish brown in hue 10 YR with values 4 to 6 and chromas 2 to 3. The texture varies from silt loam to loam and they have weakly developed subangular blocky structure. Few faint yellowish brown mottles are present. Fine silt coatings along ped surfaces and ferro-manganese concretions are observed. The B horizon grades into the C horizon through a gradual to clear smooth boundary.

The C horizon soils are loamy, friable, nonsticky and non plastic. A few very soft irregular ferro-manganese concretions of 1 to 3 mm size are observed.

2.3.8 Old Ganga Plain

The Old Ganga Plain lies on both the sides of the Ganga river and can be clearly differentiated from the Ganga Floodplain. The plain is widest in the central part (Fig. 2.1) with a width of 20 km and

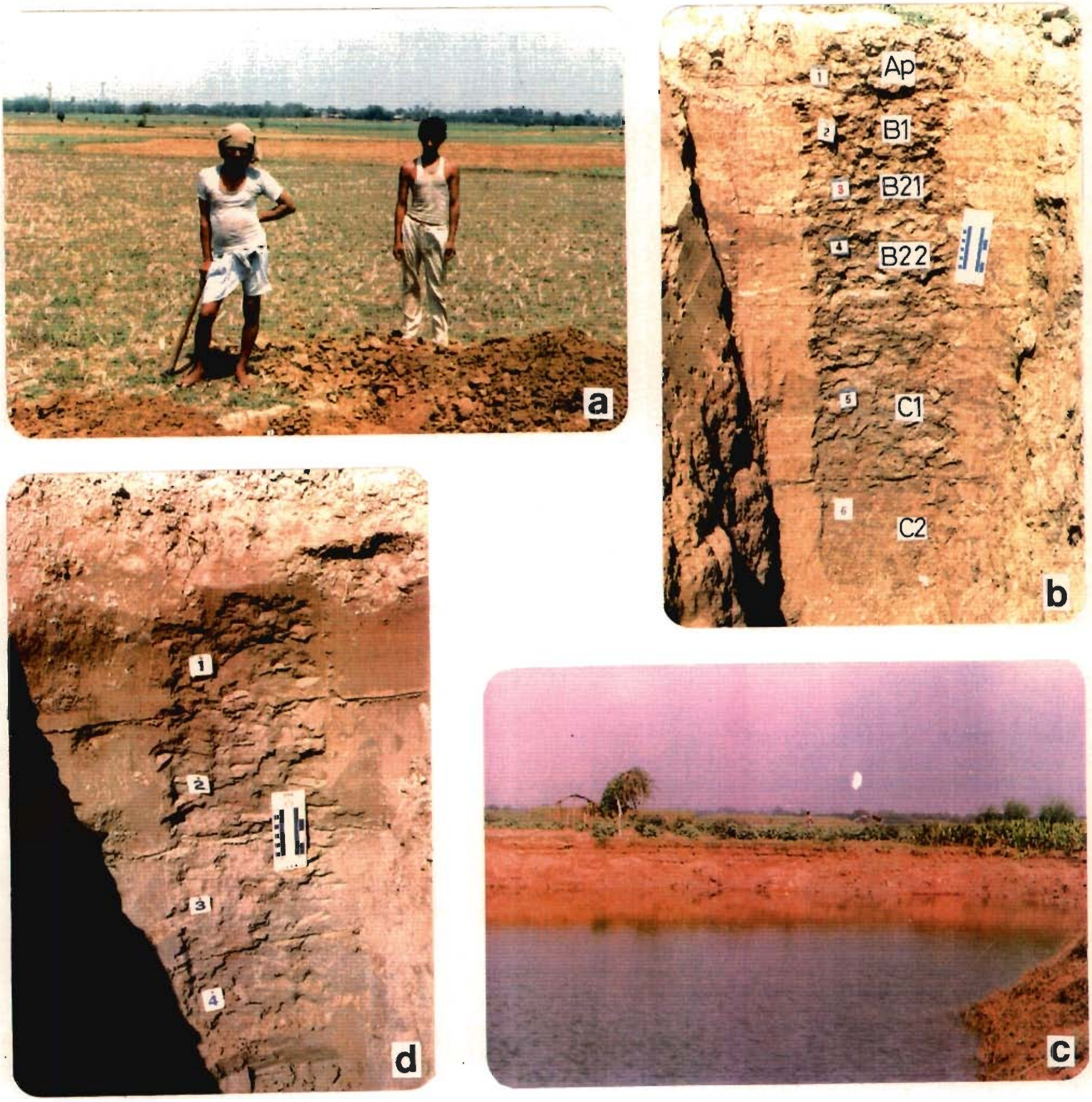

Fig. 2.8 Photographs showing (a) Field view and (b) A typical pedon (L15) from the Bhagirathi Plain; (c) Field view of the Old Ganga Plain showing sedimentary layering; (d) A typical profile from the Ganga Floodplain showing A/C type horizonation.

tapers both in the northwest and southeast directions. It consists of numerous paleochannels, ox-bow lakes and meander scars. The Ganga flows in a southeasterly direction in this region. The rivers coming from the Barind Tract dramatically change their courses from southwest to southeast after entering into this geomorphic unit. A marked difference in the level of Barind Tract and this unit is observed in the field. The Mahananda has a meandering character in this geomorphic unit. Field view of a part of this plainis shown in Fig. 2.8c.

PEDON # L2

Classification	: Typic Ustifluvent
Location	: Ankura, 10 m east of National Highway 34 near Dhulian More; Murshidabad District
Date of examination	: 10-11-91
Parent material	: Alluvium
Slope	: < 1 %
Drainage class	: Well drained
Moisture condition	: Moist
Depth of water table	: 1-2 m
Physiography	: Plain
Landuse	: Haldi
Climate	: Sub-tropical monsoonic

Hori-zon	Depth (cm)	
Ap	0-18	Olive (5Y4/3) moist, silt loam, structureless, many fine tubular pores, friable, many fine roots, animal activity widespread, shells present, gradual smooth boundary.
B1	18-35	Olive(5Y4/3) moist, silt loam, few fine faint mottles, very weak fine subangular blocky, many fine tubular pores, friable nonplastic, patchy thin clay cutans, many fine roots, abrupt smooth boundary, clay balls (< 2 mm), animal activity.
IIB2	35-75	Olive (5Y4/3) moist, few fine faint mottles, silt loam, weak to moderate fine subangular blocky, many very fine tubular pores, very friable , nonplastic, thin clay cutans, many fine roots, gradual smooth boundary.
IIB3	75-116	Olive (5Y4/3) moist, few fine faint mottles, silt loam, weak fine subangular blocky, common very fine tubular pores, firm , patchy thin clay cutans, diffuse smooth boundary.
IIC	116-150	Olive (5Y4/3) moist, silt, few fine faint mottles, weak fine subangular blocky, common very fine tubular pores, firm, diffuse smooth boundary.

Soils of this plain are moderately well drained fine silt loam and show composite profile. B1 horizon is 15-20 cm thick with soils having very weak, fine subangular blocky structure and a few fine, faint mottles. The soils have olive colour (5 Y 4/3). They are friable and non plastic. Clay balls (< 2 mm size) are present in this horizon. Evidence of animal activity is very high in these soils.

The soils of dipper part of the profile (i.e., IIB2 horizon) are weak to moderate subangular blocky. The thickness of IIB2 horizon is 30-40 cm. The soils of this horizon are firm and contain thin clay cutans. They have abrupt boundary against the overlying B1 horizon.

2.3.9 Ganga Floodplain

This unit is marked by a meandering channel of the mighty Ganges on both of its banks. The river course is guided by faults in this zone. The floodplain is marked by ox-bow lakes, abandoned channels and point bars on the northern bank of the river suggesting a south-westerly shift of the channel within its floodplain. In the FCC the floodplain is characterized by an overall bluish gray colour with some red patches. Fresh sand deposits along the active channel are marked in the FCC by bright white patches. The floodplain is widest (12 km) in the southeastern part of the unit. There is very little soil development in this unit, so its soils have not been studied in detail. A few profiles show a very weak A/C type of horizonation (Fig. 2.8d).

2.4 Tectonic Features of the Study Area

Based on relief features, changes in river courses and sinuosity of streams, drainage pattern and distribution of different Soil-Geomorphic units, two major tectonic features, (e.g. faults and tectonic blocks) have been identified in the study area (Fig. 2.9). Major faults recognized are: Chotanagpur Foothill Fault, Medinipur-Farakka Fault, Damodar Fault and Ganga-Padma Fault. The Chotanagpur Foothill Fault separates the Peninsular rocks in the west from the Lateritic Upland in the east. Earlier, Sengupta (1966) called the series of N-S trending faults in this region as Basin Margin Faults. Later

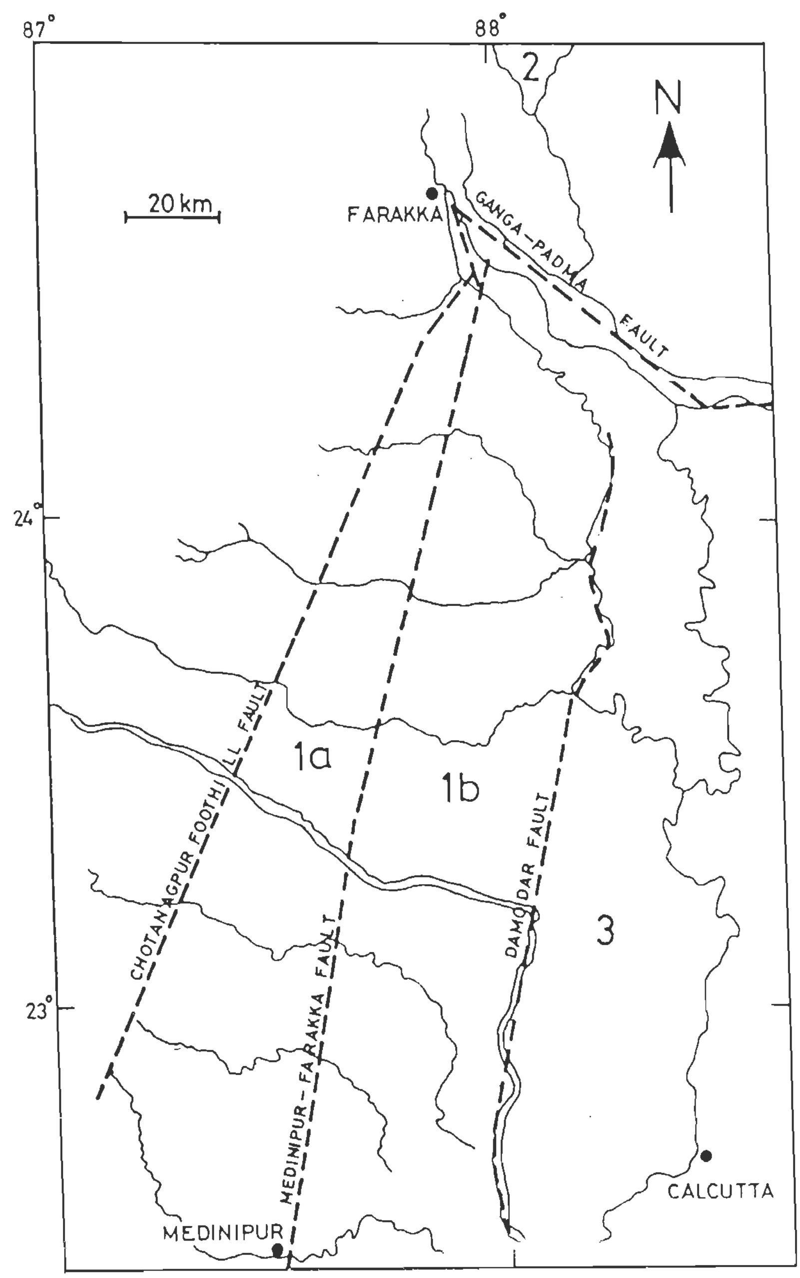

Fig. 2.9 Map showing major faults and tectonic block; 1. Tectonic Shelf (1a-Lateritic Upland, 1b-Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain and Ajay-Silai Plain); 2. Barind Tract Horst, 3. Ganga Fluvio-deltaic Plain Graben.

Agrawal and Mitra (1991, Fig.1) have shown the Basin Margin Fault along the Medinipur-Farakka Fault, which does not seem to be the case.

The Medinipur-Farakka Fault separates the Lateritic Upland in the west from the Bhagirathi-Brahmani, Brahmani-Ajay and Ajay-Silai Plains in the east. The Damodar Fault separates the Damodar Terminal Fan, Bhagirathi Plain, Old Ganga Plain and Ganga Floodplain in the east from the Bhagirathi-Brahmani, Brahmani-Ajay and Ajay-Silai Plains in the west. The Ganga-Padma Fault separates the Barind Plain in the north from rest of the soil-geomorphic units lying south of the Ganga.

The tectonic blocks recognized are: Tectonic Shelf (Sengupta, 1966) in the western part, Barind Tract Horst in the north and the Ganga Fluvio-deltaic Plain (GFDP) Graben in the eastern part. The different tectonic blocks are overlained by various soil-geomorphic units as follows: (a) Tectonic Shelf-Lateritic Upland, Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain and Ajay-Silai Plain; (b) Barind Tract Horst- Barind Tract and (c) GFDP Graben- Damodar Terminal Fan, Bhagirathi Plain. The Old Ganga Plain and Ganga Floodplain lie along the Ganga-Padma Fault.

2.5 Resume

Using remote sensing techniques followed by field studies, three major landforms were recognized and mapped in the study area. They are : Upland Areas, Old Fluvial/Deltaic Plains and Young Fluvial Plains. Within each landform a number of soil-geomorphic units were deciphered. These units are Barind Tract, Lateritic Upland, Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain, Ajay-Silai Plain, Damodar Terminal Fan, Bhagirathi Plain, Old Ganga Plain and Ganga Floodplain.

Various soil profiles in each soil-geomorphic units have been studied in the field in detail and representative soil profiles are shown in Figs. 2.3-2.8.

Soils of the study area are classified on the basis of Soil Survey Staff (1975). The major soil groups in different units are as follows. Barind Tract: Fine loamy Fluventic Ustochrepts; Lateritic

Upland: Typic Haplustalfs; Bhagirathi-Brahmani Plain: Fine Vertic to Aeric Haplaquepts; Brahmani-Ajay Plain: Fine Vertic Haplaquepts; Ajay-Silai Plain: Fine Vertic Haplaquepts; Damodar Terminal Fan: Fine Aeric Haplaquepts; Old Ganga Plain: Fine silty Typic Ustifluvents and Bhagirathi Plain: Fine loamy Typic Ustifluvents.

Representative soil profiles from different soil-geomorphic units in Figs. 2.3 and 2.4 a-b show that the soils of Lateritic Upland consist of two units : the lower unit and the upper unit. The lower unit consists of a lateritic crust (200-300 cm thick) which grades down to a kaoline-rich soft lithomarge. The upper unit lies unconformably over the lower unit and it consists of gravelly sand at the top and underlain by lateritic mudstone. The maximum thickness of the upper unit varies from 50 to 200 cm. The lateritic crust is hard and indurated. Sesquioxide cutans and hard irregular ferro-manganese concretions embedded in iron matrix are dominant in the lower unit. The field morphology of the soils of the Lateritic Upland suggest that they represent the composite soils (Duchaufour, 1982, p.144; Catt, 1986, p.171).

Soils of the Barind Tract are medium textured and have weakly to moderately developed subangular blocky structure. The B horizon thickness varies from 60-80 cm. Traces of calcareous nodules are present in lower horizon of some profiles. The B horizon is variably mottled with red colour mottles.

The soils of Bhagirathi-Brahmani, Brahmani-Ajay and Ajay-Silai Plains have moderately to strongly developed subangular blocky structure and their colour varies in 2.5 Y hue, 5-7 values and 2 or less chromas. They are poorly drained soils with vertical cracks of 3-4 mm width and extend up to a depth of 35-40 cm. The thickness of B horizon varies from 80 to 100 cm and the solum thickness varies from 100 to 140 cm. Silt coatings, patchy thin clay cutans and slickensided pressure faces are common. The presence of calcareous horizon at 1.5 m depth in Brahmani-Ajay Plain indicate that the soils of this plain may be called 'complex soils' as suggested by Duchaufour (1982).

In regions of the Bhagirathi-Brahmani, Brahmani-Ajay and Ajay-Silai Plains, a calcrete layer in probably a well developed soil occurs in the lower part of soil profiles (e.g. Brahmani-Ajay Plain), at depths of 3-4 m in wells or on topographically higher areas (e.g. an exposure in a few acres in the Bhagirathi-Brahmani Plain near Raghunathganj). It indicates the presence of an older underlying surface in these soil-geomorphic units and this soil/surface has been named here as the Raghunathganj soil/surface. Since the surface exposures of this unit are very limited, this unit has not been studied in detail and not included in soil-chronoassociation (Chapter 6). However, limited micromorphological studies and radiocarbon dating of a calcrete sample from this unit were done and have been discussed later.

The soils of the Damodar Terminal Fan are weak to moderately developed with solum thickness ranging from 90 to 100 cm and B horizon thickness of 50-70 cm. The texture of these soils varies from silt loam to silty clay loam and colour from light brownish gray (2.5Y6/2) to dark grayish brown (2.5Y4/2) with distinct yellowish red to dark reddish brown mottles. Soils show gleyed horizons due to hydromorphic conditions.

The soils of the Bhagirathi Plain have weakly developed massive to subangular blocky structure. B horizon thickness varies from 45 to 50 cm and the texture of the soils varies from medium to coarse loamy.

The soils of the Old Ganga Plain have composite profiles indicating two episodes of soil profile development separated by a period of erosion and sedimentation. The soils of this plain may be called complex soils. The upper part of this unit probably represents a catastrophic flood.

Four major faults i.e. Chotanagpur Foothill, Medinipur-Farakka, Damodar and Ganga-Padma Faults and three tectonic blocks e.g. Tectonic Shelf, Barind Tract Horst and Ganga Fluvio-deltaic Plain Graben have been recognized in the study area (Fig. 2.9).

CHAPTER 3

PARTICLE SIZE DISTRIBUTION, CHEMISTRY AND CLAY MINERALOGY OF SOILS

3.1 Introduction

Detailed field studies together with supporting petrographic, chemical and clay mineralogical analyses of representative profiles and parent materials help understand the history of pedogenic processes and of depositional and erosional events. Keeping this in view, particle size analysis, major elemental analysis and clay mineralogical studies of typical soil samples from the representative soil profiles of different soil-geomorphic units have been carried out.

3.2 Particle Size Distribution

Particle size distribution is used as an indicator of nature of parent material and some soil-forming processes, such as clay illuviation (Catt, 1986). The extent to which clay illuviation has occurred in any soil profile depends on the nature of the soil parent material and past climatic conditions. It is favoured by a seasonally dry climate, a well developed system of macrovoids such as those formed by dissolution of carbonate clasts, low concentrations of cementing and flocculating agents (e.g. carbonates, soluble organic matters, sesquioxides, exchangeable Al, Ca, Mg), a pH between 4.5 and 6.5 or a higher pH associated with exchangeable Na (McKeague, 1983). Amount of pedogenic clays or development of a B horizon can be an indicator of long or short term landscape stability and thereby estimating the ages of surficial deposits and in constructing a soil-chronosequence (Birkeland, 1984).

3.2.1 Materials and Methods

Particle size analysis for 122 samples from typical profiles from different soil-geomorphic units was carried out. After drying the samples all the lumps and clods in the samples were broken by mashing them with fingers or gently crushing them with a wooden pestle in a mortar. These samples were then mixed-up thoroughly and split.

Since soil particles adhere to each other due to the presence of organic matter, calcium carbonate, iron oxide and soluble salts, samples were treated for the removal of these binding constituents by the methods described by Galehouse (1971). The carbonates were removed by adding 10% HCl slowly into soil samples, until the effervescence stopped. Organic matter was removed by adding 6% H_2O_2 slowly with constant stirring and then boiling it. Iron oxide was removed by placing an aluminum foil and 15 grams of oxalic acid powder into the soil solution and then boiling it. Repeated washing of the soil samples was done to remove all the soluble salts. For complete dispersion sodium hexametaphosphate $[Na(PO_3)_6]$ was used as a dispersing agent.

From the dispersed samples sand fraction was separated by wet sieving on a 300 mesh (50 μm) sieve. Determination of fraction <50 μm was done by pipette method (Galehouse, 1971). Sand, silt and clay percentages were calculated according to the size classification of Soil Survey Staff (1951) (i.e. sand = 2mm to 0.05 mm, silt = 0.05 mm to 0.002 mm and clay < 0.002 mm).

3.2.2 Textural Variation and Amount of Pedogenic Clays in Soils of Various Soil-Geomorphic Units

From the particle size data obtained above, textural classes were determined according to Soil Survey Staff (1951) by plotting the sand, silt and clay percentages in a triangular diagram. Results of the particle-size analysis are given in Appendix I.

Particle size data indicate that the soil texture ranges, in general, from loam to silty clay loam with silt loam being the most common ones. Soils of the Ganga Floodplain, Old Ganga Plain, Bhagirathi Plain, Damodar Terminal Fan and Barind Tract are medium textured, whereas the soils of the Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain and Ajay-Siali Plain are medium to fine textured.

Variation of sand, silt and clay content with depth in various units has helped in the determination of soil development indices as well as an idea of the fluvial sedimentation characteristics. Particle size analysis data (Appendix I) indicate that the finer particles, particularly the clay, show a relative increase from A horizon to the B2 horizon in moderately well developed soils. This increase is attributed predominantly to the translocation of clays from the upper to the lower horizons. *In situ* weathering of the primary particles may have also contributed to some extent.

Variation in sand content with depth does not show any systematic trend in most of the soil profiles suggesting primary sedimentary layering due to fluvial deposition. But in some of the soil profiles (LB3 and LB4) a relative decrease of sand content with depth is observed up to B2 horizon. This may be due to the relative increase in the silt and clay content. An increase in silt content with depth up to B horizon has been observed in the soil profiles (LB3 and LB4) of the Damodar Terminal Fan. This may be due to the residual silt production by the weathering of sand fraction and also to some extent translocation of the finer silt to lower horizons. This is confirmed by later micromorphological studies.

Plots of total clay content and pedogenic clay content with depth for typical pedons from different units are given in Fig. 3.1. Increase of clay content in B horizon over the C horizon is the amount of pedogenic clay. When C horizon is not reached during the profile study, the increase in clay content in B horizon over the A horizon is used to calculate the amount of pedogenic clay. When both A and C horizons are present, the C horizon is preferred because the A horizon is a dynamic horizon and it continuously gets modified due to depletion of fine material and leaching. The maximum amount of pedogenic clay is observed in the Brahmani-Ajay, Bhagirathi-Brahmani and Ajay-Silai Plains followed by Damodar Terminal Fan, Barind Tract, Bhagirathi Plain and Old Ganga Plain. The amount of pedogenic clay is nil in the floodplain soils. The clay accumulation index i.e. the clay content in the B2 horizon minus that in the C/A horizon multiplied by thickness of the B2 horizon was calculated for soils of different units.

On the basis of clay accumulation index (Levine and Ciolkosz, 1983) different soil-geomorphic units have been ranked into five groups as shown in Table 3.1. However. the index was not calculated for the soils of Lateritic Upland, as these have undergone intense chemical modification.

Table 3.1 Ranking of soils of different geomorphic units based on the clay accumulation index

Group	Soil-Geomorphic Unit	Clay accumulation index
I	Ganga Floodplain	Nil
II	Old Ganga Plain Bhagirathi Plain	58-122
III	Damodar Terminal Fan Barind Tract	199-545
IV	Bhagirathi-Brahmani Plain Brahmani-Ajay Plain Ajay-Silai Plain	852-1564
V	Lateritic Upland	Not calculated

3.3 Major Elemental Analysis

Major Elemental analysis is very useful for quantifying the amount of chemical weathering and other pedogenic changes that have taken place in the parent material (Birkeland, 1984). All the data used for major elemental analysis are presented as oxides because the main balancing anion usually is oxygen. As analyses are given in percentage, they indicate relative increase and decrease.

Values for the individual oxides vary as a function of many soil-forming processes. These values are relative to the parent rock. Silica is almost always present in the parent material in amounts greater than needed to form clay minerals, so it commonly decreases on weathering in

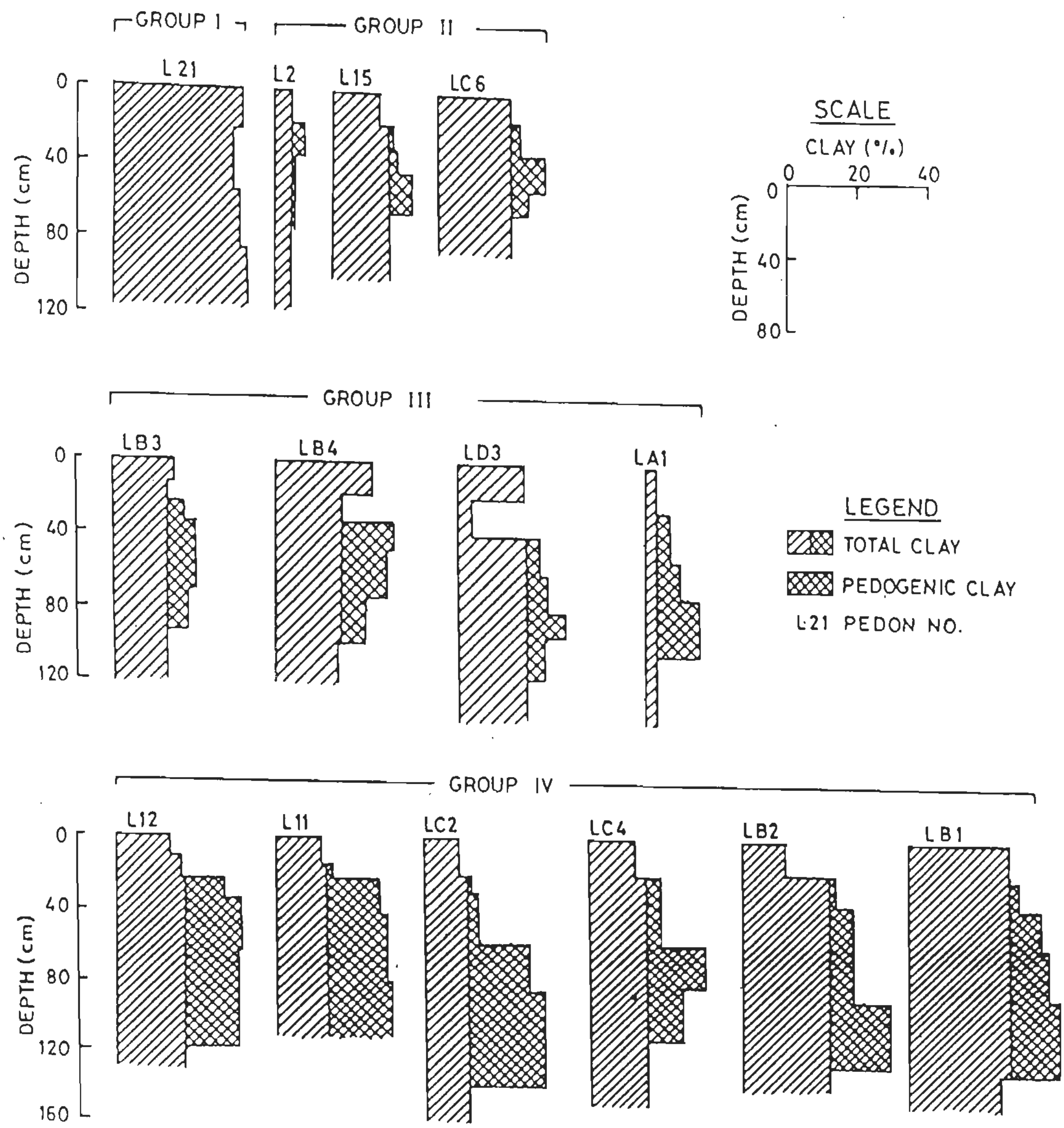

Fig.3.1 Variation of total clay and pedogenic clay in the soils of Group I to Group IV.

a leaching environment. And Al_2O_3, which has very low solubility over the usual pH range , is essential to most clay minerals, so it commonly shows a relative increase. Iron in most rock-forming minerals is present in the Fe^{2+} form, and on weathering in an oxidizing environment gets converted into Fe^{3+}-bearing substances and thus the Fe_2O_3 /Feo ratio increases on weathering. Of the major remaining elements (i.e. Mn, Ca, Mg, Na and K), Mg and K are associated with structure of clay minerals; Mn can form bluish black mottles; and Mg, Ca, K and Na are the major exchangeable cations. The weatherability of quartz is very low at ordinary temperatures as compared to other minerals which contain Al, Fe, K, Mg, Ca, etc. (Sidhu et al., 1977). As a consequence of soil development, these elements are released in the upper horizons and move downwards in response to diffusion gradients and water movement. Thus, SiO_2 concentrations on weathering in a leaching environment decrease or remain constant, while Al_2O_3 and Fe_2O_3 increase in the B horizon with increasing age. Thus the molar ratio SiO_2/R_2O_3 ($R_2O_3 = Al_2O_3 + Fe_2O_3 + TiO_2$) should decrease with time in a leaching environment (Birkeland, 1984, p.81). Variation of SiO_2, Al_2O_3, Fe_2O_3, TiO_2 and molar ratio of SiO_2/R_2O_3 with depth in different units are discussed below.

3.3.1 Materials and Methods

Major elemental analysis has been carried out for 77 soil samples from typical profiles of various units. Soil samples were air-dried, mixed and then ground in an agate mortar until the entire sample passed through 100 mesh (150 μm) size sieve. The major element analysis was carried out by the two solution method suggested by Shapiro (1975). Solution 'A' was used to determine SiO_2 ,Al_2O_3 and TiO_2 and solution 'B' for Fe_2O_3, MgO, Na_2O, K_2O, MnO and CaO.

Solution "A"

A 50 mg soil sample was decomposed by fusion with sodium hydroxide in a nickel crucible at a temperature of 500-600°C on a gas burner. After complete fusion for 20 minutes, the melt was cooled and leached with water. The solution was then acidified with 50 percent HCl and diluted to 250 ml.

Solution "B"

A 200 mg soil sample placed in a teflon beaker was heated with 10 ml of 50% HCl at a temperature of 70°C on a hot plate for 20 minutes. Then 7 ml of 48 percent hydrofluoric acid was added and the solution was kept overnight for digestion at 70°C. The remaining acid after digestion was evaporated and 4 ml of perchloric acid and 5 ml of HNO_3 were added to the digested sample and the solution was heated. This solution was again heated for 20 minutes after adding 10 ml of 50 percent HCl. The solution was diluted to 200 ml.

After preparing the solutions, SiO_2, Al_2O_3 and TiO_2 were determined on Inductively Coupled Plasma Spectrometer and CaO, MgO, Fe_2O_3 and MnO were determined on Atomic Absorption Spectrometer. K_2O and Na_2O were analyzed on a Flame Photometer. Results of the analysis are given in appendix II.

3.3.2 Variation of Major Oxides and Molar ratios in the soils of different Soil-geomorphic Units

The soils of Ganga Floodplain, Old Ganga Plain and Bhagirathi Plain show little evidence for any trend in the distribution of SiO_2, Al_2O_3 and Fe_2O_3. The significant distribution patterns of these oxides in all other units reveal that these soils have undergone pedogenic modifications after deposition of the parent material. They show a significant decrease in SiO_2 with depth from A to B horizon with a corresponding increase in Al_2O_3 and Fe_2O_3 in the soils of Damodar Terminal Fan, Brahmani-Ajay Plain, Bhagirathi-Brahmani Plain and Ajay-Silai Plain. The Lateritic Upland soils also show similar trend with depth. TiO_2 exhibits non-uniform increase and feebly follows the trends of Al_2O_3 and Fe_2O_3. Other oxides, i.e. MgO, MnO, Na_2O and K_2O do not show any definite trend with depth. Though the 2:1 swelling clay-bearing vertic intergrade soils of Bhagirathi-Brahmani Plain have a fair amount of total iron (up to 8%), the ratio of free iron to total iron remains relatively low (Nayak, 1994). The lower ratio of free iron:total iron indicates that the vertic intergrade soils have developed on sedimentary parent material (Duchaufour, 1982, p.263). In such cases a greater part of the free iron is not extracted, even by powerful reagents of the dithionite type. The iron freed by weathering is almost immediately reintegrated into the large molecules, both organic and mineral, that are rapidly formed in pedogenesis. Kornblyum (1967 in Duchaufour, 1982) and Paquet (1969 in Duchaufour, 1982) have emphasized the trapping of iron within the octahedral layers of the neoformed clays.

Though absolute values of major elements give some idea about the intensity of weathering and development of soil profile, the molar ratio SiO_2/R_2O_3 ($R_2O_3 = Al_2O_3 + Fe_2O_3 + TiO_2$) seems to be more informative in the present study. The molar ratio (MR) of SiO_2/R_2O_3 for typical profiles of different units are plotted in Fig. 3.2. As expected, the Group IV soils of BBP, BAP and ASP show the maximum percent decrease (16-34%) in the molar ratio of SiO_2/R_2O_3 from A to B2 horizon [i.e. ((MR in A horizon - MR in B2 horizon)/MR in A horizon) X 100] followed by Group III soils : 11-14% and Group II soils : 9-11%. The floodplain soils of Group I did not show any definite variation with depth for the molar ratio (Table 3.2).

Table 3.2 Range of percent decrease of molar ratio SiO_2/R_2O_3 from A to B2 horizon in soils of different groups

Group	Soil-Geomorphic Unit	% decrease of Molar ratio SiO_2/R_2O_3 from A to B2 horizon
I	Ganga Floodplain	Nil
II	Old Ganga Plain Bhagirathi Plain	9-11
III	Damodar Terminal Fan Barind Tract	11-14
IV	Bhagirathi-Brahmani Plain Brahmani-Ajay Plain Ajay-Silai Plain	16-34
V	Lateritic Upland	Not calculated

Though the decrease of molar ratio SiO_2/R_2O_3 with depth was very high for the lateritic soils of Group V, the percent decrease of the molar ratio was not calculated as these soils lack the horizonation pattern observed in the soils of other groups (e.g. A horizon, B horizon) due to intense chemical modification.

3.4 Clay Mineralogy

The process of clay mineral formation and transformation in soils is very slow depends on a number of factors such as the pcomposition of parent material, drainage conditions, climate and direction of climatic change and time. The present study aims to detrmine the semi-quantitative variation of clay minerals with depth within and between different groups of soils with a view to work out the major factors affecting the clay mineralogy of soils of the study area.

3.4.1 Materials and Methods

A total of 62 samples from different soil-geomorphic units were analyzed for clay mineralogical studies. For this, a 15-20 gm portion of each soil sample was washed with distilled water and centrifuged several times to get the desired dispersion of particles. No reagent for dissolving binding materials was used in the experiment to avoid any change in the clay mineralogy. The clay fraction (<2 μm) was then separated according to Stoke's Law.

Clay fractions of soil samples were then divided into three sub-samples in order to give different treatments. The first part was kept untreated and second and third parts were saturated with Mg^{2+} and K^{+} with 1N solutions of $MgCl_2$ and KCl respectively (Klages and Hopper, 1982). After shaking the suspensions for 12 hours in a water bath, excess solutions were removed by three centrifuge washings. The sub-samples were again centrifuged to remove excess water and to obtain thin pastes of similar consistency. These materials were used to make oriented clay films of almost equal size and thickness by pipetting equal volumes of the clay-water suspension on to glass slides and allowing them to dry at room temperature. The pipette method used in the present study for preparation of clay mounts was easy and quick and produced a fairly good and reproducible orientation as suggested by Wilson (1987). Mg^{2+} saturated clay slides were

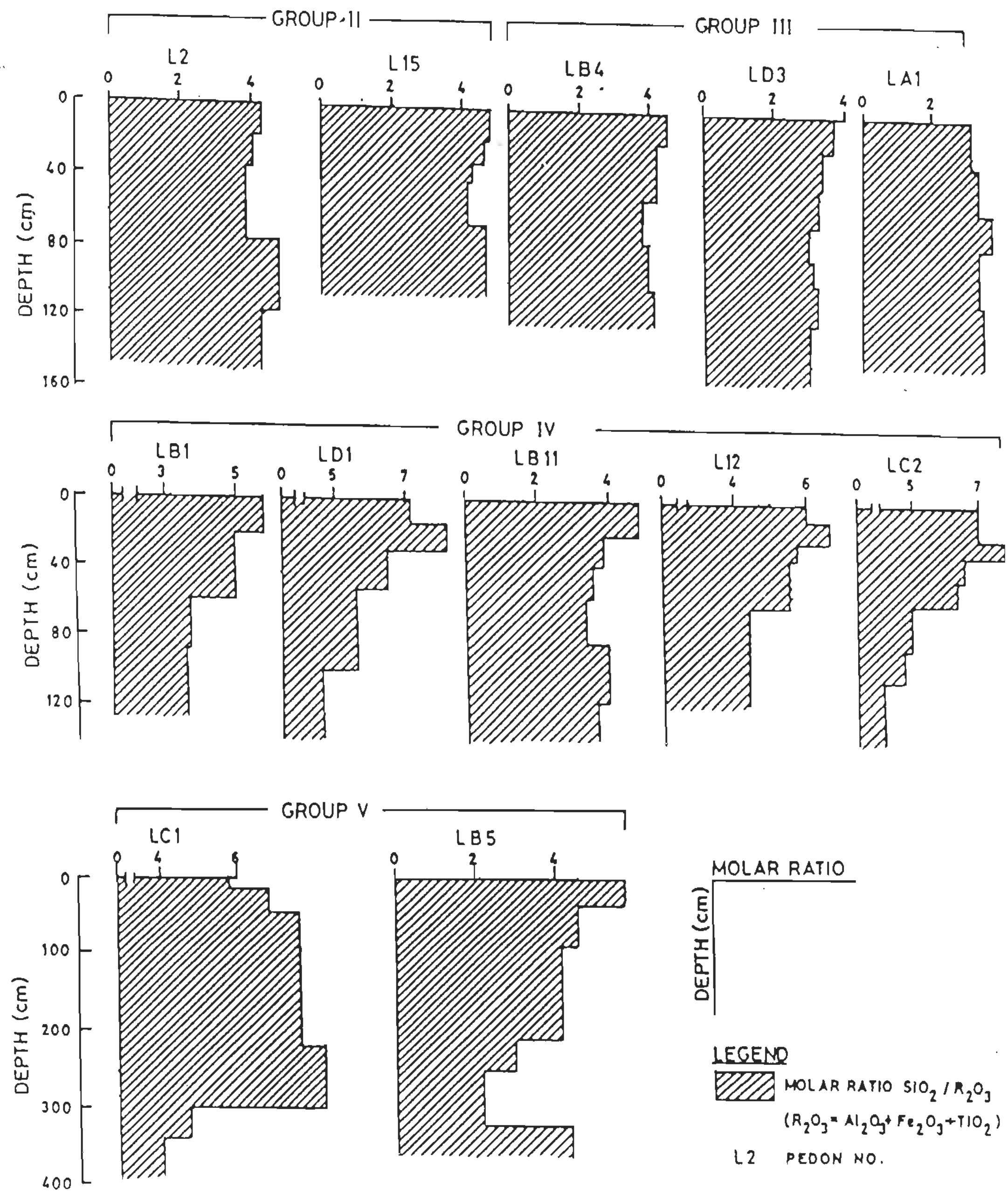

Fig. 3.2 Variation of the molar ratio SiO_2/R_2O_3 with depth in the soil profiles of Group II to Group IV.

solvated with vapours of ethylene glycol at 60°C for 24 hours in a desiccator. Two K^+ saturated clay slides were heated to 350°C and 550°C respectively. The untreated clay slides subjected to x-ray diffraction at room conditions were designated as natural; those solvated with ethylene glycol were called E.G. and those heated to 350°C and 550°C for four hours were referred as K-350°C and K-550°C respectively.

Care was taken to keep the x-ray machine operating conditions and method of preparation of slides uniform, as far as possible, for all the samples to minimize the error in estimation of clay mineral content due to these factors.

All slides were kept in a desiccator with silica gel to prevent rehydration before exposing them to x-rays. These slides were then examined on a Phillips PW 1140/90 X-ray Diffractometer at University Scientific Instrumentation Centre, University of Roorkee, under the following operating conditions: Nickel filtered Cu-K radiation, 20 mA current, 35 kV, 1° of 2Θ angle/min goniometer speed, 2 kc/s range, 3° to 30° of 2Θ scanned angle, and 1 cm/min chart speed.

3.4.2 Identification and Semi-Quantitative Estimation of Clay Minerals

In the present studies, basal reflections of the oriented clay samples in the X-ray diffractograms have been used for identification of various mineral species. The scheme followed for this purpose is essentially similar to that of Wilson (1987). The following sections provide a general description of the methods of identification of clay minerals from x-ray diffractograms.

(a) Kaolinite

Kaolinite minerals are characterized by intense first and second order basal reflections at 7.14 Å (001) and 3.57 Å (002) and by prominent groups of non-basal reflections. The presence of kaolinite is confirmed by heating the same to 550°C for one hour, which destroys the crystallinity of all kaolinites, thus causing the disappearance of basal reflections.

The diffraction patterns of disordered Kaolinite typically show a rather broad reflection at 7.2-7.4 Å, often with distinct asymmetry towards low angle side (Wilson, 1987).

(b) Chlorite

Chlorite is identified by a series of basal reflections approximately at 14 Å, 7 Å, 4.7 Å and 3.5 Å, which persist on heating the specimen at 550°C or treatment with ethylene glycol. Such simple observations have been found to be sufficient for the identification of chlorite even in many complex clay mixtures.

(c) Illite

Illites are recognized by strong basal reflections at 10 Å and 3.3 Å. In the soil the 10 Å peak of illites is often asymmetrical with a tail extending towards the low angle. Saturation with K^+ partly removes the asymmetry and produces a relatively strong 10 Å peak in such minerals.

(d) Smectite

Smectites were identified by x-ray diffraction patterns characterized by broad and diffuse non-basal reflections or bands that arose from random layer stacking. These bands were typically asymmetrical towards the higher angles. Ethylene glycol-treated smectite yielded generally a basal spacing of $\sim$17 Å with a rational series of higher order reflections. On heating, the peaks of smectite at 17 Å got destroyed. This observation was sufficient for identification of smectite.

(e) Interstratified Minerals

The layer silicate minerals such as illite, smectite, chlorite and kaolinite often occur in a mixed order of stacking because of their structural similarities and are commonly referred as mixed layer or interstratified minerals. The mixed layer structure may show a regular repetition of the different layers or an irregular interstratification of layers. From diffraction patterns of soil samples it is observed that most of the interstratified minerals in the studied soils are randomly interstratified in a manner described by Wilson (1987). The characteristics of x-ray diffractogram peaks of different interstratified minerals are given below.

(i) Kaolinite-smectite

The kaolinite-smectite interstratified minerals were identified by the presence of a broad diffraction band between 7Å and 10Å which persisted after ethylene glycol treatment and heating to 350°C.

(ii) Illite-smectite

The asymmetrical nature of 17 Å peak of glycolated samples with marked scattering towards the high angle side indicates the presence of interstratified illite-smectite (Wilson, 1987, p. 71). It is further confirmed by sharp increase in the peak height of 10 Å peak after thermal treatment at 550°C.

(iii) Chlorite-smectite

They are characterized by a 15.5 A° basal diffraction peak for Mg-saturated samples which decreses to 12.5A° on heating the samples to 550°C. In the K-saturated samples heated to 550°C the presence of a shoulder and a broadening on the low angle side of the 10 Å peak is indicative of chloritization of smectite interlayers (Wildman et al., 1968).

(iv) Illite-chlorite

The 12 Å peak which partially collapses to 10 Å on heating and partially remains in its original position and which is unaffected by glycol solvation is considered to be illit-chlorite and illite-vermiculite interstratified minerals.

The relative sizes of the x-ray diffraction peaks from the basal planes of clay minerals in the 7 to 17 Å range provide a basis for calculating the relative amounts of different clay minerals and interstratified mineral species. However, factors such as crystallinity, impurities of clay minerals, evenness and thickness of the sample mount and irraidiation set-up of x-ray machine affect such a relationship. Thus, the method of determining the contents of different clay minerals is semi-quantitative in nature. Care has been taken to minimize the above errors in the present study.

Two methods of estimation of contents of clay minerals i.e. measurement of peak height and peak areas are commonly used (Brindley, 1961; Biscaye, 1965). However, in the present study the method of Schultz (1964) to calculate peak area has been used by taking the sum of five height measurements at half degree intervals across the peak. This technique provides a good compromise between the two methods and it takes peak shape into consideration. It is also less time-consuming as compared to direct measurement of peak area technique.

Quantitative estimation of various groups of clay minerals has been made by using the factors described by Schultz (1964). The kaolinite peak area is divided by a factor 1.4 and chlorite peak area by 1.5 for quantitative comparison with 10 Å illite. Chlorite content is calculated from 14 Å peak area of K^+ aturated and heated to 350° C slides and the rest of the minerals from the Mg^{+2} saturated and glycolated slides as suggested by Wall and Wilding (1976).

3.4.3 Variation of Clay Minerals in Different Soil-Geomorphic Units

Figs. 3.3 - 3.5 shows the typical X-ray diffraction patterns of oriented clay slides of soils of B horizons of different units. The X-ray spectra clearly illustrate the heterogeneous nature of the clay fraction containing both swelling and non-swelling minerals. The most commonly occurring clay minerals, irrespective of the position in soil profiles or degree of soil profile development are illite and kaolinite. In the same way, quartz (4.26 Å peak) seems to be present in trace amounts in almost all the samples. The minerals most sensitive to the position

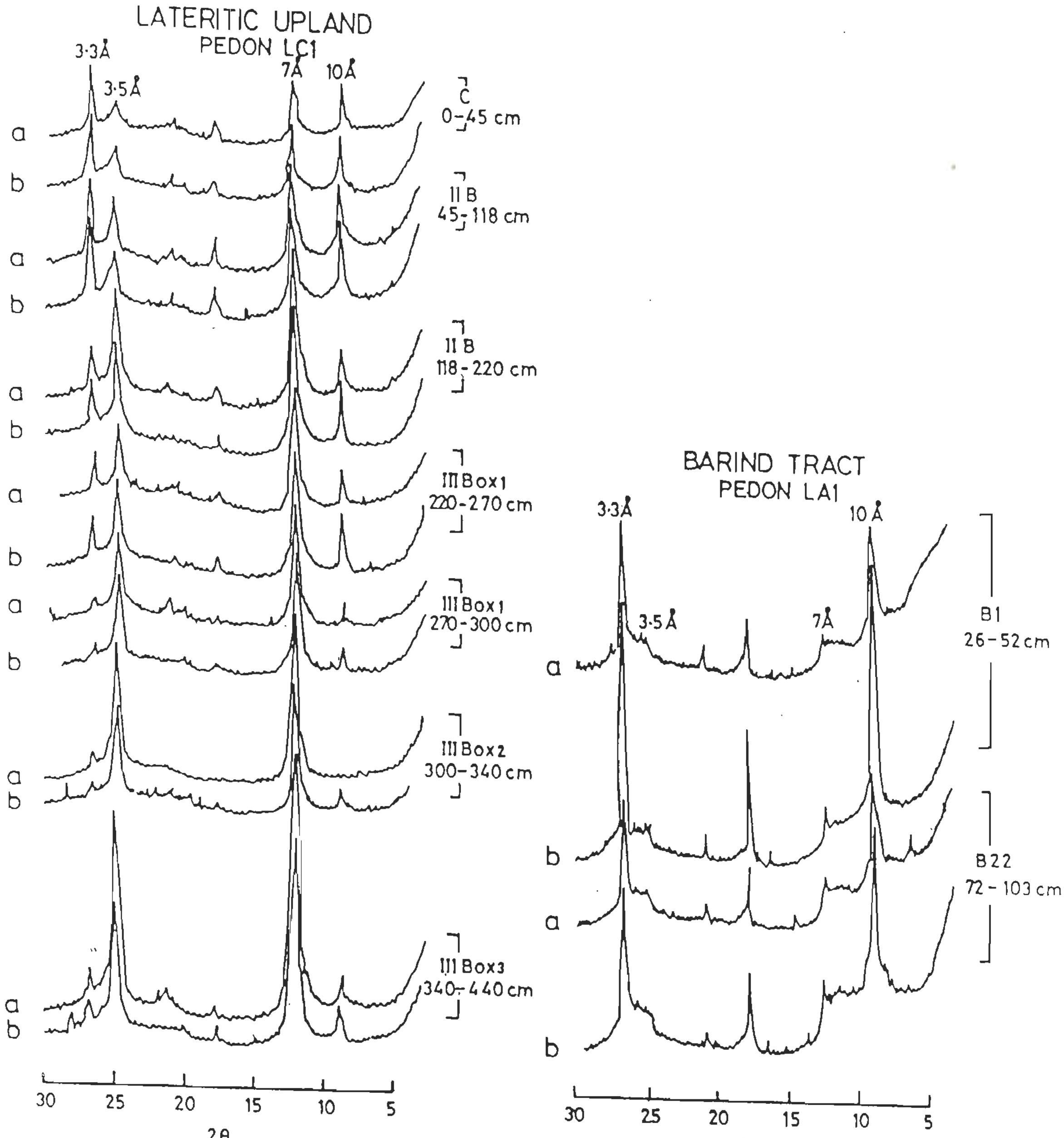

Fig. 3.3 X-ray Diffractograms of clay fractions from the typical soil profiles of the Lateritic Upland (GroupV) and Barind Tract (Group III). a- Mg saturated and glycolated and b- K saturated and heated of 350°C slides.

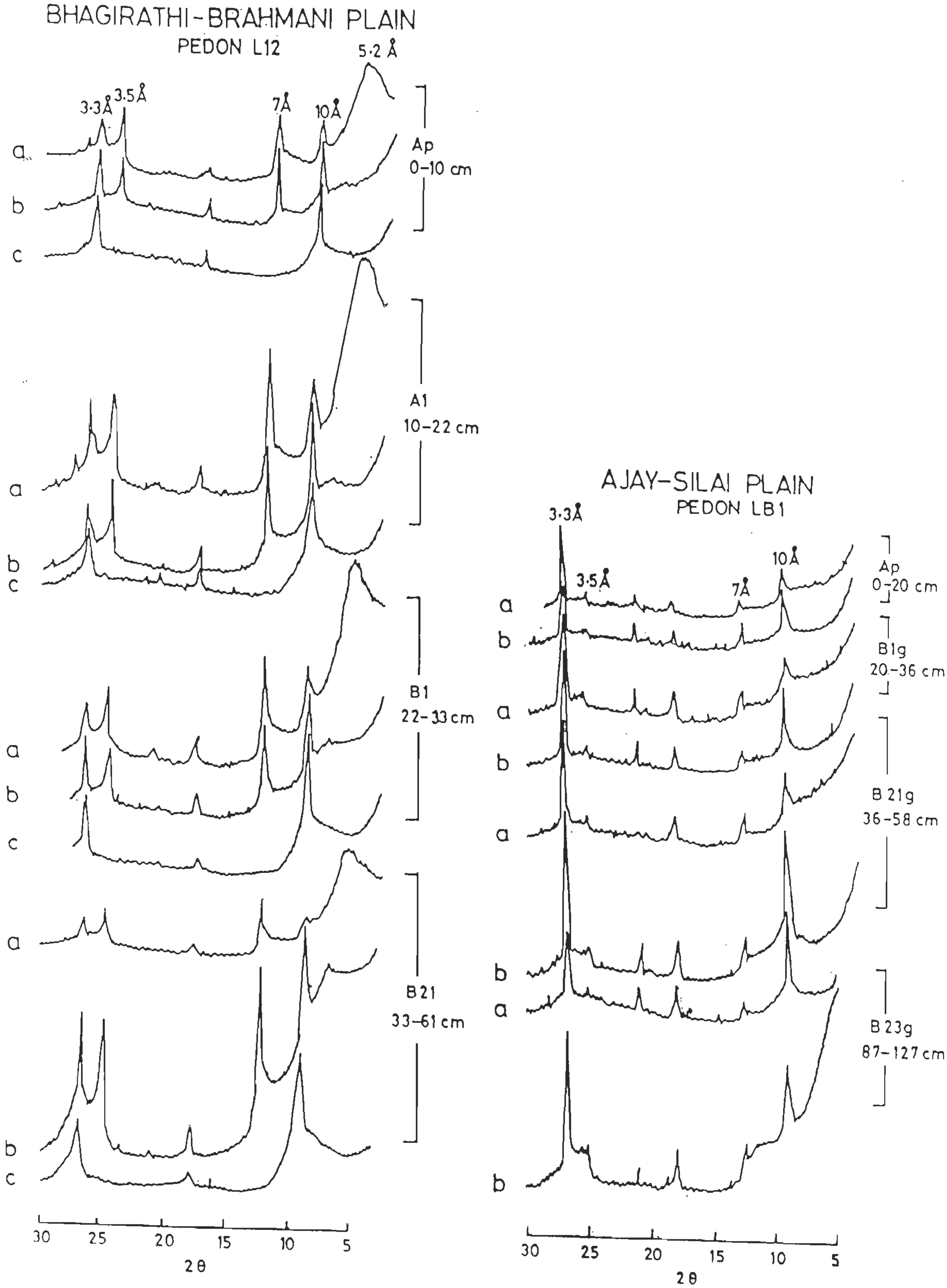

Fig. 3.4 X-ray diffractograms of clay fractions from the typical soil profiles of (Group IV soils Bhagirathi - Brahmani and Ajay Silai Plains). a- Mg saturated and glycolated, b- k saturated and headted to 350°C and C-K saturated and heated to 550° slides.

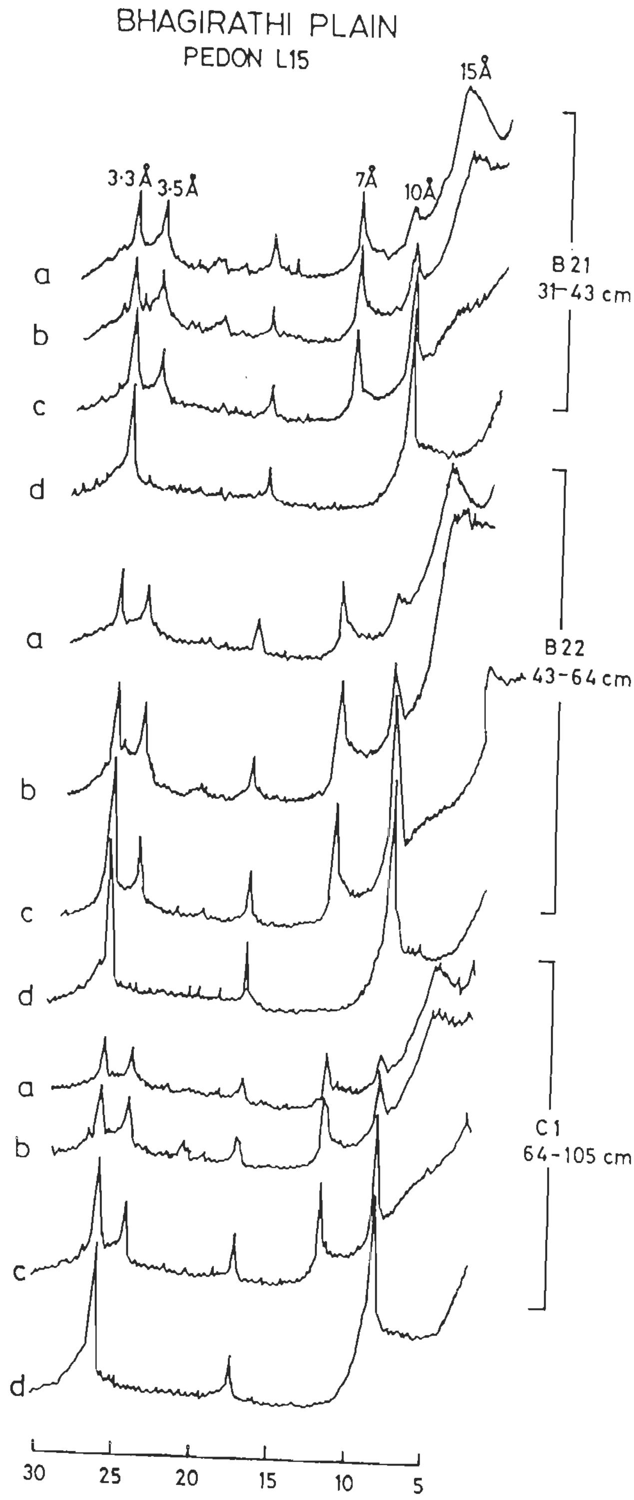

Fig. 3.5 X-ray diffractograms of clay fractions from typical soil profiles of Group II (Bhagirathi Plain) soils. a- Untreated slide, b- Mg saturated and glycolated, c- K saturated and heated to 350°C and d- K saturated and heated to 550°C slides.

they occupy within the profile are illite, smectite and illite-smectite interstratified minerals. The variation of clay mineral assemblages in various units are as follows.

3.4.3.1 Barind Tract

The soils of this geomorphic unit consist of illite, interstratified minerals (e.g. kaolinite-smectite and illite-chlorite) and kaolinite. In addition, the soils contain small amounts (2-4 %) of chlorite in the A and upper part of B horizons (Fig. 3.6, Pedon LA1).

The parent material (C horizon) consists of illite (60-65 %), kaolinite-smectite (15-16 %), kaolinite (15-20 %) and traces of illite-chlorite (2-3 %). Towards the surface horizons the illite component decreases to be replaced by illite-chlorite interstratified minerals. The complete absence of chlorite in C horizon and its increasing content from 2-3 % in B horizon to 5-7 % in the A horizon indicates the chloritization of illite-chlorite interstratified minerals has taken place.

3.4.3.2 Lateritic Upland

The clay fractions of soils of the Lateritic Upland are characterized mainly by kaolinite and iron oxide. It is followed by illite and illite-smctite interstratified minerals. Smectites, chlorites and interstratified kaolinite - smectite minerals were not found in these soils. Kaolinite content increases with depth whereas illite and interstratified minerals show a decrease in content with depth (Fig. 3.6, Pedon LC1). Interstratified minerals are almost non-existent in the deeper part of horizons.

3.4.3.3 Bhagirathi-Brahmani Plain

Soils of this unit have dominantly 2:1 minerals i.e. illite (10-30%), smectite and illite-smectite interstratified minerals followed by kaolinite. The content of kaolinite decrease slowly (45-40%) from Ap to B horizon but a sharp decrease (40-20%) is observed from B horizon to

C horizon (Fig. 3.6, Pedon L12). In addition, the soils contain small amount of illite-smectite and kaolinite- smectite interstratified minerals. Smecttite and illite-smectite interstratified minerals show a very gradual increase (11 to 20%) from A to B horizon but it increases drastically in the C horizon (35-40%).

3.4.3.4 Brahmani-Ajay Plain

The soils of this unit have illite (40-55%) as the dominant clay mineral followed by interstratified mineral and kaolinite. The contents of these two minerals decrease slowly from Ap to B horizon but a sharp decrease is observed from B horizon to C horizon (Fig. 3.6, Pedon LC2). In addition to these, the soils contain smectite-illite and kaolinite - smectite interstratified minerals. Content of interstratified mineral increases drastically in C horizon. It varies from 20-25% in Ap and B2 horizon increasing to 40-50% in C horizon.

3.4.3.5 Ajay-Silai Plain

The clay fractions of soils of this unit comprise mainly of illite (50-60%), illite-smectite and kaolinite- smectite interstratified minerals and kaolinite. Illite-smectite interstratified minerals, which are lacking in the surface horizon are present in significant amount in the B horizon. Kaolinite, illite and kaolinite - smectite interstratified minerals show an overall slight increase with depth.

3.4.3.6 Damodar Terminal Fan

The soils of Damodar Terminal Fan have illite (15-35 %), kaolinite (15-40 %) and interstrtified chlorite-smectite (20-40 %). Traces of chlorite (1-4 %) are observed in surface horizons. Kaolinite shows appreciable decrease from 35-40 % in B horizon to about 15 % in C horizon (Fig. 3.6, Pedon LB4, LD3). Intersratified chlorite-smectite and kaolinite-smectite are very sensitive to the position of their occurence. The content of illite and chlorite-smectite

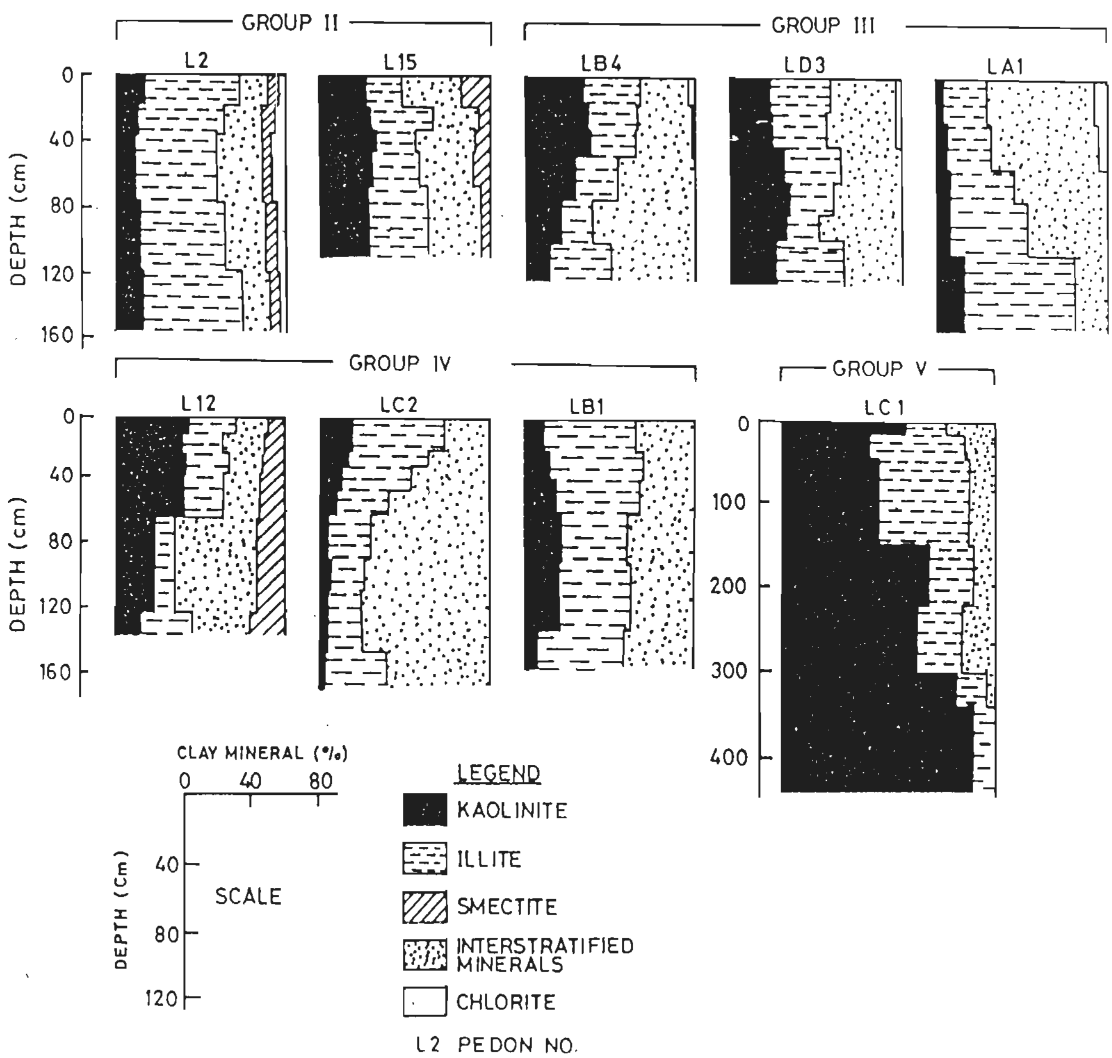

Fig. 3.6 Variation of clay minerals with depth in the soil profiles of Group II to Group V.

show a reverse relationship indicating transformation of illite to chlorite-smectite as shown in Table 3.3.

3.4.3.7 Old Ganga Plain

The dominant minerals of the Old Ganga Plain are illite (40-58%), interstratified minerals (16-30%), kaolinite (10-15%), chlorite (4-7%) and smectite (5-8%). No significant changes in clay mineral contents with depth are noted.

3.4.3.8 Bhagirathi Plain

The soils of this unit consist of kaolinite (25-35%), illite (20-35%), interstratified minerals (20-30%) and smectite (5%-17%). None of the minerals show any trend with depth.

3.5 Resume

Increase of clay content in the B horizon over A or C horizon was taken here as pedogenic clay which is attributed to the translocation of clays from the upper to the lower horizons. Increase in clay content in B horizon is a useful indicator of relative age of soils (Birkeland, 1985). There is no pedogenic clay in Group I soils, whereas there is an appreciable increase in pedogenic clay content from Group II to Group IV soils. The clay accumulation indices (Levine and Ciolkosz, 1983) in different groups are: Group II- 58-122; Group III- 199-545 and Group IV- 852-1564. The index was not calculated for the Group V soils, as these have undergone intense chemical modification.

The chemical analysis for major elements has supported the inferences made from particle size analysis. The molar ratio SiO_2/R_2O_3 ($R_2O_3 = SiO_2 + Al_2O_3 + TiO_2$) was calculated for soils of different groups. The ratio does not show any trend in the soils of Group I but it decreases with depth from A to B2 horizon in all the other groups in general. The decrease is relatively higher with increase in degree of development of soils from Group II to Group IV. The percent decrease in the ratio for Group II, Group III and Group IV members are 9-11%, 11-14% and 16-34% respectively. However, the vertic intergrade soils of Group IV do not show any systematic change in the molar ratio in the top 30-35 cm of the profile indicating homogenization of soil material due to pedoturbation. Below this depth of vertical cracks the soils show normal trend similar to Group II and Group III soils. Though the decrease of molar ratio SiO_2/R_2O_3 with depth was very high for the lateritic soils of Group V, the percent decrease of the molar ratio was not calculated as they show weak horizonation due to intense chemical modification.

Major clay minerals observed in the study area are illite, kaolinite, smectite, illite-smectite, kaolinite-smectite, chlorite-smectite and illite-chlorite interstratified minerals. Small amount of chlorite is also observed in Group III soils of the study area. The duration of pedogenesis and clay mineral assemblage of parent material seems to have controlled the occurrence and variability of clay minerals in different units south of the Ganges.

Table 3.3 summarizes the clay mineralogical compositions of the soils of C horizon (parent material) and possible transformations in different soil-geomorphic units of the study area.

The major clay minerals present in the parent material in the area south of the Ganges are illite, smectite and illite-smectite interstratified minerals released by weathering of the Rajmahal Basaltic Traps and granitic rocks in the west and transported to the east by easterly flowing rivers.

Table 3.3 Clay mineralogical composition of soils of C/A horizon (parent material) in different soil-geomorphic units

Soil-Geomorphic Units	Parent Clay Minerals	Possible Clay Mineral Transformations
Lateritic Upland	I, I-Sm, K	I --> K I-Sm --> K
Barind Tract	I, K-Sm, K, I-Ch	I-->I-Ch --> Ch K-Sm --> K
Bhagirathi-Brahmani Plain	I, I-Sm,Sm, K-Sm, K	I --> I-Sm --> K Sm -->K-Sm --> K
Brahmani-Ajay Plain	I, I-Sm, K-Sm, K	I --> I-Sm --> K K-Sm --> K
Ajay-Silai Plain	I, I-Sm, K-Sm, K	I --> I-Sm --> K K-Sm --> K
Damodar Terminal Fan	I, Ch-Sm, Sm K-Sm, K	I--> Sm--> Ch-Sm Ch-Sm --> C K-Sm --> K
Bhagirathi Plain	K, I, I-Sm, Sm	No transformation
Old Ganga Plain	I, Ch-Sm, K, Ch, Sm	No transformation

K : Kaolinite
I : Illite
Ch : Chlorite
Sm : Smectite

I-Ch : Illite-Chlorite
I-Sm : Illite-Smectite
Ch-Sm : Chlorite-Smectite
K-Sm : Interstratified Kaolinite-Smectite minerals

Smectite and illite are transforming to Kaolinite through interstratified minerals as follows:

Illite ---> Illite-Smectite ---> Smectite ---> Kaolinite
Smectite ---> Kaolinite-Smectite ---> Kaolinite

Earlier similar transformation has been observed in soils derived from crystalline rocks in warm climates (Catt, 1991). This type of transformation is caused by loss of silica from 2:1 clays, when the profile ages and acidifies due to weathering. This transformation indicates acid fersialitisation (Duchaufour, 1982). Also, some kaolinite might have been inherited from the initial stage of weathering of Rajmahal Basaltic trap in neutral conditions in a manner suggested by Duchaufour (1982).

The presence of taces of in surface horizons of Group III soils indicate chloritization of 2:1 clays (illite and smectite) perhaps due to ferrolysis in amanner suggested by Brinkman (1969/1970) as follows :

Illite --> Illite-Chlorite --> Chlorite
Smectite --> Chlorite-Smectite --> Chlorite

In the Lateritic Upland transformation of smectite, mixed layer and interstratified clay minerals and illite to kaolinite and iron oxide is complete. In Group IV and Group III (Damodar Terminal Fan) soils also the smectite and illite are transforming to kaolinite through interstratified minerals.

High content of illite in the soils of Bhagirathi-Ajay and Ajay-Silai Plains (Group IV) in the region further south is probably due to contribution from granitic rocks in addition to the Rajmahal Traps from the west. The soils of Group II and Group I have undergone little pedogenesis and hence the clay mineral composition does not change with depth in soil profiles of these members. The presence of smectite in these soils suggests that in addition to the

Himalayan source, some contribution has been made from rivers draining the Rajmahal Basaltic Traps in the west.

As described earlier, soil morphology of different groups (Group I to Group V) show systematic changes and an increase in pedogenesis from Group I to Group V can be inferred. Also, the soils of Group IV show mainly an assemblage of illite, smectite and illite-smectite interstratified minerals, whereas the soils of LU (Group V) lying further west have mainly kaolinite and illite. These observations can be explained by assuming that these units exhibit different phases of weathering. The clay mineral assemblage in Group IV soils represent fersiallitisation whereas that in Group V along with the presence of iron oxide exhibits ferralitisation of Duchaufour (1982). The semi-quantitative estimation of clay minerals from Group IV soils indicate that there is no marked variation in top 30 - 40 cm whereas very sharp variation is observed below this depth. This behaviour is attributed to the homogenization in the upper horizons caused by vertic processes (pedoturbation) in these soils.

CHAPTER 4

MICROMORPHOLOGY OF SOILS

4.1 Introduction

Applications of soil micromorphology in Quaternary research have greatly increased since the late sixties (Mucher and Morozova, 1983). Micromorphological studies involve the description, interpretation and to an increasing extent, measurement of components, features (e.g. aggregates, concretions, secondary pseudomorphs, weathered grains etc.) and fabrics in soil material at a microscopic level (Bullock et al., 1985). These studies help in inferring the degree of soil development, processes of pedogenesis and in some caces in deciphering direction of climatic changes.

Although most of the above mentioned features may be seen and identified in the field, the microscopic studies are inevitable for their precise definition and description. For these reasons, the micromorphological studies of representative soil thin sections from different soil-geomorphic units have been done with a view to infer the pedogenic processes as also degree of soil profile development.

4.2 Thin Section Preparation for Micromorphology

The procedure followed for thin section preparation was that as described by Jongerius and Heintzberger (1963), Fitzpatrick (1984) and Murphy (1986). Some modifications to the procedure were made to suit the available facilities.

The samples were air-dried slowly in a well-ventilated place. Complete drying was important because even small traces of moisture reduce the rate of polymerization of the polyester resin which was used for impregnation of the samples.

The impregnation mixture consisted of crystic resin, thinner, catalyst and hardener in the following proportions: (a) crystic resin 750 ml, (b) thinner 250 ml, (c) catalyst 6-7 ml, and (d) hardener 3-4 drops. The mixture was stirred thoroughly and then left for about 30 minutes until the air bubbles were removed. The undisturbed soil sample in the tin boxes were then immersed in the mixture and were evacuated for about one and a half hours to achieve complete resin penetration. The samples were left in the vacuum chamber for about 10-12 hours and then cured for at least 5-6 weeks at room temperature to allow them to harden.

The hard blocks of impregnated soil were used for preparation of thin section slides using standard procedures. Since most of the samples were clay-rich, kerosene was used as a coolant and lubricant during sawing and other subsequent stages in order to avoid swelling or buckling of the samples, even though they were well-impregnated.

The grinding of the slides was done in two stages. In the first stage, lapping wheel was used. Then, the remaining grinding was done by hand on a glass plate using silicon carbide (600 grit) and aluminum oxide (800 WP) powders; obtaining a final thickness of about 25 μm. The slides were washed in kerosene oil between each operation. The thin sections required no further polishing.

4.3 Systematic Description and Interpretation

Textural, structural and pedological features were identified in thin sections under the petrological microscope, with a particular emphasis on the pedological features. Attempts were made to classify these pedofeatures and to relate them to particular soil-forming processes. The description of thin sections follows the terminologies as described by Bullock and Murphy (1979) and Bullock et al. (1985). The general scheme of description is as follows.

A. General features, including microstructure and matrix.
B. Basic Mineral components.
C. Weathering features.
D. Clay translocation features.
E. Segregation features, including carbonates and iron accumulations.

F. Organic materials, including plant remains and organic accumulations.

G. Biological structures, including faunal passages and faecal materials.

H. Miscellaneous features, including detrital grains, rock fragments etc.

Two important aspects of structure are aggregates and voids, the combination of which gives rise to a particular type of microstructure. The aggregates are described as pedal or apedal and voids are described in terms of size, shape and abundance. Microstructures were studied in comparatively thick sections (about 50-60 μm thick). Basic mineral components and pedofeatures were examined in 25 μm thick thin-sections. A brief description of the above mentioned features as identified in the thin sections from different soil-geomorphic units is as follows.

4.3.1 Lateritic Upland

The gravelly sand lying at the top of the upper unit is structureless. It contains vughs and vesicles. The C/F related distribution is porphyric (Fig. 4.1 a). But the lateritic mudstone lying below the gravelly sand is subangular blocky and the groundmass is dotted due to presence of iron oxide/hydroxide. It contains broken pieces of laterites (Fig. 4.1 b). The b-fabric is undifferentiated to stipple-speckled. The pedological features are mainly the well-rounded sesquioxide nodules up to 2 mm size with sharp and well defined boundaries. These nodules contain quartz grains (Fig. 4.1 c) which have iron oxide in the cracks (termed runiquartz by Eswaran et al., 1975). Other pedological features are speckled and non-speckled ferruginous hypo-coatings and quasi-coatings around voids, infillings, embedded grain coatings of clay and papules (Fig. 4.1 d, e, f and Fig. 4.2 a).

The lateritic crust of the lower unit exhibits a crumby and angular blocky microstructure. The coarse material consists mainly of medium to fine sand sized, dominantly 300-500 μm, quartz and weatherable minerals such as mica and feldspars. Heavy minerals like tourmaline, rutile, etc. are also present in small quantities. The fine fraction is dominantly clay of yellowish red to reddish brown colour often coated with oxides and hydroxides of iron. The b-fabric is undifferentiated to weak stipple-speckled. The speckled b-fabric is mainly due to the presence of sesquioxides. It shows close and single spaced porphyric to chitino-porphyric distribution (Fig. 4.2 b).

The main pedological features observed in the lower unit are ferruginous hypo-coatings, free-grain clay coatings (Fig. 4.2 c), irregular-shaped sesquioxide nodules with sharp external boundaries and depletion and concentration features of iron oxide/hydroxide (Fig. 4.2 d). Laminated and well oriented clay coatings as thick as 300 μm are quite common in the lateritic crust and underlying lithomarge (Fig. 4.2 e). Horizontal micropans (>2 mm thick) are also observed occasionally (Fig. 4.2 f). The iron oxide seems to have moved along voids to form hypocoatings (Fig. 4.3 a). Parts of the groundmass are dotted with the droplets of this material. Similar features have been described by Zauyah (1983). Angular quartzs grains are observed commonly in the iron oxide matrix. Irregular shaped sesquioxide nodules up to 8 mm diameter and with diffuse and irregular boundaries are common in the lower unit. Some angular quartzs occurs as skeletal grains in the nodules.

The presence of rounded and irregular sesquioxide nodules in the upper and lower units respectively indicates that the upper unit formed on the transported material while the lower unit formed *in situ*. Similar irregular and rounded nodules in the lateritic soils have been used to distinguish the soils formed *in situ* from the one formed from colluvial material in Malaysia by Zauyah (1983).

The presence of weatherable minerals such as mica and feldspars (Fig. 4.3 b) in the lower part (lithomarge) of the Lower Unit may be interpreted to be due to the rejuvenation of older soils and extension of ferralitization to the lower C/R horizons. Earlier, Venugopal et al. (1990) interpreted similar features in lateritic soils of south India to be due to the rejuvenation of soils of pre-Pleistocene period by exposures of granites or metamorphosed intrusive rocks.

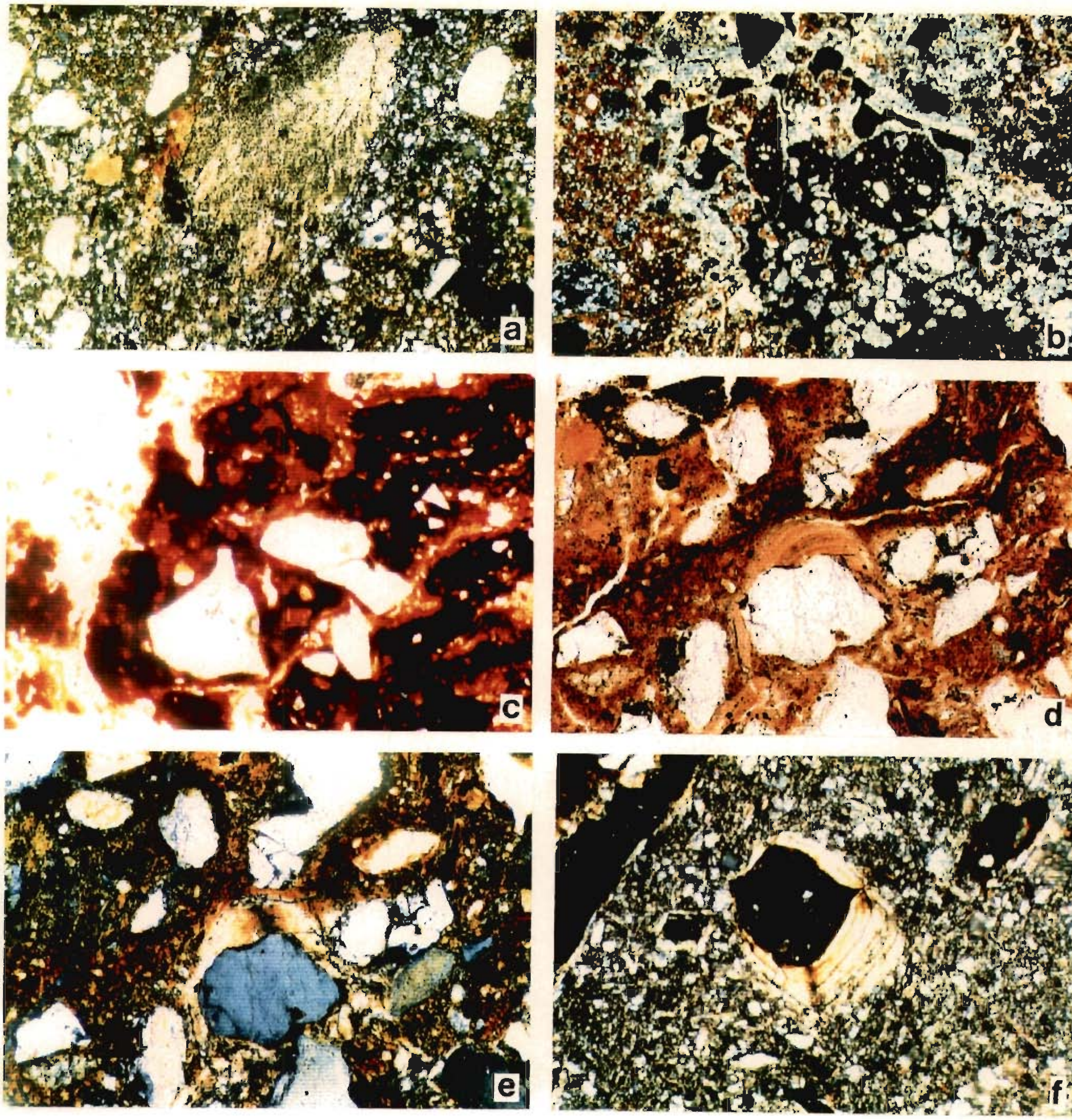

Fig.4.1 (a) porphyric related distribution and separation of matrix (finer speckled mass in coarser groundmass) at 30 cm depth, Pedon LC1, C horizon, Lateritic Upland. Frame length 1.4 mm, cross polarised light (XPL); (b) Loose infilling of void with broken laterite pieces, nodules and other mineral grains in the Lateritic Mudstone (IIB horizon Pedon LC1). Frame length 1.4 mm, XPL; (c) Sesquioxide nodules with runiquartz (at the centre) from IIB horizon of Pedon LC1. Frame length 1.4 mm, XPL; (d) embedded grain coating of ferruginous clay in IIB horizon Frame Length 1.4 mm, Plane polarised light (PPL); (e) same as (d) XPL; (f) compound embedded clay coating around an opaque grain, IIB horizon, Pedon LC1. Frame lenght 1.4 mm, XPL.

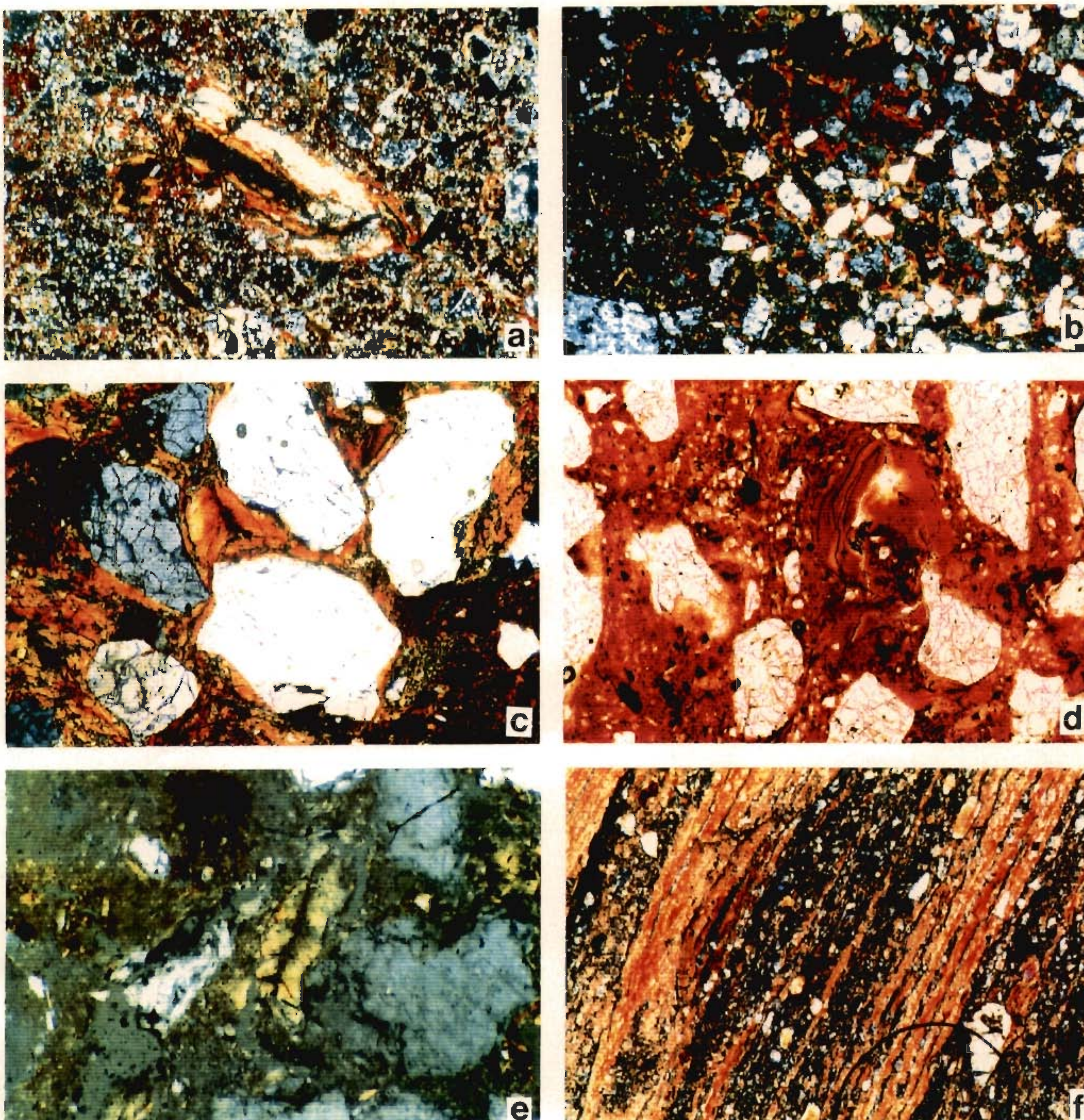

Fig.4.2 (a) Ferruginous and limpid clay coating and diffuse ferro-manganese nodules from IIB horizon of Pedon LC1. Frame length 1.4mm, XPL; (b) Chitino-porphyric distribution, $IIBox_1$ horizon, Pedon LB5. Frame length 1.4 mm 5 XPL; (c) well oriented free grain coating of ferruginous clay, $IIBox_2$ horizon, Pedon LC1. Frame length 1.3 mm, XPL; (d) irregular sesquioxide nodule with laminated iron oxide/hydroxide feature (top centre) and undifferentiated b-fabric, $IIIBox_2$ horizon, Pedon LC1. Frame length 1.4 mm, PPL; (e) well oriented and laminated clay coating from lower part of $IIIBox_2$ horizon, Pedon LC1. Frame length 1.4 mm, Partially crossed polarised light; (f) Horizontal micropan consisting of alternating ferruginous silty clay and coarser material from $IIBox_1$ horizon of Pedon LB5. Frame length 1.4 mm, XPL.

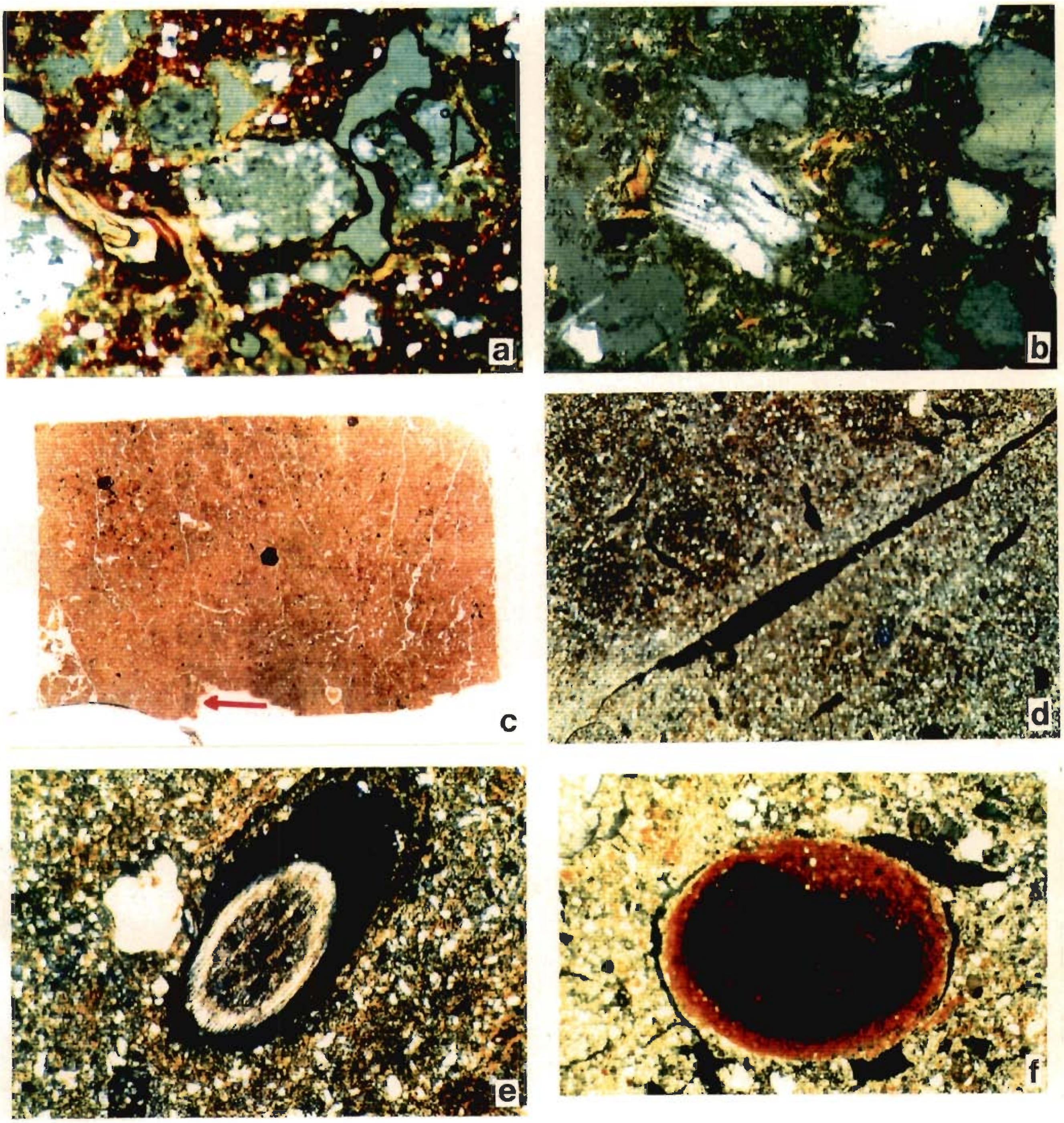

Fig. 4.3 (a) Sesquioxide hypo-coating along channels in the $IIBox_2$ horizon, Pedon LB5 of the Lateritic Upland. Frame length 1.4 mm, XPL; (b) Partially weathered plagioclase feldspar from $IIIBox_2$ horizon, Pedon LC1. Frame length 1.4 mm, XPL; (c) Moderately developed angular blocky structure, B2 horizon, Pedon L11 from the Bhagirathi-Brahmani Plain. Length of arrow 10 mm, ordinary light; (d) Elongated voids and channels from B1 horizon of Pedon L11. Frame length 3 mm, XPL; (e) Partially decomposed root fragment from A horizon of Pedon L11. Frame length 1.3 mm, XPL; (f) Granostriated b-fabric around a sesquioxide nodule from B2 horizon of Pedon L12. Frame length 1.4 mm, XPL.

4.3.2 Bhagirathi-Brahmani Plain

The soils of this unit are moderate medium to coarse angular blocky (Fig. 4.3 c). They are medium textured in the A and upper part of B horizon and fine textured in the deeper parts of B horizon. Randomly distributed elongated voids with length up to 5 mm and width up to 200 μm (Fig. 4.3 d) are common in A and upper parts of B horizon. The coarse fraction mostly consists of quartz grains and has commonly size of 300-500 μm and rarely up to 1 mm. The coarse particles are randomly distributed. In the deeper part of the B horizon a few grains of altered mica are observed. Biotite grains are opaque due to weathering leading to release of iron oxide. Some resistant heavy minerals with sharp boundaries are found embedded in the matrix. Common coarse root fragments are also present in A horizon and upper part of B horizon (Fig. 4.3 e). The coarse/fine limit (C/F) is 20 μm and the C/F related distribution is porphyric.

The fine fraction is mostly fine silt and clay. At places it is stained by ferruginous material. It occurs as groundmass and very thin coatings around pores and coarse mineral grains. The groundmass shows moderately developed speckled b-fabric in the A horizon and porostriated and granostriated (Fig. 4.3 f) in the B horizon. Oriented domains of stress coatings are quite common in Ap and upper part of B horizon (Fig. 4.4 a). Thin clay coatings (Fig. 4.4 b) and a few rounded sesquioxide nodules with diameters up to 4 mm and sharp external boundaries are present in the B horizon. 30-60 μm thick illuvial clay coatings are observed which constitute less than 1% of the area of the thin section. In the upper part of B horizon irregular clay concentrations are also observed (Fig. 4.4 c). In all the thin sections voids are partially or almost completely filled with fine material (Fig. 4.4 d). Excrement pedofeatures are also observed commonly in A and upper part of B horizon (Fig. 4.4 e). These features decrease with depth.

From the description of micromorphological features it can be concluded that

(a) Swell and shrink of the soil material has greatly influenced the structure and pedofeatures of the soils of this unit causing pedoturbation.

(b) Clay illuviation has taken place to a very minor extent.

(c) Features related to depletion and accumulation of sesquioxides occur throughout the studied depth (Fig. 4.5 a, b). These features are hypocoatings and small segregation and nodules of sesquioxides. The small sesquioxides accumulations <1 mm with diffuse or clear smooth boundaries indicate that they have been formed due to current processes and sesquioxide nodules with sharp external boundaries appear to have been inherited from parent material.

4.3.3 Brahmani-Ajay Plain

The soils of this plain have moderate angular blocky structure with ped faces being partially accommodated (Fig. 4.5 c, d). Voids are mostly vesicles with some vughs, planar voids and channels. The C/F limit is 10 μm and related distribution is single spaced porphyric to chitonic (Fig. 4.5 e). The soils are medium textured in A and upper part of B horizon and fine textured in deeper parts of B horizon.

The coarse fraction consists mainly of subrounded to subangular quartz grains with most common size range of 50-100 μm in upper part and 20-50 μm in the deeper parts of the profile. Other minerals are partially altered feldspars (orthoclase and plagioclase), mica (mostly muscovite) and some heavy minerals. Fine material is yellowish brown colour micaceous material and often contains micro-contrasted (black) particles in the deeper part. A horizon and upper part of B horizon show mostly porostriated and granostriated b-fabrics. But in the lower part of B horizon the parallel striated b-fabrics are more common. Crystallitic b-fabric is observed in petrocalcic horizon (II Km).

In the upper part of B horizon 50-60 μm thick oriented ferruginous clay coatings around voids occur at a few places (Fig. 4.5 f). A few ferruginous hypo-coatings and quasi-coatings in the same void were observed suggesting two different stages of accumulation. Stress coatings with oriented clay domains are observed occasionally (Fig. 4.6 a). Some micaceous material

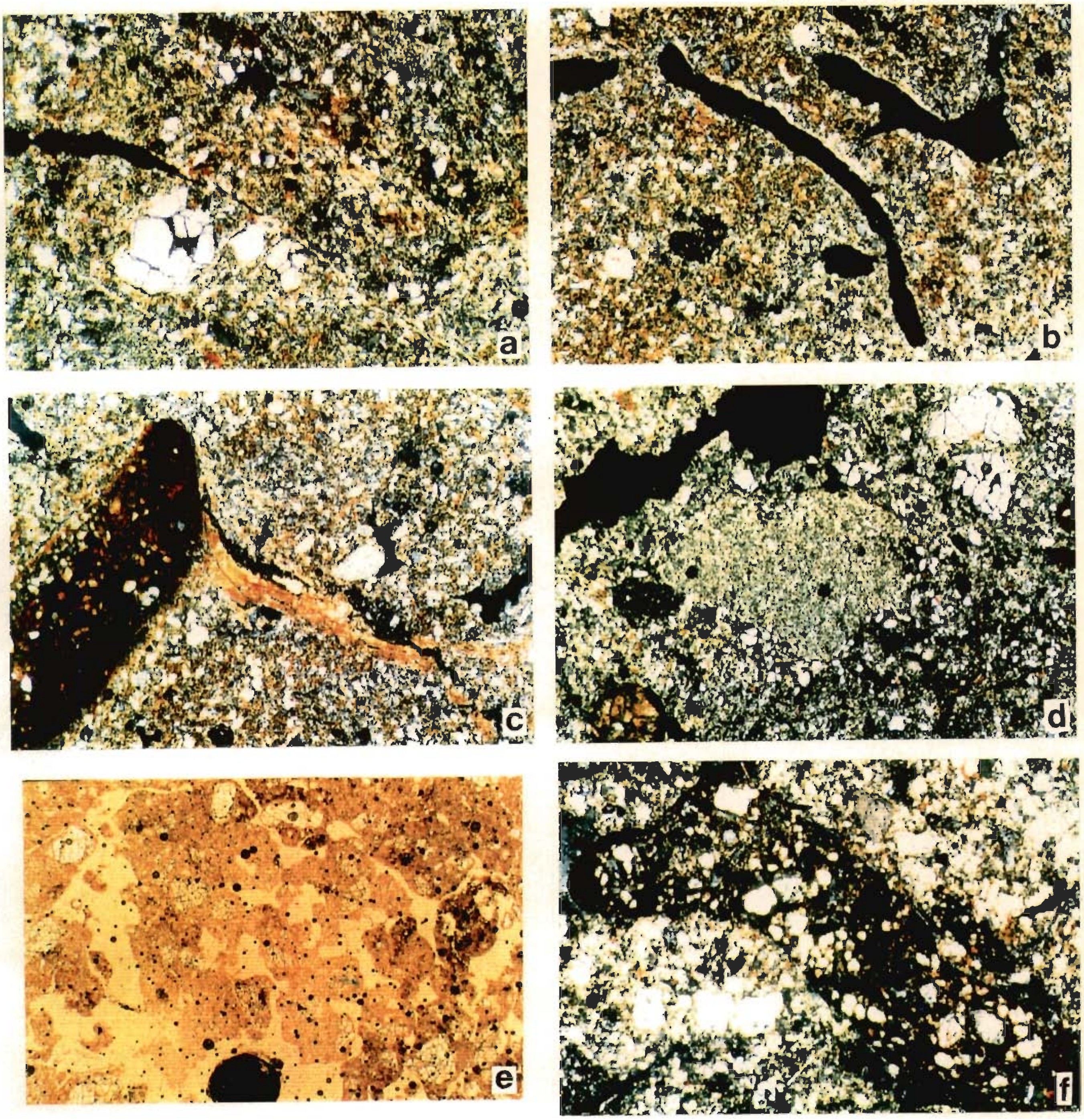

Fig. 4.4 (a) Stress-oriented clay domain along voids in B1 horizon of Pedon L12. Frame length 1.4 mm, XPL; (b) Thin clay coating around channel in B1 horizon of Pedon L 12. Frame length 1.4 mm, XPL; (c) Irregular ferruginous clay concentration along channel void in B1 horizon of Pedon L 11. Frame length 1.4 mm, XPL; (d) complete infilling of void with fine material in A horizon of Pedon L11. Frame length 1.4 mm, XPL; (e) excrement pedofeature in A horizon. Frame length 1.4 mm, PPL; (f) Loose continuous infilling of mineral excrements in A horizon of Pedon TL2, Bhagirathi-Brahmani Plain.

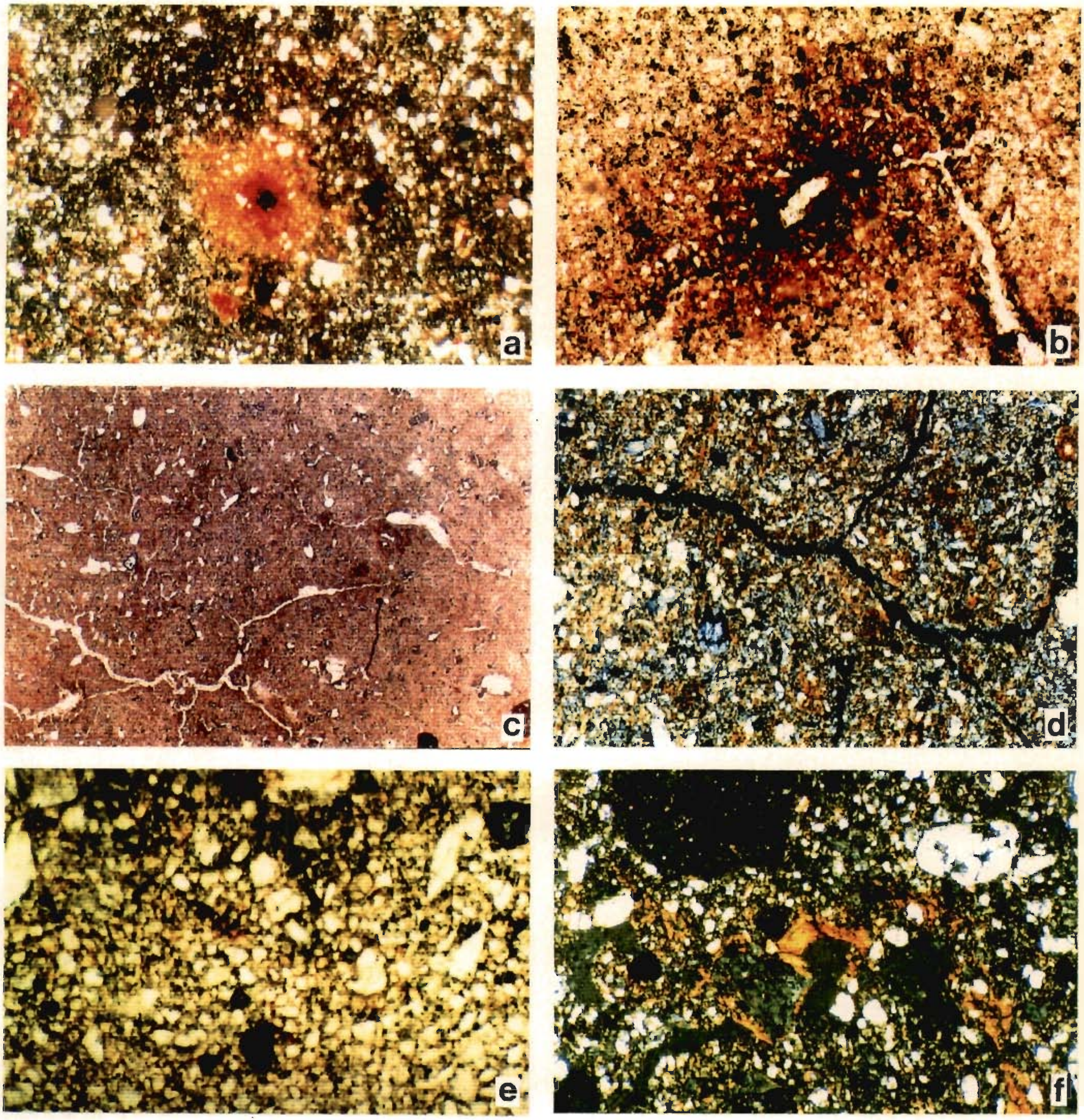

Fig. 4.5 (a) Sesquioxide accumulation and depletion features around root channel in A horizon of Pedon LC2. Frame length 1.4 mm, XPL; (b) ferruginous hypo-coating around void. Frame length 1.4 mm, PPL; (c) Partially accommodating and moderately well separated angular blocky peds from B2 horizon of Pedon LC4, Brahmani-Ajay Plain. Frame length 2 mm, ordinary light; (d) Same as (c) but frame length is 1.4 mm and XPL; (e) Chitino-porphyric related distribution in B1 horizon of Pedon LC2. Frame length 1.4 mm, XPL; (f) Illuvial clay coating around void in lower part of B2 horizon, Pedon LC2. Frame length 1.4 mm, XPL.

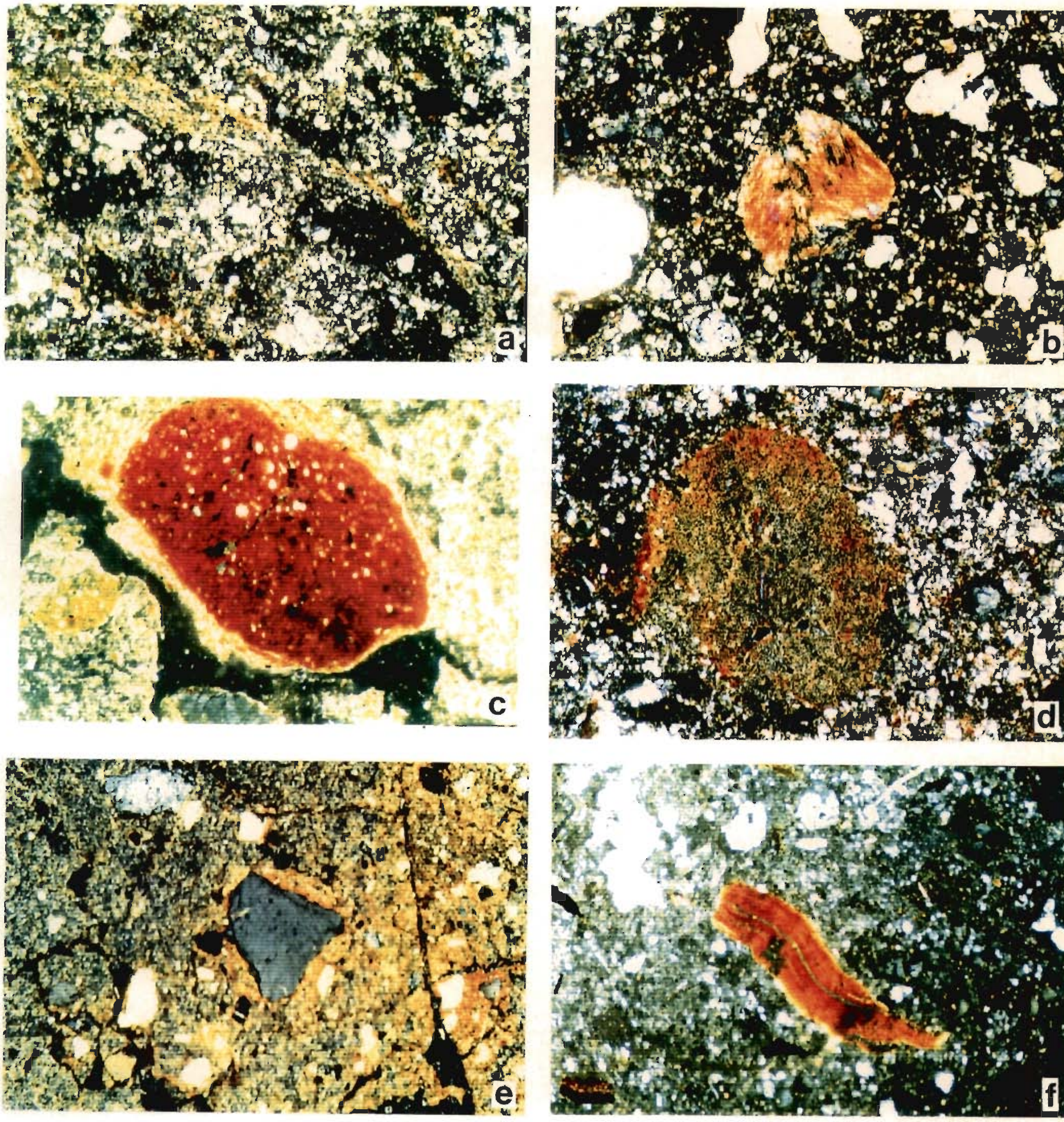

Fig. 4.6 (a) Stress-oriented clay coating around void in B2 horizon of LC2 Pedon. Frame length 1.4 mm, XPL; (b) feather-like weathering grain of mica, Pedon LC2. Frame length 1.4 mm, XPL; (c) Sesquioxide nodules with sharp external boundary from B2 horizon of Pedon LC3. Frame length 1.4 mm, XPL; (d) weakly impregnated sesquioxide nodules with diffuse external boundary in B1 horizon of Pedon L18. Frame length 1.4 mm, XPL; (e) Coarse angular blocky structure with accommodating boundaries (right half) and granostriated b-fabric in B1 horizon of Pedon LB1, Ajay-Silai Plain. Frame length 1.4 mm, XPL; (f) Biotite grain showing exfoliation weathering, Pedon LB1. Frame length 1.4 mm, XPL.

shows feather-like weathering pattern (Fig. 4.6 b). A few deformed papules are also observed. Over the whole studied depth a few sesquioxide nodules of diameter up to 3 mm, with sharp external boundaries occur (Fig. 4.6 c) whereas small sesquioxide accumulations, diameters < 1 mm, with clear or diffuse external boundaries are common (Fig. 4.6 d) only in the upper part of the profile.

4.3.4 Ajay-Silai Plain

Soil thin sections from this unit show fine texture and moderate to strong coarse angular blocky structure (Fig. 4.6 e). Channels and planer voids are common. The coarse fraction consists mainly of fine sand size quartz. A few grains of partially altered microcline and mica are also observed (Fig. 4.6 f). The fine fraction consists of silt and clay size particles and occurs as coatings on voids and grains. Clay particles are speckled and dotted in appearance. The coarse/fine limit is 20 μm and the C/F related distribution is gefuric and porphyric. Granostriated and porostriated b-fabrics are commonly observed in upper part of B horizon (Fig. 4.6 e and Fig. 4.7 a). Towards the deeper parts parallel striated b-fabrics become more common (Fig. 4.7 b).

Textural pedofeatures include mostly of typic clay coatings about 30-50 μm around voids at a few places. Sesquioxide accumulations and nodules are observed in all the thin sections. They are of <2 mm diameter in the Ap and B1 horizon (Fig. 4.7 c) and increase to 5 mm in B2 horizon, and have very sharp external boundaries. Strongly developed stress coatings are also observed in upper part of B horizon (Fig. 4.7 d). In the dipper parts of profile specks of calcite disseminated in the voids and in the groundmass are observed.

Accumulation of sorted materials around voids and infillings may have taken place due to periodical waterlogging in the topsoil causing movement of the particles in the existing voids. Occurrence of sesquioxide accumulation along root channels of topsoil and upper part of B horizon is perhaps due to periodic oxidation and reduction caused by periodic wetting and drying of soil material.

4.3.5 Damodar Terminal Fan

Soils of this unit have weakly to moderately developed medium subangular blocky structure and medium texture (Fig. 4.7 e). The voids are mostly vughs and vesicles which are not interconnected or intersected (Fig. 4.7 f). The C/F ratio varies from 50/50 to 40/60. the coarse fraction (mostly 100-150 μm) consists mainly of subangular to subrounded quartz, weakly altered mica (Fig. 4.8 a), feldspars, hornblende and a few heavy minerals. Plant remains are very commonly observed in Ap horizon. The finer fraction consists of yellow colour fine silt and clay with microcontrasted particles and they are often stained by iron-oxide (Fig. 4.8 b). They show weakly to moderately developed reticulate to cross striated b-fabric (Fig. 4.8 c). Parallel striated b-fabric is also observed occasionally.

Well developed bluish grey colour gleyans and flood-coatings (Gerrard, 1992) up to 150 μm thick are commonly observed in B horizon (Fig. 4.8 d). These coatings are very weakly oriented and have diffuse boundaries against groundmass and contain some silty material. These features suggest that the formation of coatings might have taken place due to the movement of finer material (silt and clay) during flooding (Fig. 4.8 e, f). Elongate thin ferruginous clay accumulations with diffuse boundaries occurring in the groundmass may be due to the weathering of mica. Disturbed fragments of thick laminated clay often observed in the lower part of A and B horizon are of relict origin and might have been derived from the older units lying further west (Fig. 4.9 a, b). Sesquioxide nodules in the form of pedorelict (Brewer and Sleeman, 1960) embedded in the groundmass are observed in B1 horizon (Fig. 4.9 c, d). Small accumulations of sesquioxides are common. They have clear or diffuse external boundaries which indicate that their formation is due to current processes (Fig. 4.9 e).

4.3.6 Barind Tract

The soils of this unit have weak to moderate fine subangular blocky structure. Randomly distributed channels and intrapedal planar voids are observed commonly. The coarse fraction consists mainly of quartz with some mica and plagioclase feldspars and a few heavy minerals

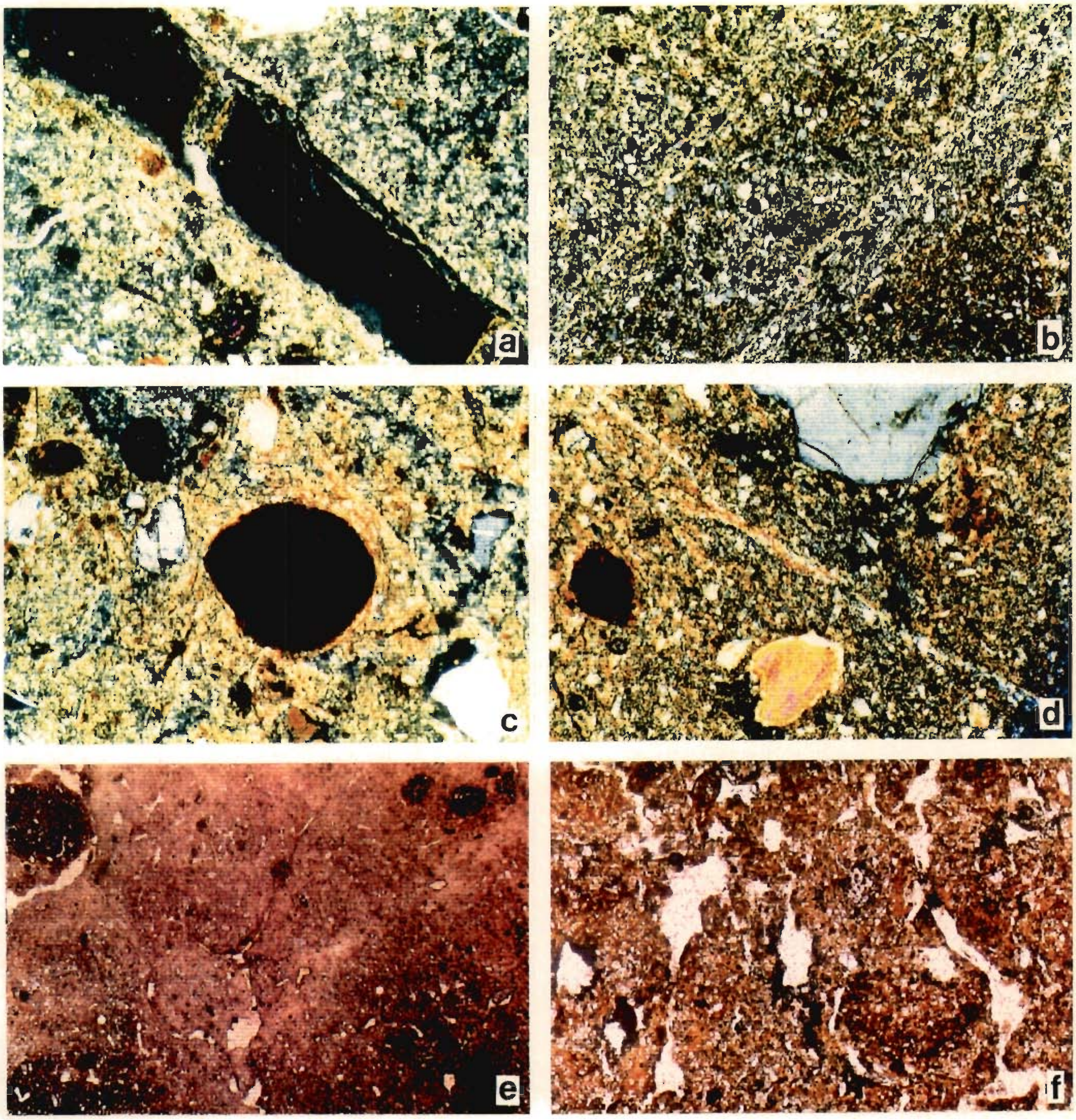

Fig. 4.7 (a) Porostriated b-fabrics in B1 horizon of Pedon LB11. Frame length 1.4 mm, XPL; (b) Parallel striated b-fabrics in deeper part of B2 horizon of Pedon LB2. Frame length 1.4 mm, XPL; (c) strongly impregnated sesquioxide nodule with sharp external boundary, B1 horizon of Pedon LD1. Frame length 1.4 mm, XPL; (d) stress-oriented clay domain in B1 horizon of Pedon LB1. Frame length 1.4 mm, XPL; (e) weakly developed and partially separated subangular peds (left centre) from B2 horizon of Pedon LB4, Damodar Terminal Fan. Frame length 20 mm, ordinary light; (f) vughy structure from B1 horizon of Pedon LB3. Frame length 20 mm, ordinary light.

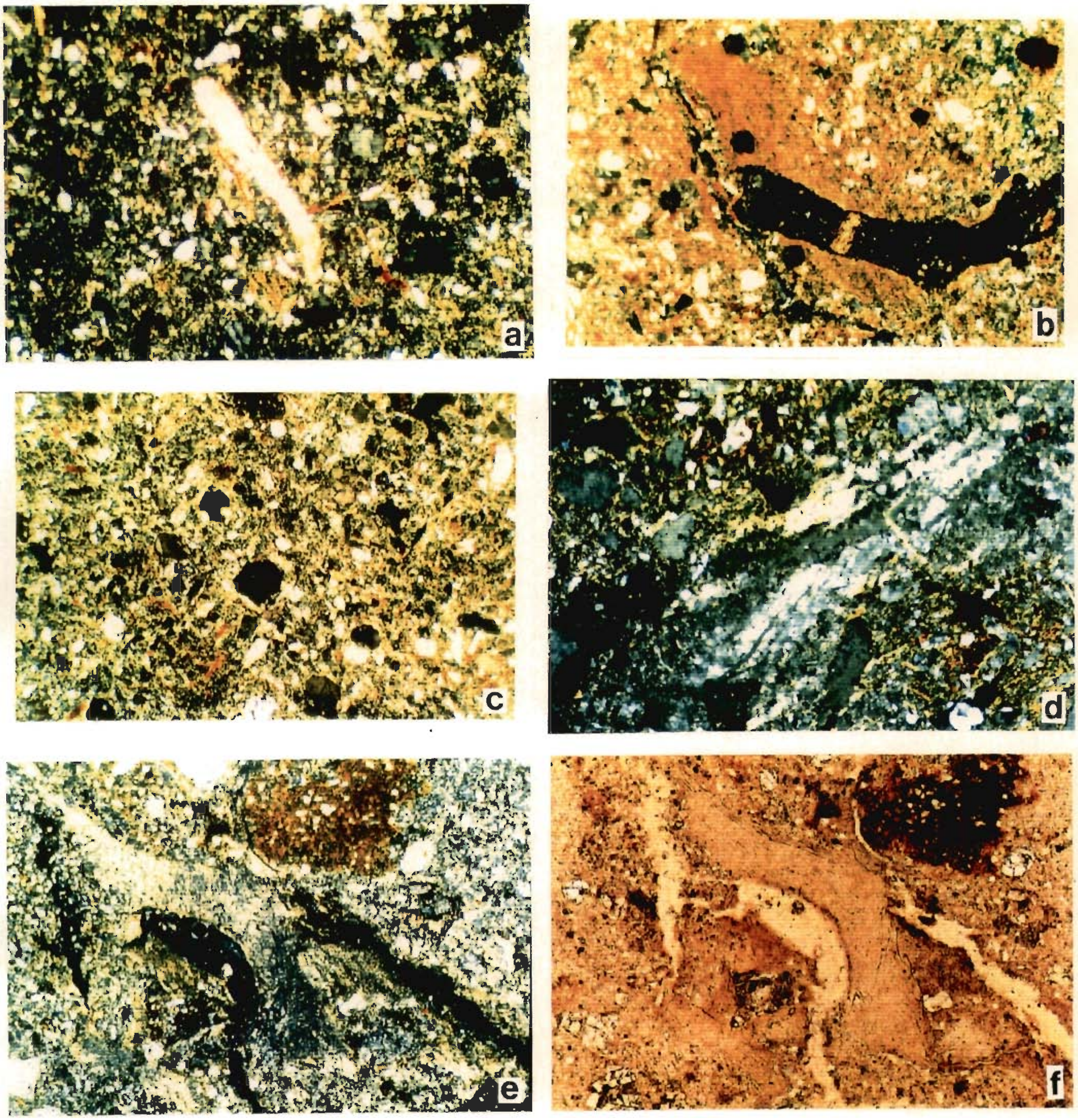

Fig. 4.8 (a) Weakly altered muscovite from B1 horizon of Pedon LB4. Frame length 1.4 mm, XPL; (b) clay concentration feature around void with micro contrasted particles, Pedon LD1, B2 horizon. Frame length 1.4 mm, XPL; (c) weak reticulate striated b-fabric, B2 horizon, Pedon LB4. Frame length 0.3 mm, XPL; (d) Bluish gray colour gleyans around voids in B1 horizon of Pedon LB3. Frame length 2.8 mm, XPL; (e) Feature indicating movement of silty material around void, from A1 horizon of Pedon LB3. Frame length 1.4 mm, XPL; (f) Same as (e) but PPL.

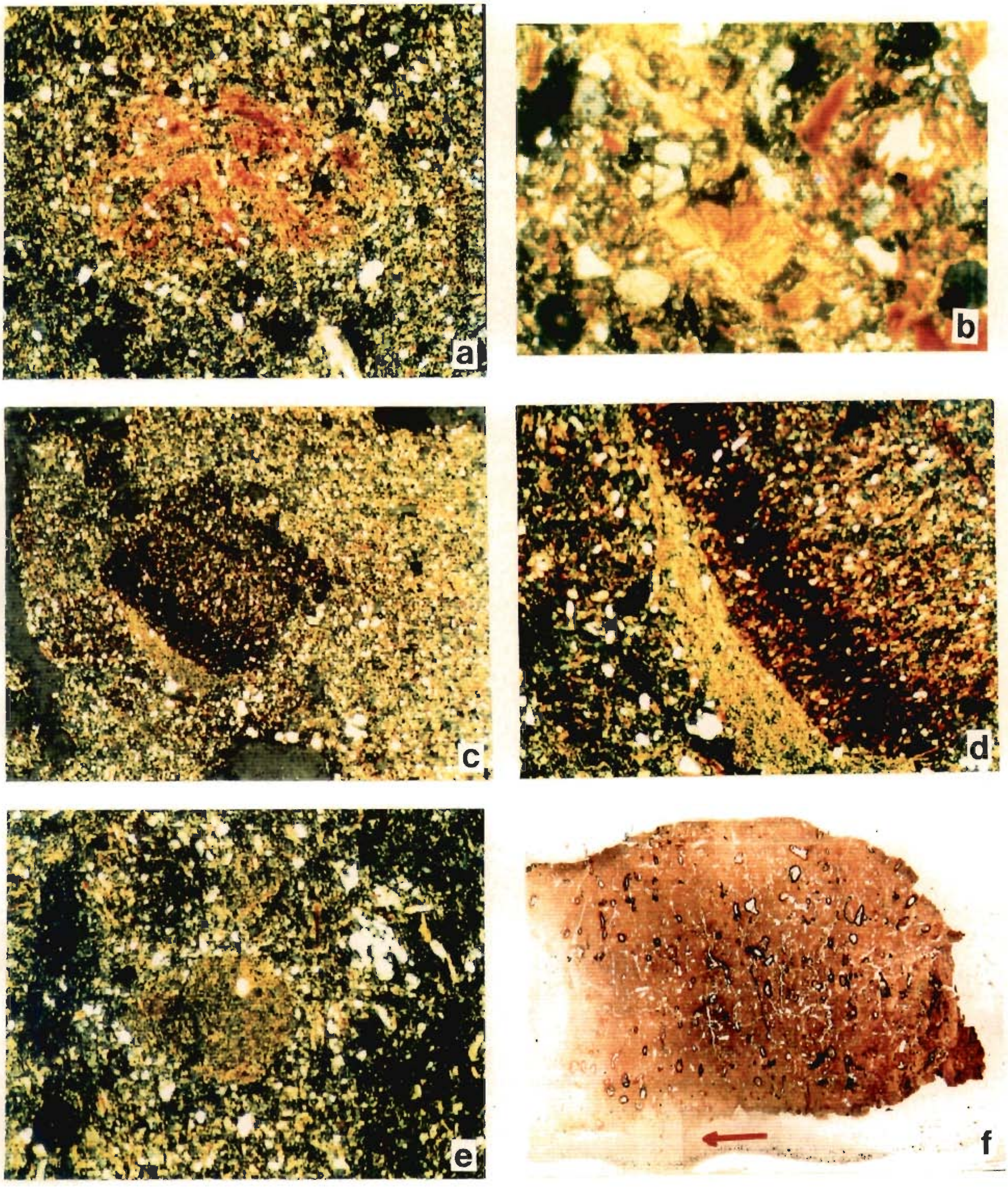

Fig. 4.9 (a) Derived disrupted papules from A horizon of Pedon LD3. Frame length 1.4 mm, XPL; (b) Disrupted ferruginous clay accumulation zone and weathering biotite in B2 horizon of Pedon B4. Frame length 0.3 mm, XPL; (c) Pedorelicts from B1 horizon of Pedon LD3. Frame lenght 7.5 mm, XPL; (d) same as (c) but Frame length 1.4 mm; Note the difference in fabric orientation; (e) weakly impregnated nodule with diffuse boundary from Pedon LD3. Frame length 1.4 mm, XPL; (f) Iron oxide segregation features forming mottles and nodules in A1 horizon of Pedon LB4. Length of arrow 10 mm, ordinary light.

of silt size ranging between 20 to 50 μm. Some heavy mineral (pyroxene) grains with diameters up to 500 μm have hacksaw edges due to corrosion. They occur in a random distribution pattern. Micas show exfoliation due to weathering. Intensity of weathering is moderate.

The groundmass consists mainly of clay-size particles. The coarse/fine (C/F) size limit is 20 μm and the C/F related distribution is porphyric. Weak to moderate cross and reticulate striated b-fabrics are observed (Fig. 4.10 a). Occasionally parallel and monostriated b-fabrics are also observed (Fig. 4.10 b). Occasional thin (30-40 μm) clay coatings along channels and planar voids are also observed (Fig. 4.10 c). Some papules occur between 0.5 to 0.7 m depth. Various types of calcrete pedofeatures such as moderately impregnated orthic micritic nodules of >2 mm size with diffuse boundary, hypo-coatings and infillings in voids (Fig. 4.10 c) occur in lower part (0.7 m depth). Irregular, generally compound, sesquioxide nodules with diffuse to abrupt outlines increase with depth from 0.4 m onwards (Fig. 4.10 e). Digitate and aggregate nodules are also very common. Locally, ferruginous hypo-coatings are superimposed on clay coatings and papules (Fig. 4.10 d). The rounded sesquioxide nodules with abrupt outlines contain fewer coarse soil material than the surrounding groundmass. This, together with their abrupt outlines, suggests that they may date from an early stage of soil formation. In the lower horizon (C horizon) clay intercalations (Fig. 4.10 f) are also observed.

4.3.7 Bhagirathi Plain

The soils of this unit have weak angular blocky structure and medium texture. Voids are mostly vughs, vesicles and channels which are randomly distributed. The C/F limit is 10 μm and related distribution is monic to close porphyric (Fig. 4.11 a). The coarse fraction consists of angular quartz, feldspar and weakly altered mica. The most common size range of coarse fraction is 50-100 μm. Fine fraction consists mainly of clay-size particles which show stipple-speckled b-fabric. Some fine silty accumulations are observed around voids (Fig. 4.11 a, b). Voids are infilled with soil material and welded, shaped mineral excrements (Fig. 4.11 c). Small accumulations of sesquioxide with generally diffuse external boundaries occur in the B horizon. Remnants of sedimentary layering is observed in the B horizon (Fig. 4.11 d). Occurrence of sorted fine material around voids indicate that the soil is periodically saturated with water causing movement of fine grained materials in the existing voids (Fig. 4.11 a). Over the whole studied depth accumulations of sesquioxide in the form of mottles and diffuse nodules are found.

4.3.8 Old Ganga Plain

The soils of this unit are apedal to weakly pedal. The voids are mostly packing voids and intergrain channels with a few vughs and vesicles. They are medium textured. The C/F limit is 20 μm and related distribution is monic to close porphyric. The coarse material consists mainly of sub-rounded quartz (50-75 μm in upper part and <50 μm in the deeper part), slightly altered mica (Fig. 4.11 e), feldspar and other minerals in minor quantities. The finer fraction consists of yellowish brown to grayish brown colour fine silt and clay. Stipple-speckled b-fabric (Fig. 4.11 f) is common in the A horizon. The mica grains have preferred orientation throughout the studied depth. The deeper part of the profile shows well developed parallel striated b-fabric (Fig. 4.12 a). Also a few coatings of fine silt and sesquioxide are found in the deeper part. The sesquioxide accumulations have diffuse external boundary. A few voids are completely filled with soil material. Shells and snails are common in surface horizon suggesting fluvial action. Remnants of sedimentary layering are observed in the deeper part of the horizon.

The presence of shells and snails, remnants of sedimentary layering and absence of illuvial clay coatings in the upper part of the profile suggests that the soil is very slightly developed. Occurrence of moderately developed b-fabric and accumulation of sesquioxides and fine silt around voids at 116-150 cm depth suggests that some development has taken place in the lower part. The top portion might have been deposited on the eroded surface of weakly developed soil at a comparatively recent time. Thus the lower part indicates the presence of a weakly developed paleosol.

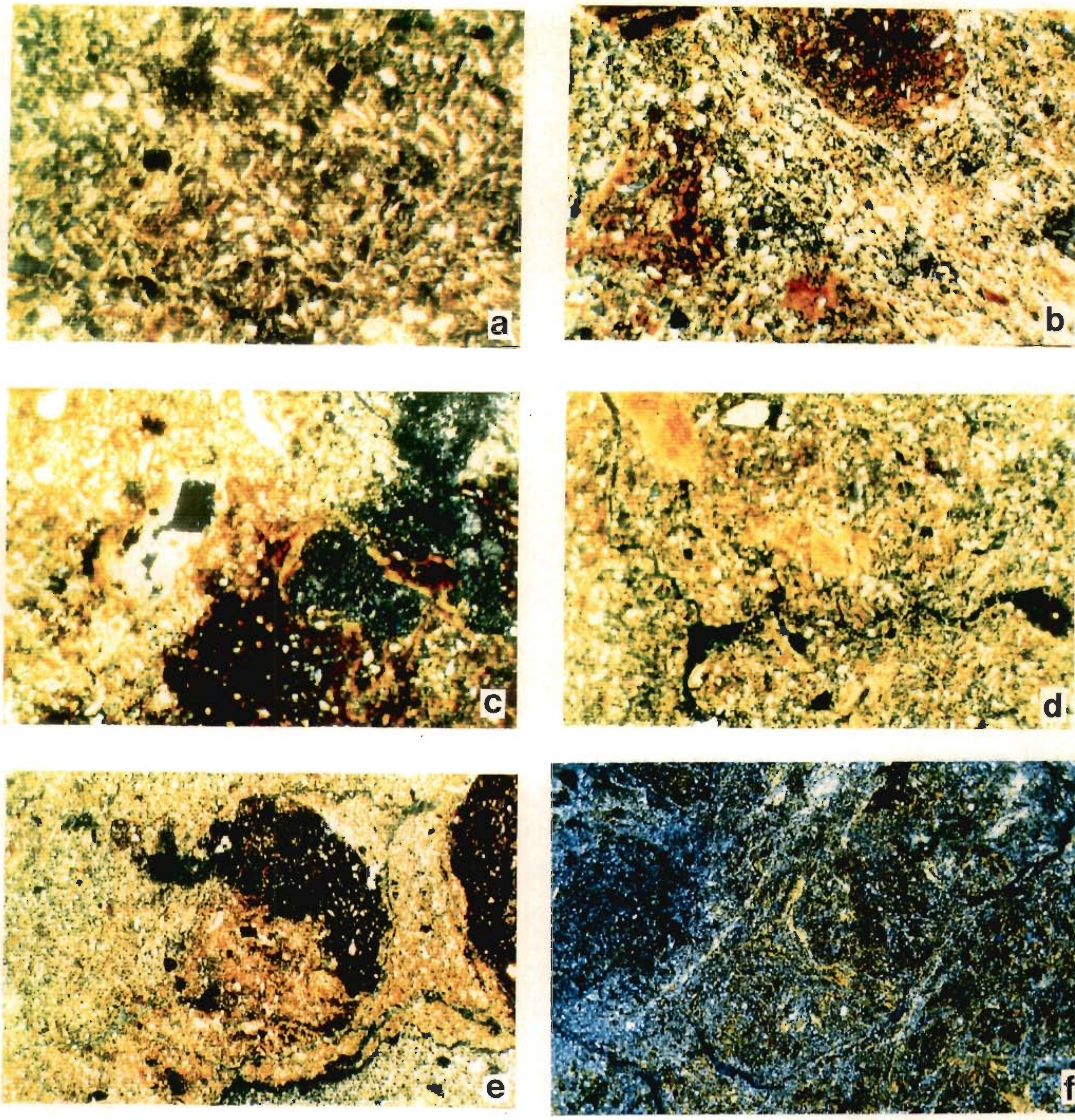

Fig. 4.10 (a) Cross and reticulate striated b-fabrics and weathering muscovite in B2 horizon, Pedon LA1, Barind Tract. Frame length 0.7 mm, XPL; (b) Parallel striated b-fabrics from B2 horizon of Pedon L1. Frame length 1.4 mm, XPL; (c) clay coating around voids. B2 horizon of Pedon LA2. Frame length 1.4 mm, XPL; (d) Disrupted shaped papules in the centre of the photograph, B2 horizon, Pedon LA1. Frame length 1.4 mm, XPL; (e) irregularly impregnated compound nodules from B2 horizon of Pedon LA2. Frame length 3 mm, XPL; (f) clay intercalations in C horizon, Pedon LA2. Frame length 1.4 mm, XPL.

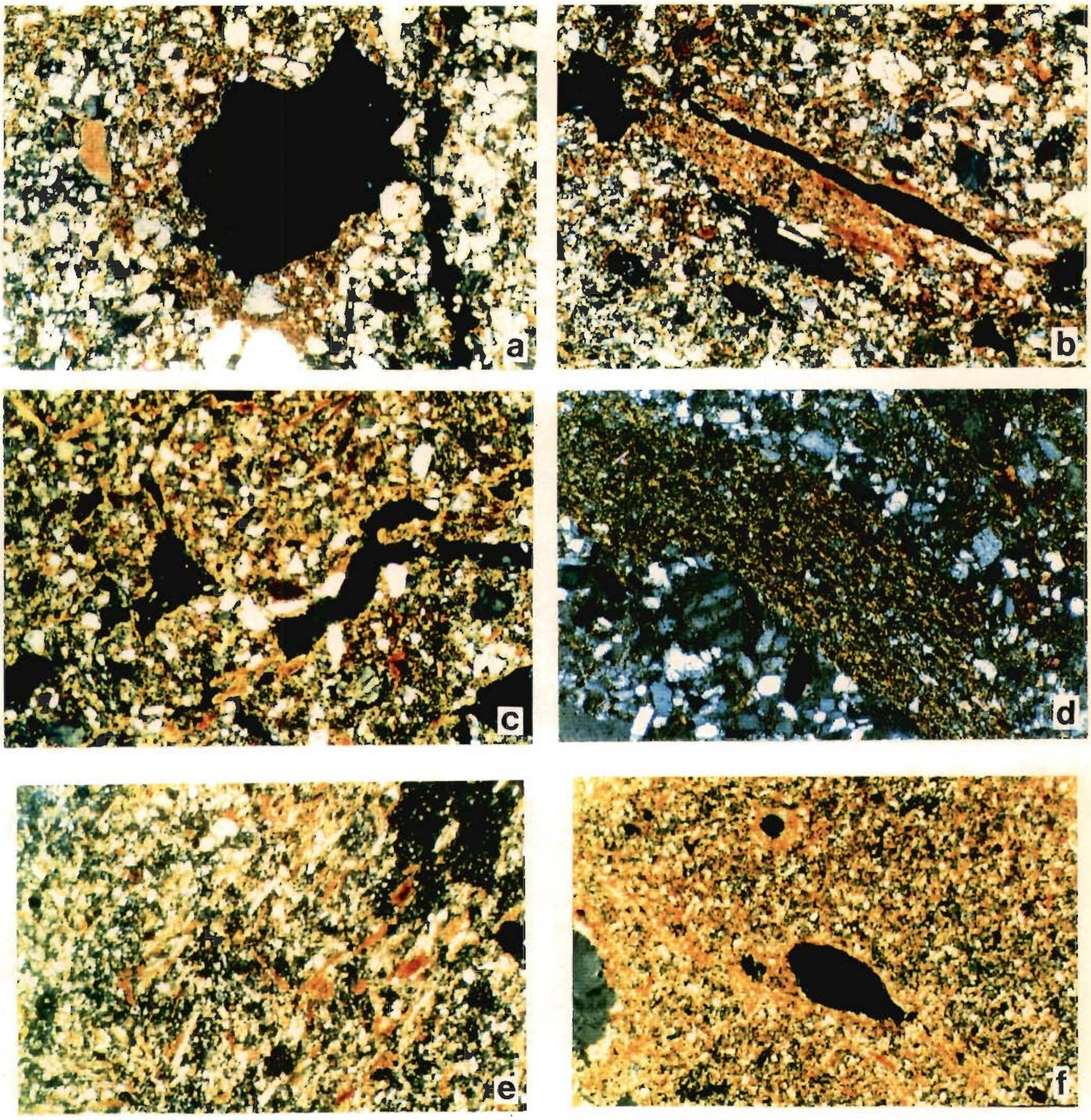

Fig. 4.11 (a) Monic to close porphyric related distribution in B horizon, Pedon L15, Bhagirathi Plain; also, note the accumulation of fine matter around the void. Frame length 1.4 mm, XPL; (b) Accumulation of silty material stained with iron-oxide around channel void, Pedon C5. Frame length 1.4 mm, XPL; (c) Loose infilling of void with soil material in A horizon, Pedon L15. Frame length 1.4 mm, XPL; (d) Remnants of sedimentary layering in B horizon; mark the alternate layering of coarse and fine material. Frame length 1.4 mm, XPL; (e) slightly altered mica from IIB horizon of Old Ganga Plain, Pedon L2. Frame length 1.4 mm, XPL; (f) Stipple-speckled b-fabric and accumulation of fines around void in Pedon L2 indicating their accumulaltion during flooding. Frame length 1.4 mm, XPL.

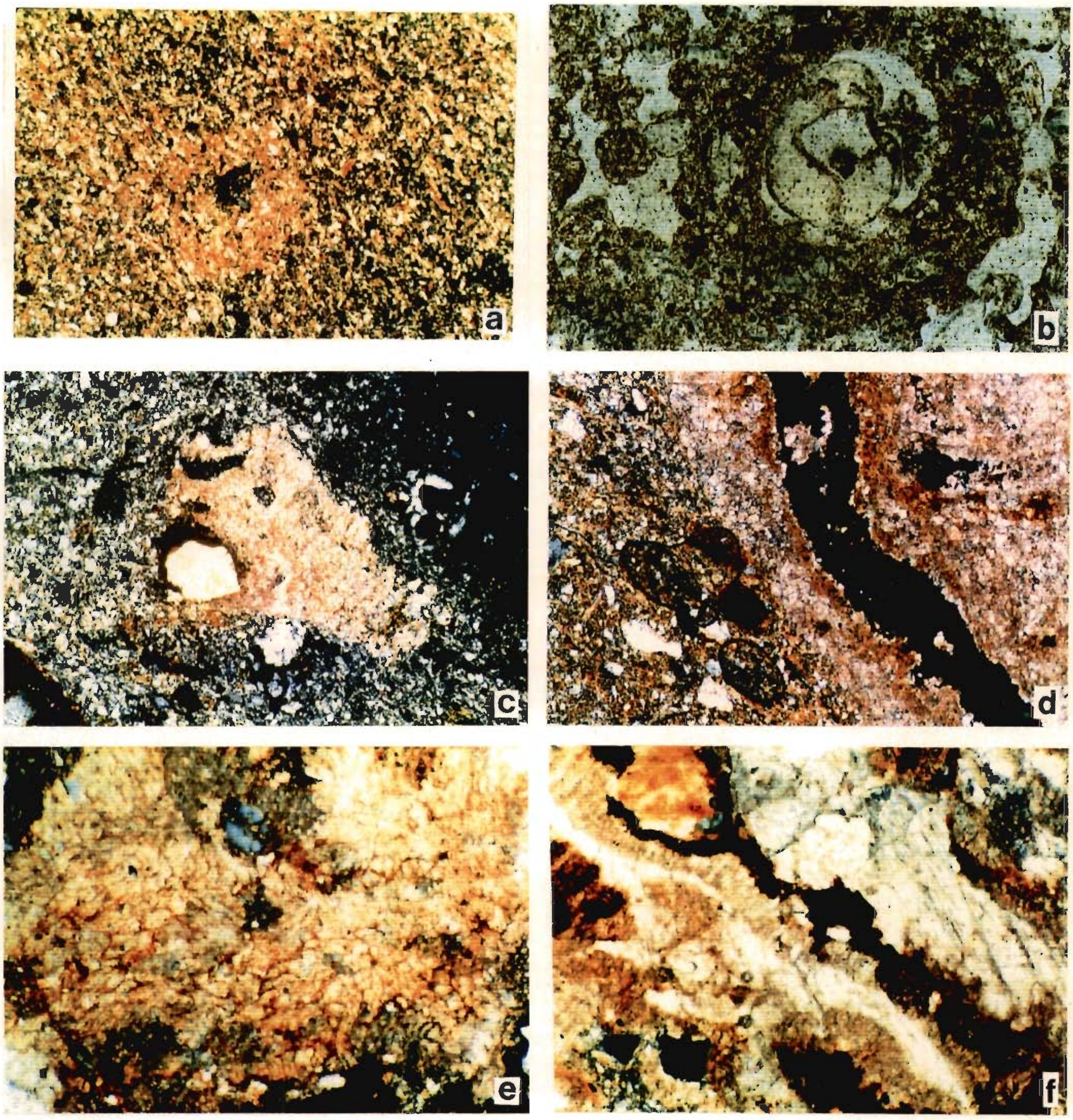

Fig. 4.12 (a) Parallel striated b-fabrics showing preferred orientation of mica grains, Pedon L21, Old Ganga Plain. Frame length 1.4 mm, XPL; (b) Gastropod sheil from Pedon L2. Frame length 1.4 mm, PPL; (c) Micritic calcite showing crystallitic b-fabric from IIKm horizon of Brahmani-Ajay Plain. Frame length 1.4 mm, XPL; (d) Calcite hypo-coating in the same horizon superimposed by sesquioxide hypo-coating. Frame length 1.4 mm; (e) Strongly impregnated descrete sparitic calcite nodule with ferruginous impregnation. Frame length 2.8 mm, XPL; (f) Sparitic clacite nodule variously impregnated with iron oxide/hydroxide, IIKm horizon. Brahmani-Ajay Plain. Frame length 1.4 mm, XPL.

4.3.9 Raghunathganj Soil/Surface

Micromorphological studies of calcrete from the II Km horizon of the Brahmani-Ajay Plain show the presence of micritic as well as sparitic calcrete occurring in the form of matrix impregnation, coatings, infillings and as descrete nodules (Fig. 4.12 c, d, e, f). The sparitic nodules have sharp boundaries and show the presence of ferric oxide/hydroxide impregnations. The discrete nodules with sharp boundaries indicate that they have been formed by past pedogenic processes. The presence of ferric oxide/hydroxide impregnation together with its association with diffuse micritic calcrete features indicate that the sparitic nodules formed in the past is being modified by the current pedogenic processes occurring in the upper part of the profile. Earlier Sehgal and Stoops (1972), Bal (1975) and Kemp (1985) suggested that the formation of similar sparitic nodules with ferruginous impregnations indicate multicyclic formation in course of soil development.

4.4 Resume

Micromorphological studies of the undisturbed soil samples indicate that from Group I to Group V member soils distinct variations are observed in the features such as the grade of pedality, degree of b-fabric development, intensity of weathering, alteration of primary minerals, formation of sesquioxide nodules and abundance and thickness of illuvial argillans.

Soils of Group I are apedal. Pedality is weakly developed in Group II soils and they contain remnants of sedimentary layers. Soils are weakly to moderately developed in Group III and moderately to strongly developed in Group IV. Peds are very strongly developed in Group V soils.

Most commonly observed microstructure in majority of soils is subangular blocky type. However, the oxic horizon of Lateritic soils of Group V shows crumby microstructure.

Voids are channels, chambers, vughs and planar voids. The nature and abundance of voids are closely related to the C/F ratio. The fine grained soil material is deeply intersected by channels and chambers, with occasional microvughy structure, whereas the coarse grained soils have fewer channels or chambers. In active floodplains (group I) and the Old Ganga Plain (Group II) generally intergrain voids are observed giving rise to various intergrain microstructure. The void surfaces get smoothened in the horizons having clay coatings around the voids e.g., in Group III, Group IV and most commonly in Group V soils.

The soils with coarser parent material as those of the Old Ganga Plain and associated paleochannels exhibit commonly monic and close porphyric related distributions whereas fine textured soils of the other groups have predominantly porphyric related distribution.

The finer fraction of the soil material shows a variety of b-fabrics. The degree of development and abundance of b-fabrics increase from Group I to Group IV soils. In Group I and Group II soils stipple-speckled to parallel striated b-fabrics are more common. The Group III soils (e.g DTF) show weak to moderate cross and reticulate b-fabrics. Soils of Group IV show mostly poro-striated and grano-striated b-fabric in upper part of the profile and parallel striated b-fabrics in lower part. The extensive and frequent wetting of 2:1 swelling clays of these soils might have caused swelling of soil matrix. This probably led to compression and realignment of particles adjacent and parallel to the void surfaces and thus gave rise to poro-striated b-fabric. Parallel striated b-fabrics may have developed due to the closure of some of the planar voids caused by repeated wetting. Lateritic soils of Group V show undifferentiated to weak stipple speckled b-fabric probably due to the presence of sesquioxides.

The soils of the study area show different stages of weathering ranging from weak to strong alteration of the minerals. The effects of weathering are particularly observed in the coarse grains of the soil materials. Weathered flakes of biotite split and open up along the cleavage plains giving rise to exfoliation weathering pattern. Pellicular, cross-linear and irregular weathering features are also observed.

Clay illuviation features are absent in Group I and Group II soils. Group III soils of the Damodar Terminal Fan have flood-coatings together with thin (20-30 μm) illuvial clay coatings. The flood-coatings have lamellae which are very weakly oriented and contain some silty material. Lack of directional anisotropism and presence of silty material in these clay coatings indicate that their formation might have taken place due to the movement of the finer material (silt and clay) during flooding and they don't represent the true illuviated coatings (Bullock and Thompson, 1985; Gerrard, 1992). The Barind Tract (Lower Level) soils of Group III have thin (30-40μm) clay coatings, deformed and broken papules and calcretes.

The vertic intergrade soils of Group IV show deformed clay feature (papules), slickensided ped faces, stress coatings and thin (30-60 μm) illuvial clay coatings. The clay coatings in these soils generally consist of limpid to speckled clay. The presence of poro-striated, grano-striated and parallel striated b-fabric in these soils indicate stress-oriented origin. The presence of illvial clay coatings in the Ap horizon of BBP soils indicate that they would have been formed in the underlying B horizon and subsequently would have been lifted up due to pedoturbation. The soils of this unit wet deeply because of the cracks which open to the surface. This probably causes the soils at the bottom of the cracks to wet first. Due to expansion the wet soil lifts the column of drier soil between the cracks leading probably to churning or mixing. Translocation of clay might have occurred in the upper part of B horizons also but the peds are too unstable to preserve the illuvial clay coatings due to pedoturbation. As mentioned earlier, thin (30-60 μm) illuvial ferruginous clay coatings are observed in lower part of profile in these soils.

The upper unit of Lateritic Upland soils show the presence of rounded sesquioxide nodules, papules, embedded grain-coatings and runiquartz. The lower unit contains microlaminated thick (200-300 μm) clay coatings, micropans, irregular shaped nodules, void hypocoatings of ferruginous material and angular quartz.

The presence of a variety of ferruginous segregation features indicate that their formation must have taken place in response to a number of pedogenic processes such as weathering of iron-bearing minerals followed by reduction and oxidation leading to different forms. The diffuse nature of boundaries of nodules is indicative of their formation by current pedogenic processes whereas the nodule with sharp external boundaries may be interpreted as having been inherited from the parent material or past pedogenic processes.

Calcrete pedofeatures were observed in Group IV soils are of two types. The micritic calcrete features with diffuse boundaries indicate their formation due to current pedogenic processes whereas the descrete sparitic nodules with ferruginous impregnations in the Raghunathganj soils/surface seems to be of relict origin. The later variety is in the stage IV of carbonate morphology of Gile et al. (1966). Calcretes of Group III soils of the Barind Tract are of current pedogenic origin.

CHAPTER 5

THERMOLUMINESCENCE STUDIES

5.1 Introduction

Once the characteristics and the genesis of a particular soil has been established by field and laboratory studies, it is important to date the soil-forming episodes in order to reconstruct the past climatic regimes and deduce stable/unstable phases in the history of landscape. Thus, an attempt was made to date the soils of various soil-geomorphic units of the study area. In view of the questionable reliability of ages obtained by various radiometric methods such as radiocarbon due to the dynamic nature of soil-forming processes i.e. activity of soil organisms, mobility of salts and pedoturbation, luminescence method was used to attempt the dating of different groups (Group I to Group V) of soils. This chapter presents a brief review of various radiometric methods and their limitations. Also, a brief summary of the methodology used in thermoluminescence (TL) dating, the effect of soil-forming processes on the dating signal and TL dates for soil development in different units have been discussed in this chapter.

5.2 Methods for Dating of Soils

5.2.1 Radiocarbon Dating

The radiocarbon, an isotope of carbon is produced in the atmosphere by nuclear reaction between slow cosmic-ray neutrons and the stable ^{14}N. The atoms of $^{14}_{6}C$ form $^{14}_{6}CO_2$ molecules in the atmosphere. The concentration of $^{14}_{6}C$ i.e. the ratio of $^{14}C/^{12}C$ in living organisms is maintained at a constant level by its absorption from the atmosphere and its continuous decay. When the plant or animal dies, the absorption of ^{14}C from the atmosphere stops and thus the $^{14}C/^{12}C$ ratio starts declining as a result of radioactive decay of ^{14}C. If the activity of ^{14}C in living tissue is known, the activity of ^{14}C of dead tissue can be used to calculate the time elapsed since death. This is the basic principle behind radiocarbon dating. An important aspect in application of this method is the fact that the sample should have behaved as a closed system i.e. since its death there was no addition of any young or old carbonate.

In this context, a major difficulty is due to contamination by younger materials in the sample (e.g. roots, humic acid) and thus the date obtained from the total soil carbon is the 'mean residence time' of the various organic components (Scharpenseel, 1971). The less resistant components have small mean residence times (<400 years) than the more resistant ones, which have mean residence times reaching up to 5000 years (Paul et al., 1964). Another problem with radiocarbon dating is that the incorporation of ^{14}C produced by recent thermonuclear testing into the organic matter of modern biologically active soils has decreased their apparent radiocarbon ages (Scharpenseel and Schiffman, 1977). Thus depending on the local geology and hydrology, precipitation, extent of leaching, the age of a soil horizon can be over (or under) estimated.

5.2.2 Beryllium-10 Method

Beryllium-10 is produced in the atmosphere by the interaction of cosmic protons and neutrons with nitrogen and oxygen. Radioactive ^{10}Be with a mean life of $\approx$ a million years is then deposited into soils, sediments and rocks by precipitation. Ideally, as the soil develops, the ^{10}Be inventory in the soil column increases as a function of time and hence it can be used for dating of soils. But the production rate of ^{10}Be is known to vary with time. This raises the question that whether the ^{10}Be input to geological reservoirs has remained sufficiently constant with time to permit its use as a dating tool.

5.2.3 Chlorine-36

^{36}Cl is produced by spallation reactions induced by cosmic-ray protons interacting with argon atoms. The half-life of ^{36}Cl is 3.08×10^5 years. After a residence time $\approx$ 1 week, ^{36}Cl is removed from the atmosphere by rain and snow and is introduced into hydrosphere. The ^{36}Cl abundance in an exposed chloride-containing sediment increases until a saturation activity of ^{36}Cl, A_∞ is reached. If the sediment is exposed, ^{36}Cl is produced for a length of time (t_{exp} -t_d) (sediment exposure age), followed by a period t_d (decay age) during which the sediment is covered and only ^{36}Cl decay occurs. The ^{36}Cl activity, A, due to both the processes is given by

$$A = A_{\infty}(1-e^{-\Gamma(texp-td)})e^{-\Gamma td} \text{ --------- } (1)$$

Since the equation (1) contains two unknowns, t_{exp} and t_d, one of these must be estimated using geological considerations. Another uncertainty exists in the evaluation of the saturation concentration A_{∞} of ^{36}Cl which is necessary for age calculation. Its concentration depends on the cosmic radiation flux at the sampling site and is thus dependent on latitude and elevation. All these constraints limit the use of ^{36}Cl in dating soils.

In view of the above mentioned constraints of the various radiometric dating techniques, it was thought that the thermoluminescence (TL) dating technique with its success in the dating of buried soils could also provide an reasonable chronological framework for the soils developed on fluvial sequences of the study area. The basic advantages of this method are:

(i) it has a dating range of 10^2 - 10^6 years, which makes it useful for the study of recent geological processes.

(ii) it utilizes the constituent minerals of the landform itself for dating, consequently avoids ambiguities of correlation between the sample and the event being dated.

(iii) the TL dates are absolute dates based solely on laboratory analysis of samples and their enviroment.

5.3 Thermoluminescence Dating

5.3.1 Introduction

Thermoluminescence (TSL or TL) is the light emitted on heating minerals which have been subjected to ionizing radiation. It has been used for dating Quaternary sediments (Wintle, 1987 a,b) and has been tested for soils (Wintle et al., 1984; Wintle and Catt, 1985; Singhvi et al., 1987; Zoller et al., 1989). Despite the complexity of this process the TL output bears a simple proportional relationship with the total radiation flux (radiation dose) and this fact is exploited in dating.

The principles of TL dating of sediments have been descrbed in detail extensively (Wintle and Huntley, 1982; Aitken, 1985; Singhvi and Mejdahl, 1985; Singhvi and Wagner, 1986; Berger, 1986; Wintle, 1987 a,b). Briefly, TL dating of sediments/soils is based on the fact that all sediments contain small fractions of naturally occurring radionucleides viz. ^{238}U(ppm level), ^{232}Th(ppm level) and ^{40}K (% level). α, ß and Γ radiations emitted by the decay of these radionucleids are absorbed by natural ubiquitous minerals such as quartz and feldspars. The electrons produced are trapped at defects in the minerals but are released on heating or exposure to sunlight during the process of weathering and transport by photobleaching of trapped charges (Singhvi et al., 1982). A sun exposure is essentially equivalent to thermal resetting of the 'TL clock', but with a difference that it does not totally detrap all the charges but leaves out a small amount (the unbleachable or the residual TL). Thus at the time of deposition (i.e. at 'zero age'), the sediment minerals have a small but finite residual TL level I_0. On deposition, further sun exposure ceases and a rebuild up of TL is initiated (over and above the level I_0) due to irradiation from ambient radioactivity of the sediment. This regrowth continues unabated till sample's excavation. The observed TL level I_{nat} (natural TL) in a sample thus comprises, I_0 and I_d, where I_d is the TL acquired since sedimentation i.e.

$$I_{nat} = I_0 + I_d$$

or $$D(I_{nat}) = D(I_0) + D(I_d) \quad ----------- (2)$$

where, D's are the equivalent beta radiation dose needed to induce a TL level I.

I_0 is estimated by suitable laboratory photo bleaching experiments. $D(I_d)$, when scaled by the rate of TL acquisition expressed as radiation dose rate, provides the TL age. The rate of TL acquisition is estimated by measuring the elemental concentrations of ^{238}U, ^{232}Th, ^{40}K and cosmic ray dose-rate, appropriately corrected for the ambient moisture and inhomogeneity in the distribution of radioactivity within the sample and the host strata. Additional complexities arrises due to the fact that alpha, beta and gamma radiations have different TL inducing capacity. Alpha particles owing to their higher mass and charge cause extensive ionization along their short track length such that the free charges exceed the trap density along the track (a saturation effect). Thus from the view point of TL production, most of the free charges get wasted. The beta and gamma have lesser mass and energy, resulting in a weak ionization track, thus resulting in a several fold higher TL induction capacity. Thus an alpha efficiency factor 'a' is used in the age equation. The factor 'a' for a sample is derived experimentally by examining the rate of TL growth curves with alpha and beta radiations. The age equation is thus:

$$\text{TL age} = \frac{D(I_d)\,(D(I_{nat}) - D(I_0))}{aD_\alpha + D_\beta + D_\Gamma + D_c}$$

Where D(I) reflects the radiation dose or the equivalent dose (ED) needed to induce a TL level I in the sample and D_α, D_β, D_Γ are the components of dose-rates from various radioactive decay modes of ^{238}U, ^{232}Th, ^{40}K and cosmic rays.

5.3.2 Zeroing of the TL at Deposition Time

The TL dating of a sediment is based on the premise of a predepositional exposure of the constituent mineral to sunlight during weathering and transport. This sun exposure results in a photo bleaching of the "geological luminescence" signal to a small residual value. The photo bleaching with sun exposure, initially proceeds rapidly and with a prolonged exposure asymptotically approaches a residual level I_0. Typically it requires a few hours of sun exposure to arrive the residual level I_0.

In applications to sediments, two practical situations arise which depend on the extent of predepositional sun exposure that can be assumed. The first category of sediments are the aeolian sediments where long distance transport ensures that they received sufficient sun exposure to reduce the geological TL level to I_0 level. The second category of samples comprise fluvial, fluvioglacial and lacustrine sediments where a complete quantum of sun exposure can not be assumed apriori. This be because of the water media, the sediment load and the turbulence in it, all modify the net solar flux and its spectrum reaching the mineral grains. Such partially exposed sediments pose some difficulties in dating as should the laboratory simulation of predepositional photobleaching exceed the sun exposure received by the samples in entiquity, an age over estimation is likely.

Thus considerable effort has been expended towards the basic methodology aspects relevant for the dating of fluvial sediments. The presence of suspended sediment shifts the solar spectrum toward the red by selective removal of the shorter wavelengths. Berger (1985a) observed that for quartz the TL was relatively insensitive to visible wavelengths > 450 nm. Thus the TL of most waterborne quartz may not be reduced sufficiently during transport for effectively using the present TL dating methods. On the other hand, the TL of feldspars is more rapidly reduced by all visible wavelengths (Kronborg, 1983; Berger, 1985a), though the longer wavelength light is less effective than the shorter wavelengths in draining this TL. Consequently, for dating water-lain deposits it is generally advisable to use only the more easily bleachable feldspars and employ only long wavelengths solar illumination (e.g. > 550 nm) alongwith the partial bleach technique. The use of 7550 nm for solar simulation is advisable as in nature the shorter wavelengths would have been attenuated under turbid conditions. A correct estimation of zeroing of water-laid sediments is further maid complicated by a probable mixing of bleached and unbleached grains. Thus within a strata it is quite likely that a sediment has a mixture of well bleached, partially bleached and unbleached grains and it is quite obvious that even minor traces of the latter category may upset the signal of well bleached grains and hence the analysis.

Several laboratory simulation studies have been made to estimate the effect of flow on bleaching, Gammell (1985) conducted an experiment in which rates of bleaching of suspended sediment undergoing fluvial transportation in a closed laboratory flume beneath a U.V. lamp were measured. It was found that the speed of zeroing was inversely related to the speed of flow. This was attributed to the effects of turbulent flow and suspended sediment load, both of which reduced the net short wave length radiation flux. The time required to reduce TL to the residual levels indicated by sunlamp bleaching experiments suggested that at faster flows, sediments in a heavily-laden stream are unlikely to attain complete bleaching. This study also confirms that only partial bleach method is the best suited for fluvial deposit. Another appropriate procedure for ascertaining the extent of predepositional exposure is to carry out partial bleach equivalent dose plateau with different laboratory solar illumination levels. A plateau of the equivalent doses corresponding to different durations of solar illumination, then can be taken as a reasonable assurance that the over bleaching effects have been avoided.

Spooner (1987) studied the dependence of bleaching on the wavelengths present in the incident beam because such information is useful in predicting how bleaching proceeds, particularly in case of fluvial environment which selectively attenuates the incident light. Based on these spectral dependent bleaching studies he concluded that ultra-violet is the principal bleaching component of the solar spectrum for natural TL of quartz at all glow curve temperatures. In another experiment he could find that the 325°C peak was easily bleachable even by UV-depleted illumination. The relevance of this to dating water-laid sediments is that optically most bleachable 325°C glow peak of quartz could be isolated using a UV-transmitting UG-11 filter. Use of this filter enables the spectral isolation of glow peak which is sensitive to an optical bleaching. This minimizes to some extent, the constraints on the estimation of predepositional solar illumination.

Many workers have discussed the zeroing behaviour of soils to test the suitability of TL for dating of soils. Vares (1982) confirmed that zeroing occurs in soils by showing that the TL signal obtained from quartz in upper horizons of podzols developed in glaciofluvial sands in Estonia was much less than that from the B and C horizons. However, he attributed the decrease to sensitivity changes caused by weathering of quartz in the acid environment. Zoller and Wagner (1989) suggested that soils cannot be dated directly with TL as soil formation is normally not accompanied by optical bleaching (except the thin soil layer at the uppermost few mm which is exposed to the sunlight). Therefore, one has to date the sediments directly above and below the soil (i.e. indirect dating by 'bracketing'). In some cases, the entire A horizon of a soil may suffer bleaching due to bioturbation or slow removal and redeposition of the top layer, allowing direct TL dating of soil formation (Chawla, et al., 1989; Huntley, et al., 1983; Wintle and Catt, 1985). It seems unlikely, however, that deeper soil horizons such as Bt horizons are affected by any optical bleaching during soil formation. Therefore, TL ages from B horizons indicate the sedimentation age rather than the age of soil formation.

5.3.3 Methodology of TL Dating

5.3.3.1 Sample Collection

All the samples were collected from the B horizon of the different soil-geomorphic units of the study area. Two samples from each pedon were collected to establish the stratigraphy. Table 5.1 provides the details of samples. Fig. 5.1 provides the location of sampling sites. Description of the profiles is given in chapter 2. The samples were collected with due care to eliminate their exposure to sunlight during and after sampling. An outer layer of thickness of about one centimeter was removed from the sample prior to their use to avoid any material that could have been accidentally exposed to sunlight while sampling. All the experiments were carried out in subdued red light.

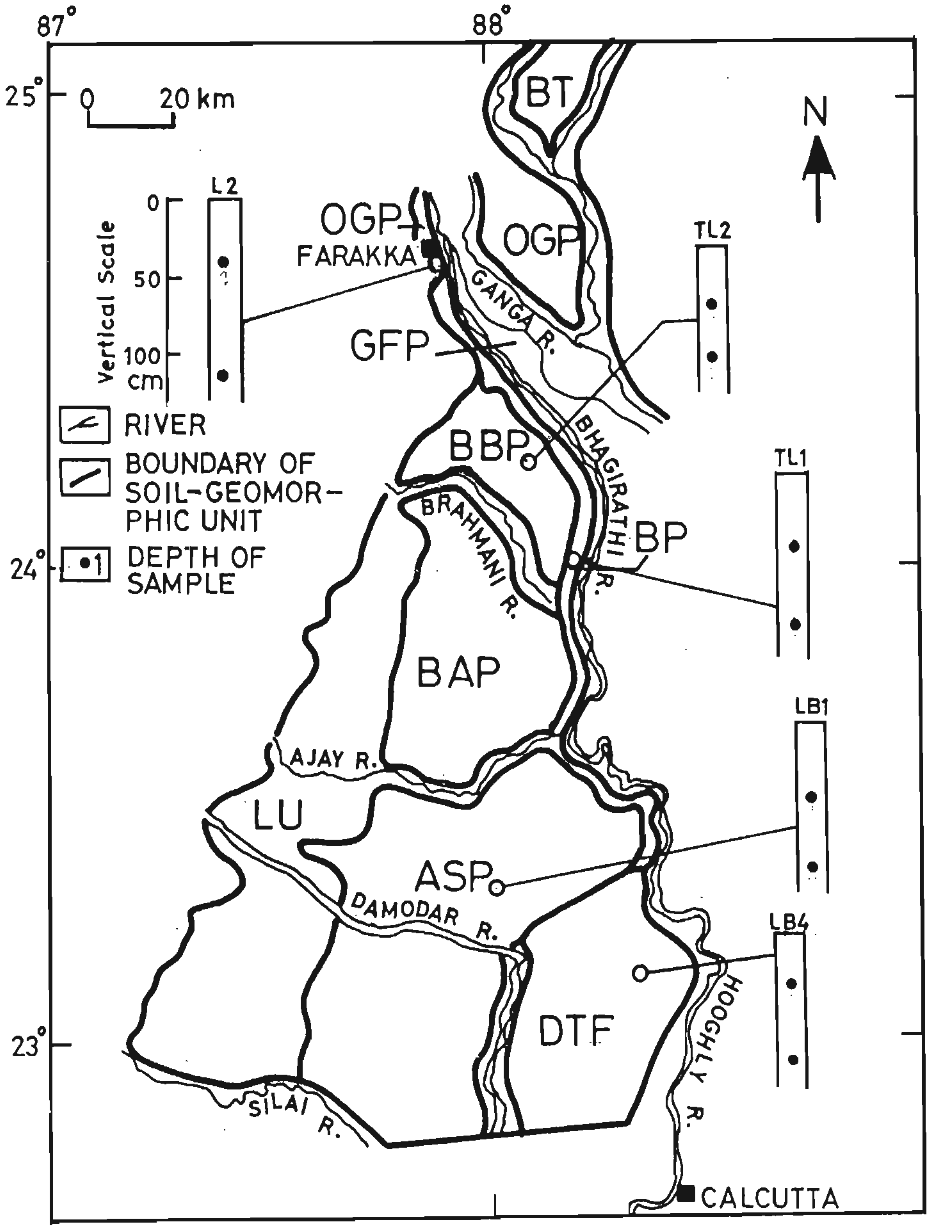

Fig. 5.1 Soil-geomprhic map showing location of sampling sites for TL dating.

Table 5.1 Details of samples for TL Dating.

Soil-Geomorphic Unit	Location	Pedon No.	Sample No.	Depth (cm)	Horizon
Ajay-Silai Plain	Panowa	LB1	LB1/1	50	B21g
	- do -	- do-	LB1/2	100	B23g
	Rukmini				
Damodar Terminal Fan	- do -	LB4	LB4/1	30	B1
		-do-	LB4/2	80	B22
	Brahmani-				
Bhagirathi-Brahmani	gram				
Plain	- do -	TL2	TL2/1	37	B1
		-do-	TL2/2	70	B22
	Farakka				
Old Ganga Plain	- do -	L2	L2/1	40	C1
		-do-	L2/2	115	II B2
	Mukund-pur				
Bhagirathi Floodplain	- do -				
		TL1	TL1/1	50	C1
		-do-	TL1/2	100	II C2

5.3.3.2 Sample Preparation

The sample preparation involved extraction of 4-11 μm polymineralic fraction. The sample was sequentially pretreated with 0.1 HCl to remove carbonates and 30 % H_2O_2 to remove organic matter and 0.01 N sodium oxalate to defluculate the sample. Subsequently, the required grain-size (4-11μm) fraction was separated using Stoke's Law and equal volume of 4-11 μm grains suspended in an acetone suspension was deposited on aluminium discs. For each sample about 50 discs were made for TL measurements.

5.3.3.3 TL Measurements

The TL measurements were done using a Daybreak manual TL system. The schematic diagram of the TL system is given in Fig. 5.2. The TL glow curves were recorded under inert high purity nitrogen atmosphere using an EMI 9635QA photomultiplier tube coupled to a high speed photon counting system. Heating rate used was 5°C/sec. A heat absorbing filter HA3 and a Schott UG11 filter were interposed between the sample and the photomultiplier tube to select U. V. portion of TL emission signal. The temperature was recorded using Chromel Alumel thermocouple and the entire system was interfaced with a PC/AT.

5.3.3.4 Estimation of Equivalent Dose

The R-ß method or the partial bleach method (Wintle and Huntley, 1979) was used for determining the equivalent dose of the samples. The basic philosophy of this method to ensure that the extent of the laboratory solar illumination be such that traps that were not photo-bleached during the antiquity do not get photo-bleached in the laboratory. Also, as the method avoids any irradiation after sun bleaching, the possibility of TL sensitivity changes due to sun exposure is eliminated.

Typical glows from natural (N), ß-irradiated (N+ß) and sun bleached (N+ß+SL) portions of the sample are provided in Fig. 5.3. Two growth curves (N+ß and N+ß+SL) were constructed for each temperature at 10°C intervals (Fig. 5.4). The intersection of the above two curves gave the equivalent dose for that particular temperature. A mean ED for the sample was then determined from the 'plateau' value (Fig. 5.5) from a plot of ED vs temperature. The ß-irradiation were done using a 30mCi $^{90}Sr/^{90}Y$ beta plaque source and the net dose delivered to 4-11 μm polymineral was 2.2 Gy/min.

5.3.3.5 Estimation of Annual Dose

The estimation of dose-rate was done by estimating the elemental concentration of U, Th and K. Thick source alpha counting method was used for estimation of U and Th concentration and the NaI(Tl) gamma ray spectrometry was used for ^{40}K estimation. In the thick source alpha counting, thinly powdered sample was spread on to a ZnS(Ag) screen and the α-induced scintillations in it were counted using a photomultiplier tube and a counting system. With an appropriate calibration using known activity standards, the α-scintillation rate can be simply related to the alpha activity of the sample which in turn can be related to the U and Th

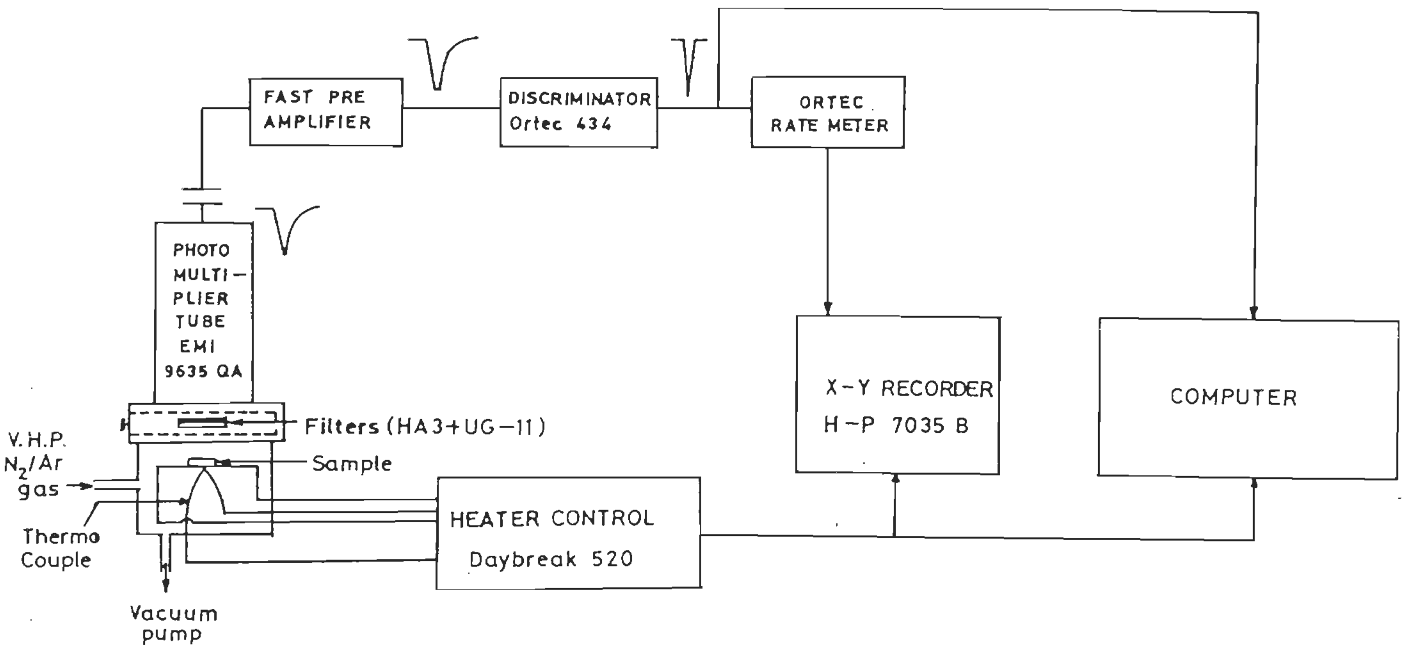

Fig. 5.2 Schematic of the TL apparatus.

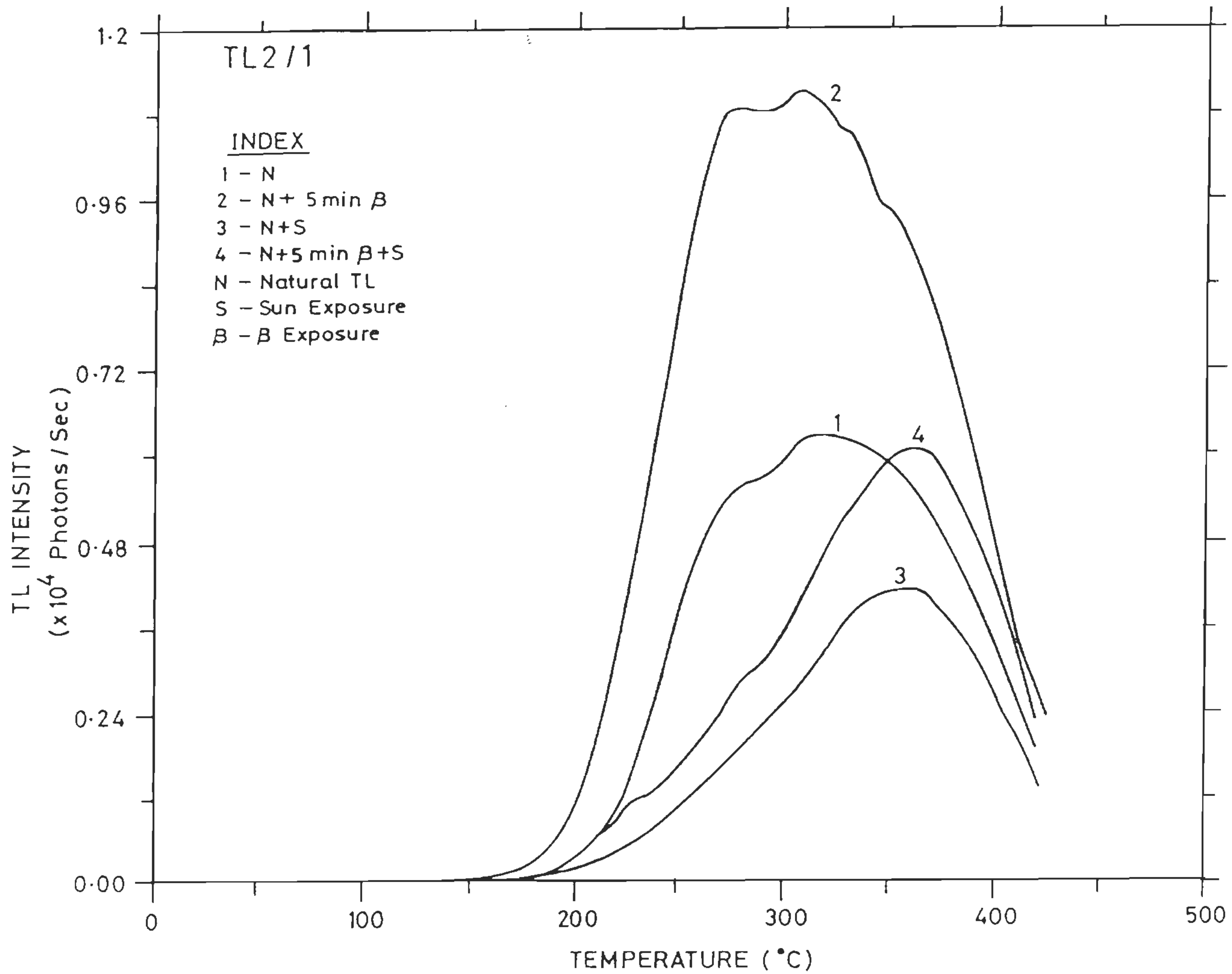

Fig. 5.3 Glow curves from (1) natural, (2) ß-irradiated, (3) sun bleached and (4) ß-irradiated plus sun bleached portions of samples.

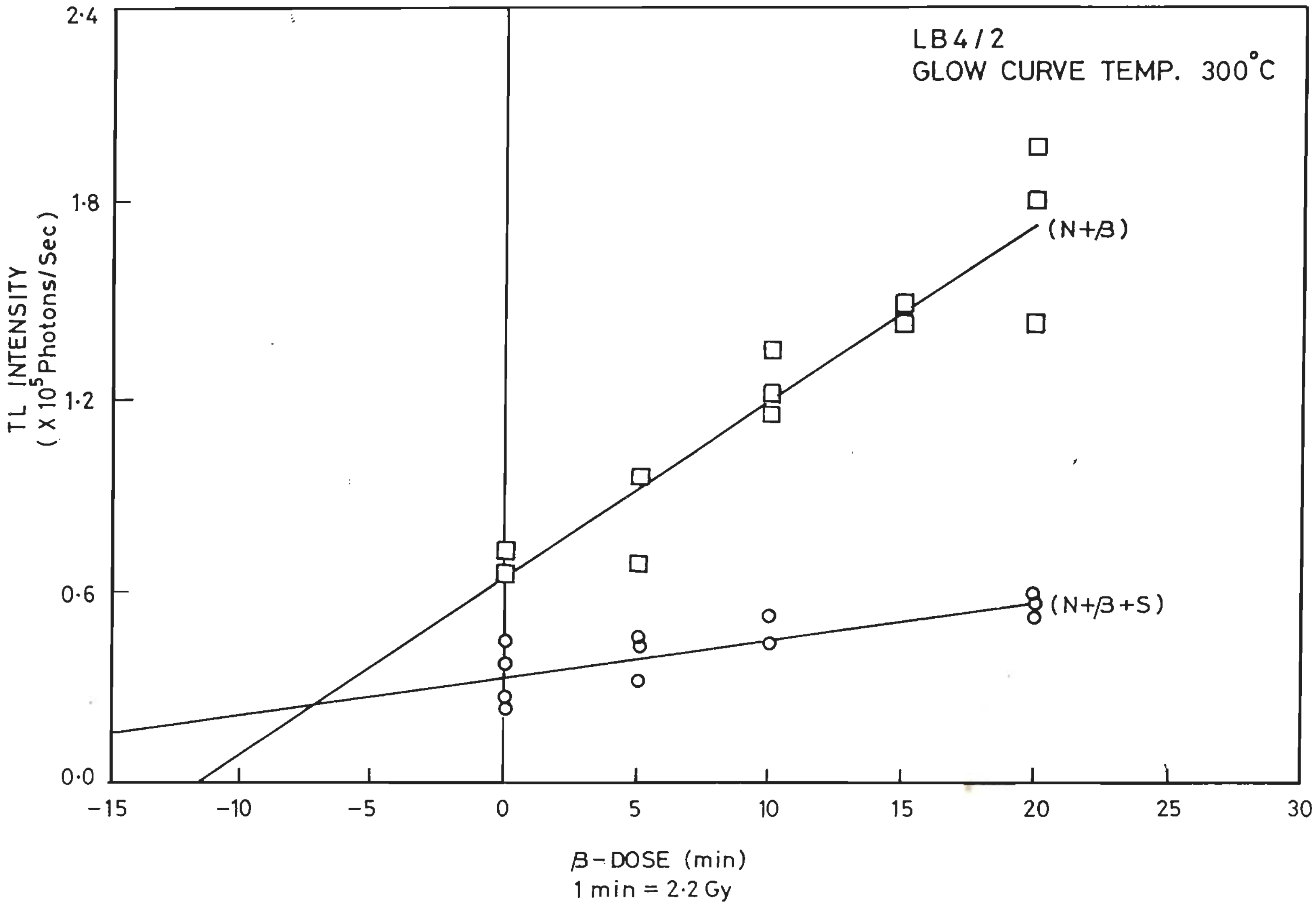

Fig. 5.4 Growth curves at 300°C constructed from ß-irradiated (N + ß) and ß-irradiated plus sun bleached (N + ß + SL) portions of samples.

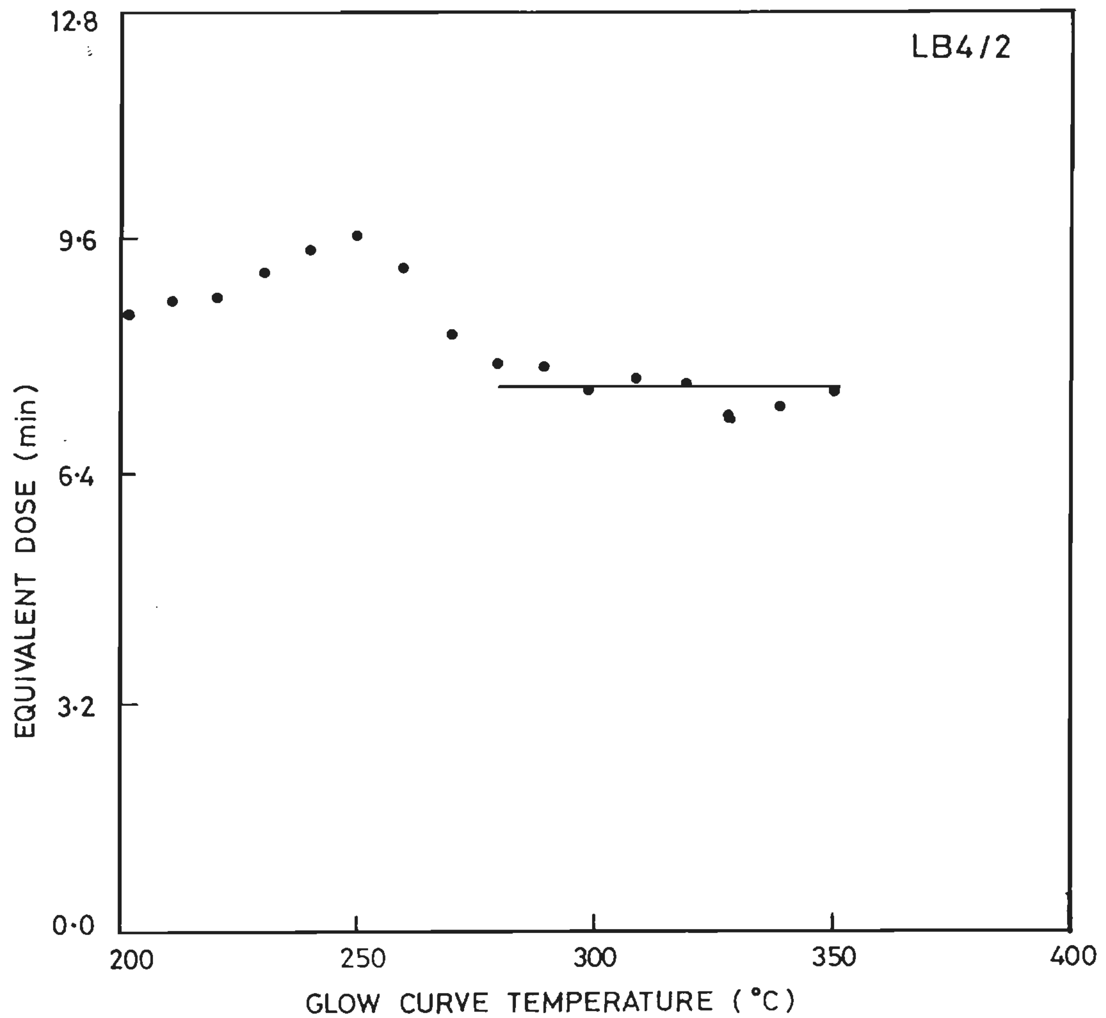

Fig. 5.5 Plot showing plateau value of equivalent dose.

concentration based on assumption of equal activities for U and Th. Using the above procedures, the U and Th concentration in different samples was determined. For determining ^{40}K in the samples, a NaI(Tl) gamma ray spectrometer was used to count 1.46 MeV Γ-rays produced in the decay of ^{40}K. By comparing the activity of the sample with that of high purity standard (e.g. KCl), the percentage elemental concentration (by wt.) of K was computed for the samples. Having determined these concentrations, the well-known conversion factors (Wintle and Huntley, 1980) were used for determining the dose-rates from each of these radionucleides. The dose rates were then corrected for the water content. Various components of annual dose are shown in Table 5.2. A water content of 25 % was used for the present study.

Table 5.2 Components of annual dose (in μGy/a) for the naturally occurring radionucleides (After Bell, 1979).

Radionuclide	Concentration	α	β	Γ
Thorium Series	1 ppm ^{232}Th			
no thoron loss		738	28.6	51.4
100% thoron loss		309	10.3	20.8
Uranium Series	1 ppm ^{238}U			
no radon loss		2783	146.2	114.8
100% radon loss		1262	60.9	5.6
Natural Potassium	1% K_2O		689.3	206.9
	1% K		830.3	249.2
Natural Rubidium	100 ppm Rb		46.4	

5.3.3.6 Photobleaching Experiments

In photobleaching experiment a simple and practical approach of laboratory simulation of solar exposure was atempted. In this zero-age samples were analyzed and the most appropriate bleaching was the one that provided near zero ED for the samples. Thus samples were sun-bleached. Glow curves were recorded for varying sun exposure durations for finding the residual levels $_{10}$ of the sample after predepositional sun exposure (Fig. 5.6). A bleaching curve was constructed from glow curves of different sun exposure durations (Fig. 5.7). Typical bleached level fractions at 2 min sun exposure were 0.3-0.4 at a glow curve temperature of 360°C. Aditionally, the partial bleach EDs for three different laboratory solar illumination levels were estimated and a plateau of the equivalent doses with the respective solar illumination were obtained. This experiment was done for all the samples and it was found that a solar illumination of 2 minutes provided a reasonable illumination for majority of the cases.

5.3.4 Results and Discussion

Table 5.3 summarises the experimental results and the preliminary TL ages on an assumed 'a' value and a water fraction of 25 %. A working estimate of ± 15 % has been assumed in the estimation of error in age calculation. The following observations are made from the above mentioned figures and tables.

(i) In general, all samples showed $D(I_{nat})$ of a few grays. This suggests that there had been a recent bleaching event, otherwise they should have yielded a much higher value of $D(I_{nat})$ (>100 Gy) which is common for unbleached geological samples.

(ii) The ages for samples from each profile were stratigraphically consistent.

(iii) $D(I_{nat})$ for samples of the Old Ganga Plain (L2/1, L2/2) and Bhagirathi Floodplain (TL1/1, TL1/2) is ≤ 20 Gy while the ED was quite high (25-37 Gy) for samples from deeper horizons of Bhagirathi-Brahmani Plain (TL2/1), Damodar Terminal Fan (LB4/2) and Ajay-Silai Plain (LB1/2).

(iv) All the samples with the exception of LB4/2, TL2/1 and L2/2 exhibited an extended age plateau. Sample LB4/2 gave a double age plateau corresponding to two different temperature ranges suggestive of a recent minor reworking (?) event. Sample L2/2 from the Old Ganga Plain did not yield a plateau. However, the fact that the total TL signal was very low ($D(I_{nat})$=20 Gy) suggested that there had been a recent bleaching event.

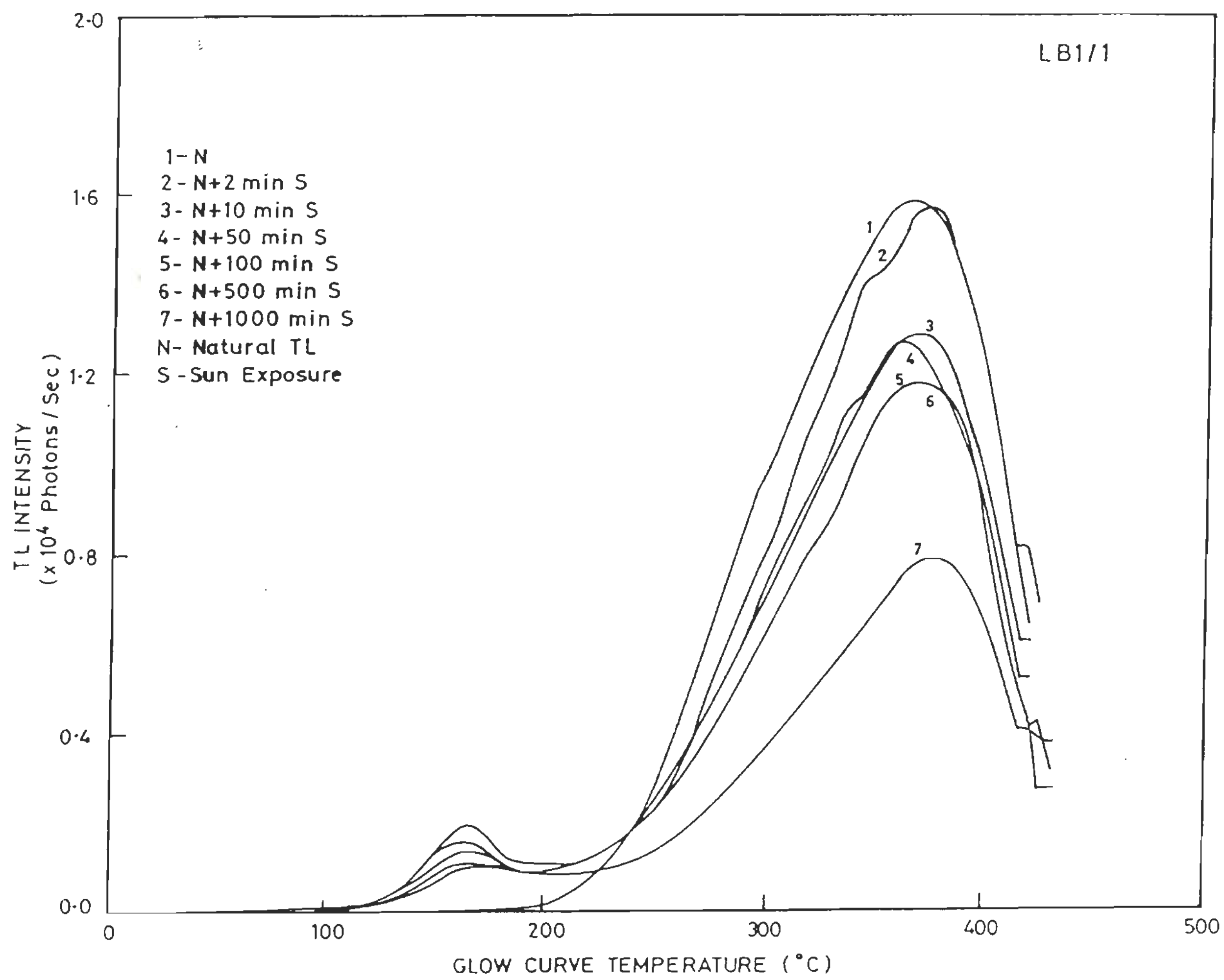

Fig. 5.6 A set of glow curves recorded at various durations of sun exposures.

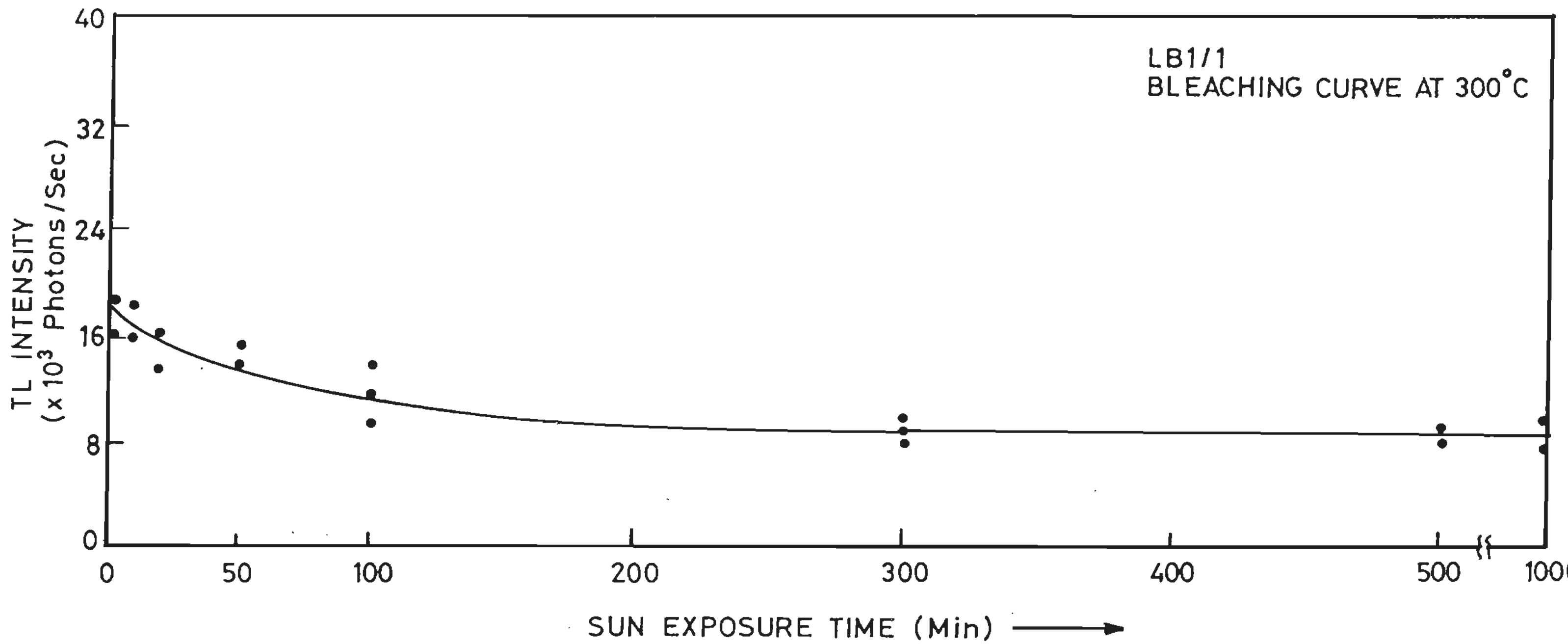

Fig. 5.7 A typical bleaching curve showing TL intensity at different sun exposure durations.

Table 5.3 Equivalent dose, radioactivity values and preliminary ages on different soil samples.

Sample No.	Plateau Region (°C)	ED (Gy)	Alpha Activity (a)	Th (μg/g)	U (μg/g)	K (%)	Water Fraction(%)	Dose Rate (μGy/y)	Apparent TL ages[1] (Years)
LB1/1	260-310	1.6	0.1	15.7	5.2	1.2	0.25	4112	375
LB1/2	280-350	20.0	0.1	12.9	4.5	1.3	0.25	3677	5440
LB4/1	300-340	4.8	0.1	13.8	4.9	2.3	0.25	4642	1050
LB4/2	275-350	16.9	0.1	19.2	3.4	2.3	0.25	4687	3600
L2/1	310-360	3.1	0.1	13.8	4.7	2.2	0.25	4570	670
L2/2	No plateau	7.2	0.1	18.5	3.0	2.5	0.25	4638	1550
TL2/1	310-370	7.7	0.1	23.9	4.8	0.99	0.25	4576	1700
TL2/2	320-360	30.0	0.1	24.8	3.1	1.4	0.25	4464	6700
TL1/1	280-340	0.7	0.1	13.2	5.7	1.3	0.25	4093	150
TL1/2	240-300	3.3	0.1	6.6	3.6	2.2	0.25	3515	900

1. Error estimation for TL ages has to be attempted but a working estimate of ±15% is reasonable.

Thus probably a significant amount of reworking had taken place in the area.

(v) Sample TL 2/2 from the soil of B horizon of Bhagirathi-Brahmani Plain yielded a high ED of 61.6 Gy both at 15 min and 30 min sun exposure but the ED at 2 min sun exposure was only 30 Gy. In the latter case the error in ED was very large due to paucity of data set. The higher ED at 15 min and 30 min sun exposure should reflect laboratory overbleaching. TL age calculated on the basis of 2 min sun exposure has been presented in Table 5.3.

(vi) The decrease in the apparent age from deeper horizon to the surface horizon suggests that the TL signal was zeroed in the uppermost soil horizons but the mechanism of zeroing is different in different soils. The vertic intergrade soils of Bhagirathi-Brahmani Plain gave TL dates of 1.6 ka and 6.7 ka at depths of 37 cm and 70 cm respectively. These strikingly different ages at such short intervals is attributed to homogenization caused by pedoturbation and vertic processes in the upper 35-40 cm of the profile. Field studies have shown that vertical cracks up to a depth of 35-40 cm are present in the vertic intergrade soils of Bhagirathi-Brahmani Plain. Also, clay mineral variation and micromorphological features observed in the upper 30-40 cm of the soilos of this unit suggest that pedoturbation has taken place in this zone. Hence the age at 37 cm may be interpreted to be the age of turnover of sediments in the Bhagirathi-Brahmani Plain.

(vii) The ages from deeper horizons (>50 cm depth) gave age of deposition of parent material. These also provide upper limit to the initiation of pedogenesis as the chances of pedoturbation at greater depths are rare.

5.3.5 Apparent TL ages

The ages summarized in Table 5.3 are notional TL ages. These ages may correspond to the times since their deposition. On the basis of TL ages (Table 5.3) the different soil-geomorphic units of the study area can be grouped into five age groups. The active floodplains have ages of <500 followed by Old Ganga Plain and Bhagirathi Plain which gave TL ages of 1.5 ka and 0.9 ka respectively. The ages increase as one moves to the west in the Bhagirathi-Dwaraka Plain which gives TL dates of 6.7 ka. The TL dates onsamples from southern parts of the area also show a similar trend from west to east. On a west to east transect the TL age of soil-geomorphic units decreases. The Ajay-Silai Plain gave a TL age of 5.4 ka whereas the Damodar Fan lying immediately east of Ajay-Silai Plain gave a TL age of 3.6 ka. From these ages it can be reasonably concluded that as we move from west to east near the active floodplain of Bhagirathi-Hooghly river the ages of soil-geomorphic units decreases.

5.4 Conclusions

The zeroing of the TL of mineral grains in the surface horizons of soils, as indicated by the present study, suggest that the TL dating technique can be used to date soils developed on fluvial parent material. The zeroing in the present surface soil samples does reflect a recent exposure to sunlight. The depth of zeroing in soil probably depends on the extent of surface turbation, which in the present case was about 35 cm in the vertic intergrade soils but is likely to be much less in soils of other soil-geomorphic units of the area. Below the turbated zone, underestimates of the age of the soil parent material resulting from gleying and other soil forming processes is possible and hence the true date deposition of parent material is probably indicated by samples which have not undergone these processes. Further work is needed to understand the effects of soil forming processes on the TL of sub-soil horizons.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Introduction

The Lower Gangetic Plains form one of the most extensive fluvio-deltaic plains of the world. It conceals the Bengal Basin which has been continuously affected by tectonism since its inception (Sengupta, 1966; Roybarman, 1983). Quaternary climatic changes have been witnessed in other parts of the Gangetic Plain (Singh, 1971; Singh et al., 1974) and hence the possibility of such climatic vicissitudes affecting the Lower Gangetic Plains is high. Also, the proximity of coast line suggests that these plains must bear the imprints of Quaternary sea level changes. Study of soils is important in deciphering the history of landform evolution and climatic changes because the soils represent episodes of land surface stability with little or no deposition and thus record Quaternary environments in areas where there is no depositional or erosional evidence of subaerial Quaternary history (Catt, 1992). Keeping these points in view the present study is aimed at the following objectives.

i) Identification and mapping of different landforms and soil-geomorphic units

ii) To prepare a soil-chronoassociation for the study area.

iii) To elucidate the roles of paleoclimatic and sea level changes and tectonics on the evolution of landforms and soils in the study area.

6.2 Investigation Procedure

Contoured topographic maps, Landsat images and field checks were used to recognize nine major geomorphic units in the study area. As the soils within geomorphic units were fairly uniform and their properties varied within a narrow range, these have been called soil-geomorphic units. A total number of 40 pedons were studied in the field and soil properties of horizons were recorded. Then disturbed (bulk) and undisturbed soil samples from various horizons were collected. Of the 40 pedons, 21 were selected for detailed laboratory investigations such as grain-size analysis, clay mineralogy, major elemental analysis, micromorphology and thermoluminescence chronology of soils. Soil samples were analyzed for grain size distribution using the method of Galehouse (1971). Clay fractions (<2 μm) of the soil samples were used for clay mineral analysis. Clay minerals were identified by using a procedure described by Wilson (1987) and semi-quantitative analysis was done using the method described by Schultz (1964). Major elemental composition of soils was determined using the two solution method of Shapiro (1975).

For micromorphological studies, undisturbed soil samples were collected in metal boxes. The samples were impregnated with crystic resin and large (60 x 40 mm) sections were prepared according to the procedure described by Jongerius and Heintzberger (1963), Fitzpatrick (1984) and Murphy (1986). Thin sections were described according to the terminology of and Bullock et al. (1985).

The ages of different soil-geomorphic units were determined by Thermoluminescence technique using partial bleached method described by Wintle and Huntley (1980).

6.3. General Features

Physiographically the study area consists of three major units; steep easterly sloping plains in the western parts, fluvio-deltaic plains of the Bhagirathi in the east and the Barind Tract in the north. All the major rivers of the northern part flow in a generally southerly direction. The rivers draining the easterly sloping plains originate in the west in the Peninsular Shield and flow in an easterly direction following the regional slopes of the plains. The Bhagirathi river flows in a southerly direction along a structurally controlled course.

In general the region experiences a hot and humid monsoonal climate and is mainly controlled by the proximity to the Bay of Bengal in the south and the alignment of the Himalaya in the north. The rainfall (1200 mm to >4000 mm) is fairly widespread in the region though with uneven seasonal and spatial distribution characteristic of the monsoonal climate. Nearly 80% of the total annual precipitation is concentrated during the four months of monsoon (June to September). The northern and southern parts of the area, owing to the proximity of the Himalaya and the Bay of Bengal respectively, experience relatively more annual rains than the central and the western parts. Four well marked seasons i.e., hot summer, wet summer, pre-winter transition and winter can be recognized. The temperature rises gradually from February, and rapidly from March onward till May and attaining maximum average temperature between 29°C - 33°C. The temperature starts declining gradually from June onwards and sharply from October onwards. This marks the start of the winter season. The average winter temperature varies from 17°C-24°C which increases southward.

6.4 Major Landforms and Soil-Geomorphic Units

Using remote sensing techniques followed by direct observation in the field, three major landforms were recognized and mapped in the study area. Within each landform a number of soil geomorphic units were recognized.

Landforms	Soil-Geomorphic Units	Abbreviations Used
Upland Areas	Lateritic Upland	LU
	Barind Tract	BT
Old Fluvial/ Deltaic Plains	Bhagirathi-Brahmani Plain	BBP
	Brahmani-Ajay Plain	BAP
	Ajay-Silai plain	ASP
	Damodar Terminal Fan	DTF
Young Fluvial Plains	Old Ganga Plain	OGP
	Ganga Floodplain	GFP
	Bhagirathi Plain	BP

6.4.1 Upland Areas

The Upland Areas occur at the highest elevation in the study area and are characterized by their dissected topography and distinct levels. The highest levels are overlain by strongly developed polygenetic soils. These include the Lateritic Upland and Barind Tract soil-geomorphic units.

6.4.1.1 Barind Tract

The Barind Tract is an uplifted region in the northern part of the study area. It is horst block trending E-W and the major portion of the Tract falls in Bangladesh. A number of Himalayan rivers flowing southwards cut across this tract and divide it into four exposures trending almost N-S. In India the Punarbhaba river forms the eastern boundary of the Tract and it occupies an area of about 1200 sq km. The major southerly flowing streams of the Tract have entrenched floodplains. Numerous small, tightly meandering streams with dendritic drainage pattern on the Tract flow into the major streams.

At least three topographic levels with their heights varying from 5-20 m can be recognized on the Barind Tract, with degree of soil development decreasing from the highest to lowest level. In the study area mainly the lowest level is present and has been studied.

6.4.1.2 Lateritic Upland

The Lateritic Upland is a steeply sloping, highly dissected belt of laterites lying east of the Chotanagpur-Rajmahal highlands. The slope of this plain ranges from 1.2 to 1.8 m/km and it lies at the highest elevation (35 to 120 m asl) in the study area. Several large patches of laterites are covered by forest. The drainage pattern is dendritic in general, but in the southern parts annular pattern is present. A number of meander scars and valley-fills are clearly distinguished in the imageries and in the field.

6.4.2 Old Fluvial/Deltaic Plain

The Old Fluvial/Deltaic Plains are gently sloping (average slope 1.2 m/km) plains lying to the east the Lateritic Upland. These are overlain by moderately developed soils. They include (i) Bhagirathi-Brahmani Interfluve, (ii) Brahmani-Ajay Interfluve, (iii) Ajay-Silai Interfluve and (iv) Damodar Terminal Fan..

6.4.2.1 Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain and Ajay-Silai Plain

These three plains are a part of a large plain trending NW-SE and in general have a gentle easterly slope. Most of the rivers originate in the western highlands and flow in an easterly direction forming a sub-parallel pattern. However, in the southern parts (Ajay-Silai Plain), the Dwarkeshwar, Silai and Kasai rivers show annular drainage pattern. The floodplains of most of the rivers have an incised character and easterly flowing rivers are flowing presently along the southern margins of their floodplains.

Some rivers show drastic changes in their courses, e.g. the Damodar river in the southern parts of the plains after flowing in an easterly direction takes a sharp turn of 90° and acquires an almost N-S course. Also, the Bansloi river in the northern part (Bhagirathi-Brahmani Plain) which flows towards east in its upper reaches, takes a north-easterly turn running meeting the Bhagirathi river.

6.4.2.2 Damodar Terminal Fan

The Damodar Terminal Fan is a low gradient, meandering to low sinuosity dominated stream fan confined between the Damodar river in the west and the Hooghly river in the east. Its maximum N-S extent is about 70 km and maximum E-W extent is about 40 km. The fan tapers down towards south (Fig. 2.1). The asymmetry may be attributed to the two styles of slope patterns in the fan-from west to east in the northern part and NW to SE in the southern part. The fan is characterized by a network of abandoned channels of the ancient Damodar, relict natural levees and swamps. A number of distributary channels chute cut offs and anastomosing paleodrainage pattern are clearly observed in the FCC of the area. According to Deshmukh et al. (1973) the Damodar, which was flowing in easterly direction during the middle of 17th century to meet the Bhagirathi shifted its mouth 128 km to the south since 1770. The Damodar river has a braided channel in its upper reaches and acquires a low sinuous channel morphology after entering the fan. This landform resembles a fan and forms at the terminal stage of the river and thus has been called a 'terminal fan'.

6.4.3 Young Fluvial Plains

These plains are identified in the satellite images by their clear association with some rivers. The slopes of these plains range between 0.5-0.1 m/km. These include (i) Old Ganga Plain, (ii) Ganga Floodplain and (ii) Bhagirathi Plain.

6.4.3.1 Old Ganga Plain and Ganga Floodplain

The Ganga Plains separate the N-S trending Lateritic Upland and Old Fluvial/Deltaic Plains and the E-W trending Barind Tract and lie along a fault. The rivers coming from the Barind Tract change their courses from southwest to southeast after entering into this unit. The Mahananda has a meandering channel in this geomorphic unit. Within these plains, two soil-geomorphic units can be recognized: Old Ganga Plain and Ganga Floodplain. The Old Ganga Plain is at a higher level than the Ganga Floodplain and lies on both sides of the Ganga Floodplain. The Old Ganga Plain is widest in the central part (15-20 km) and tapers at both ends. It is marked by numerous paleochannels, oxbow lakes and meander scars.

The Ganga Floodplain is marked by a meandering channel of the mighty Ganges. The floodplain is marked by oxbow lakes, abandoned old channels and point bars on the northern bank of the river suggesting a south-westerly shift of the channel in the floodplain. In the FCC the flood plain is characterized by an overall bluish gray colour with some red patches. Fresh sand deposits along the active channel are marked in FCC by bright white patches and hence they are clearly distinguishable from other finer deposits. The floodplain is widest (12 km) in the south- eastern part of the unit. There is little soil development in this unit.

6.4.3.2 Bhagirathi Plain

This plain lies to the east of the Old Fluvial/Deltaic Plains in the floodplains of the Bhagirathi river. It lies at an elevation 10-20 m and its slope is less than 0.8 m/km. The Bhagirathi river, a distributary of the Ganges, takes off from the ganges about 15 km north of Jangipur (West Bengal) and flows in a southerly direction. Its course is guided by faults. All through its course in the floodplain, it flows in a number of straight stretches punctuated by sharp and acute meanders at places. Well preserved meander scars, cut offs, abandoned channels and levees are clearly observed in the images. All the rivers of the Old Fluvial/Deltaic Plains drain through this plain before meeting the Bhagirathi.

6.4.4 Raghunathganj Surface/Soil

Another unit named the Raghunathganj Surface/Soil has been recognized. It has an undulating surface with a minor surface exposure in the Bhagirathi-Brahmani Plain and occurring at a depth of 1.5 to 3 m under the Brahmani-Ajay and Ajay-Silai Plains. It has a petrocalcic horizon with calcretes developed to stage IV of carbonate morphology of Gile et al. (1966). It has not been considered in the construction of soil-chronoassociation, as it was not studied in detail.

6.5 Soil-chronoassociation

An integrated approach of utilizing field observations and laboratory analysis such as the soil morphology, thickness and development of solum (particularly B horizon), clay accumulation index, variation of the molar ratio SiO_2/R_2O_3 ($R_2O_3 = SiO_2 + Al_2O_3 + TiO_2$), degree of pedality, thickness and nature of clay coatings and development of the fabric has been used to determine the degree of soil profile development. On the basis of relative degree of development, the soils of the area were divided into five groups from Group I to Group V, Group I having the least developed soils. These groups can be called the members of a soil-chronoassociation (Mohindra et al., 1992) and have been given the names QGWB1 to QGWB5 respectively. Various units included in different members are: QGWB1 - Ganga Floodplain; QGWB2 - Bhagirathi Plain and Old Ganga Plain; QGWB3 - Barind Tract (Lower Level) and Damodar Terminal Fan; QGWB4 - Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain and Ajay-Silai Plain and QGWB5 - Lateritic Upland.

6.5.1 Variation in Soil Characteristics Among Different Members of Soil-chronoassociation

The systematic changes observed in the soil characters of different soil-chronoassociation members are as follows.

6.5.1.1 Soil Morphology

A/C type of horizonation is observed in QGWB1 member soils of active floodplains of the Ganges and other larger rivers of the study area. Weakly developed soils are encountered in QGWB2 member. Weakly to moderately developed soils are observed in QGWB3 member. The soils of QGWB2 and QGWB3 have bluish grey colour gleyed horizons due to hydromorphic condition caused by the presence of near-surface water table. Soils of QGWB4 are moderately to strongly developed, poorly drained, fine textured, vertic intergrade type and with vertical cracks. The thickness of B horizon increases in general from QGWB2 (15-20 cm) to QGWB4 (80-110 cm) soils.

The soils of the Lateritic Upland occur on an undulating region and they consist of two distinct units. The lower unit starts with a lithomarge at the base grading up into pisolitic laterite (200-300 cm thick). The pisolitic concretions have been cemented by iron oxide. The upper unit with a maximum thickness of 50-200 cm is comprised of alternating gravelly sand and lateritic mudstone consisting of detrital lateritic particles bound by iron oxide. The upper unit occurs only on the lower slopes (eastern parts) of the unit. Morphological features of different members of soil-chronoassociation (i.e. QGWB1 to QGWB5) have been shown in Fig. 6.1.

According to Soil Survey Staff (1975) classification, most soils of the QGWB1 and QGWB2 can be classified as Ustifluents and Haplaquepts respectively. QGWB3 soils are mostly Aeric Haplaquepts (in Damodar Terminal Fan) and Typic Ustochrepts (in Barind Tract). Vertic Haplaquepts are most common in the QGWB4 member soils. The QGWB5 member soils are mostly Haplustalfs.

The Calcium carbonate concretions are observed in the Raghunathganj Surface/Soil and the Barind Tract (Lower Level) soils.

Ferro-manganese concretions and mottles are common in the lower parts of most of the soil profiles in the area. The concretions are fine to medium in size and constitute 2-5% of the matrix. In general, amount of concretions increase with depth.

6.5.1.2 Textural Variation

Grain size analysis of soils of different chronoassociation members indicate that most of the soils are medium to fine textured and lie in the loam to silty clay loam textural classes. Medium to coarse textured (loam) soils in QGWB1 do not show any significant variation in sand, silt and clay content with depth. These are very weakly pedogenised sediments. Soils of other members are mainly silty loams and become heavier (higher clay content) with greater soil development, especially in the B horizon. Increase of clay content in the B horizon over A or C horizon was taken here as pedogenic clay which is attributed to the translocation of clays from the upper to the lower horizons. Increase in clay content in B horizon is a useful indicator of relative age of soils (Birkeland, 1985). There is no pedogenic clay in QGWB1 soils, whereas there is an appreciable increase in pedogenic clay content from QGWB2 to QGWB4 member soils. The clay accumulation index (Levine and Ciolkosz 1983) in different members are:

QGWB2- 58-122; QGWB3- 199-545 and QGWB4- 852-1564. The index was not calculated for QGWB5 soils, as these have undergone intense chemical weathering.

6.5.1.3 Major Elemental Analysis

The weatherability of silica is very low at ordinary temperatures as compared to Al_2O_3, Fe_2O_3, K_2O, MgO and Cao. As a consequent of soil development in a leaching environment, Al, Fe, K, Mg and Ca are released in the upper horizons and move downwards in response to diffusion gradients and water movement. Thus, SiO_2 concentrations decrease while Al_2O_3 and Fe_2O_3 increase in the B horizon with increasing age. TiO_2 also follows the trend of Al_2O_3 and Fe_2O_3. It implies that the molar ratio SiO_2/R_2O_3 ($R_2O_3 = SiO_2 + Al_2O_3 + TiO_2$) should also decrease with depth. In the study area, in general, leaching environment prevails.

The molar ratio SiO_2/R_2O_3 ($R_2O_3 = SiO_2 + Al_2O_3 + TiO_2$) was calculated for different chronoassociation members. The ratio does not show any trend in the soils of QGWB1 but it decreases with depth from A to B2 horizon in other soil-chronoassociation members in general. The decrease is relatively higher with increase in degree of development of soils from QGWB2 to QGWB4. The percent decrease in the ratio for QGWB2, QGWB3 and QGWB4 members are 9-11%, 11-14% and 16-34% respectively. However, the vertic intergrade soils of QGWB4 member do not show any systematic change in the content of major elements in the top 30-35 cm of the profile indicating homogenization of soil material due to pedoturbation. Below this depth of vertical cracks the soils show normal trend similar to QGWB2 and QGWB3 member soils.

6.5.1.4 Clay Mineralogy

The major clay minerals observed in the study area are illite, kaolinite, smectite, illite-smectite and kaolinite-smectite and chlorite-smectite interstratified minerals. Small amount of chlorite is observed in the northern part (north of the Ganges) of the study area. The duration

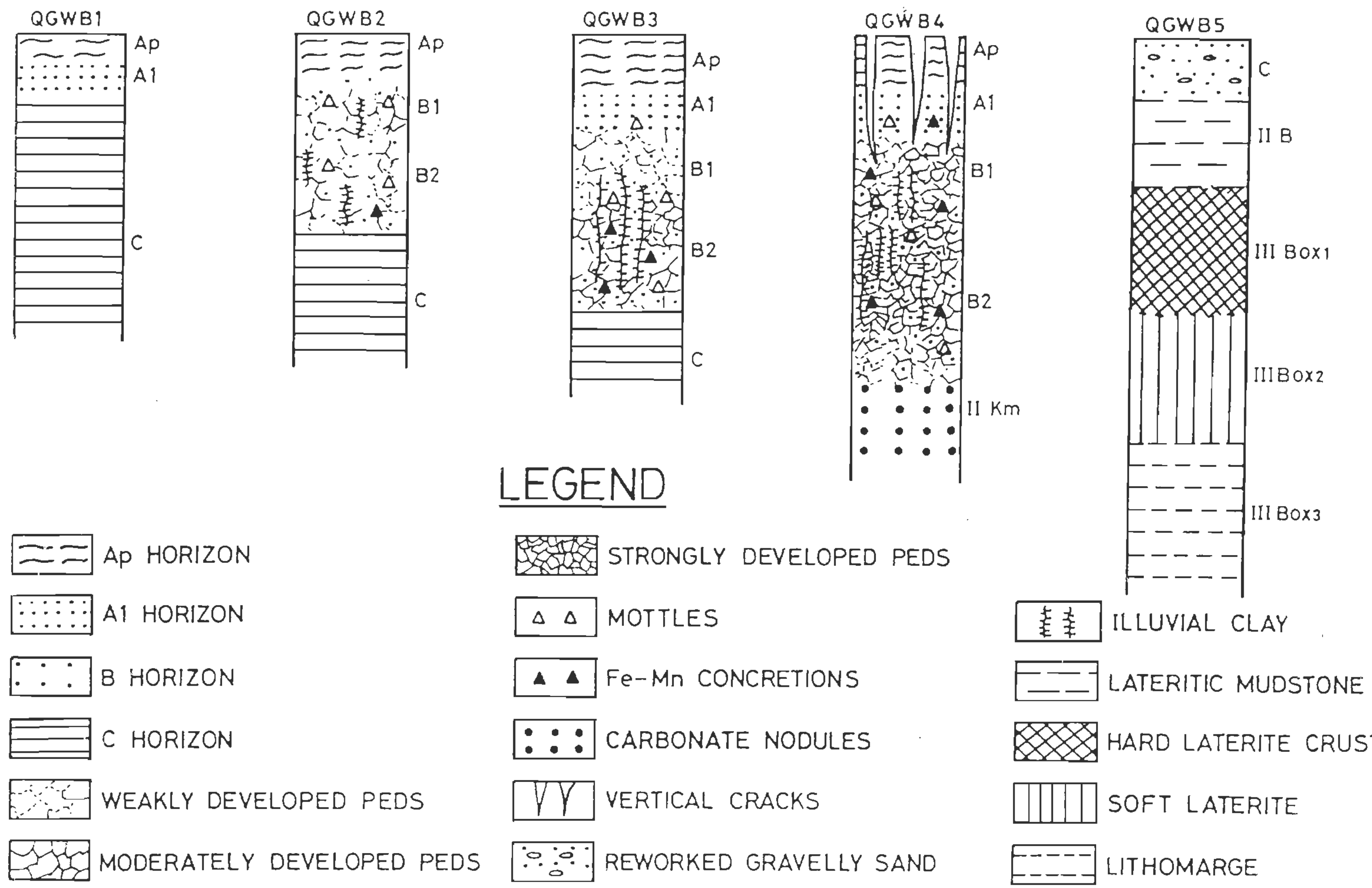

Fig. 6.1 Morphological features of the QGWB1 to QGWB5 members of the soil-chronoassociation.

of pedogenesis and clay mineral assemblage of parent material seems to have controlled the occurrence and variability of clay minerals in different units.

The major clay minerals of the parent material of soils in the region south of the Ganges are illite, smectite and illite-smectite interstratified released by the weathering of the Rajmahal Basaltic Trap and granitic rocks in the west and transported to the east by the easterly flowing rivers. In the Lateritic Upland transformation of illite, smectite and interstratified clay minerals to kaolinite and iron oxide is complete. In the QGWB4 and QGWB3 (Damodar Terminal Fan) smectite and illite are transforming to kaolinite through interstratified minerals. Also, transformation of illite and smectite to chlorite due to ferrolysis (Brinkman, 1969/1970) is observed on a small scale in the surface horizons of QGWB3 member soils. High content of illite in the Bhagirathi-Ajay Plain and Ajay-Silai Plain soils (QGWB4) in the region further south is probably due to contribution from granitic rocks in addition to the Rajmahal Traps from the west. Soils of the QGWB2 and QGWB1 members have undergone little pedogenesis and hence the clay mineral composition does not change with depth in soil profiles of these members. The presence of smectite in these soils suggests that in addition to the Himalayan source, some contribution has been made from rivers draining the Rajmahal Basaltic Traps in the west.

6.5.1.5 Micromorphology

Micromorphological studies of the undisturbed soil samples indicate that from QGWB1 to QGWB5 member soils, distinct variations are observed in the features such as the grade of pedality, degree of b-fabric development, intensity of weathering and alteration of primary minerals, formation of sesquioxide nodules and abundance and thickness of illuvial clay coatings.

Soils are apedal in QGWB1 member and the grade of pedality increases from weakly developed p[eds in QGWB2 to the most strongly developed peds in QGWB5. The nature and abundance of voids in different members are closely related to the coarse/dine ratio. Channels, chambers, planar voids and vughs are more common in fine grained soil material whereas intergrain packing voids are more common in coarse soil material. Also, the void surfaces get smoothened in the horizons having clay coatings around voids, e.g., in QGWB3, QGWB4 and most commonly in QGWB5 member soils.

The finer fraction of the soil material shows different types of b-fabric. The degree of development and abundance of b-fabric increases from QGWB1 to QGWB5 soils. In QGWB1 and QGWB2 member weakly developed stipple-speckled are more common. Also, parallel striated b-fabric are observed occasionally. The QGWB3 soils are marked by weak to moderate cross and reticulate b-fabrics. Soils of QGWB4 member show mostly porostriated and granostriated b-fabric in the upper part but with increasing depth the parallel striated b-fabric dominates. The extensive and frequent wetting of 2:1 swelling of these soils might have resulted in swelling of soil matrix. This probably led to compression and realignment of particles adjacent and parallel to the grains and void surfaces and thus gave rise to grano- and porostriated b-fabrics. Parallel striated b-fabric in QGWB4 soils might have developed due to the closure of some of the planar voids caused by the repeated wetting in linear birefringent zones. Laterites of QGWB5 member show undifferentiated to weak stipple-speckled b-fabric due to the presence of sesquioxides.

Ferro-manganese nodules and mottles with diffuse external boundaries are observed in QGWB2 and QGWB3 member soils. In QGWB4 member soils ferro-manganese nodules with sharp external boundaries are common but they are most conspicuous in the lateritic soils of QGWB5 member. The diffuse nodules in QGWB4 and QGWB5 are indicative of their formation by current pedogenic processes whereas the nodules with sharp external boundaries may be interpreted to be due to past pedogenic processes and having been inherited from the parent material respectively.

Two types of calcretes have been recognized. The micritic calcrete features with diffuse boundries are observed in soils of Barind Tract and they indicate their formation due to current pedogenic processes, whereas the descrete sparitic nodules found in the petrocalcic horizon of Raghunathganj soil seems to be of relict origin. The presence of ferric oxide/hydroxide impregnations in the sparitic nodules indicate that they are being modified by the current pedogenic processes occurring in the overlying soils. Earlier Sehgal and Stoops (1972), Bal (1975) and Kemp (1985) suggested that the formation of similar features indicates multicyclic formation in course of soil development.

Clay coatings are absent in the QGWB1 and QGWB2 soils. The QGWB3 member soils of the Damodar Terminal Fan have flood-coatings together with thin (20-30 μm) illuvial clay coatings. The Barind Tract (Lower Level) soils of QGWB3 members have thin (30-40 μm) illuvial clay coatings, flood coatings and deformed and broken papules. Vertic intergrade soils of QGWB4 member show deformed clay feature (papules), slickensided ped faces, stress-oriented coatings and thin (30-60 μm) illuvial clay coatings. The clay coatings in these soils generally consist of limpid and speckled clay.

The upper unit of Lateritic Upland soils show the presence of rounded sesquioxide nodules with sharp boundaries containing quartz which have iron oxide in the cracks (termed runiquartz by Eswaran et al., 1975), papules, embedded grain clay coatings. These features combined with their occurrence as interbeds with sands suggest their allochthonous origin. The lower unit exhibits a crumby microstructure and contains microlaminated thick clay coatings (200-300 μm), micropans (> 1 mm), irregular shaped nodules, void hypocoatings of ferruginous matter, free-grain clay coatings and fragments of angular quartz in the iron oxide matrix or in nodules indicating autochthonous origin.

6.5.2 Ages of Soil-chronoassociation Members

In the present study samples from base and top of B horizons of some soil-geomorphic units were dated by Thermoluminesce (TL) dating technique. The ages from the basal samples indicate the time of deposition and approximate maximum age of soils. The ages of samples from the top of B horizon are discussed later. TL ages obtained for the soils of different units are: (i) Ganga Floodplain -500 yr (ii) Old Ganga Plain -1.5 ka, (iii) Bhagirithi Plain -1 ka, (iv) Damodar Terminal Fan - 3.6 ka, (v) Ajay-Silai Plain -5.4 ka and (vi) Bhagrithi-Brahmani Plain -

6.7 ka. These ages helped to give tentative ages to QGWB1 to QGWB4 members as 500 yr, 1-1.5 ka, 3-4 ka and 5-6 ka respectively.

Lateritic soils similar to the present have been found to contain Middle Pleistocene vertebrate fossils and paleolithic tools (Vaidyanadhan and Ghosh, 1993) and similar tools have been given a maximum age of 125 ka (Mishra, in press). On this basis, the lower unit of Lateritic soils are assigned a tentative maximum age of 125 ka. The minimum age is 22 ka that marks the beginning of the Last Glacial Stage, as discussed later. A radiocarbon date of 23 ka has been obtained from a calcrete from the Raghunathganj Surface/Soil.

6.6 Development of Landforms and Soils

6.6.1 Pedogenic Processes

Integration of field and laboratory data indicates that broadly soils of the study area can be divided into three groups: (a) Lateritic Upland soils (QGWB5), (b) moderately developed soils associated with old fluvial/deltaic plains like Bhagirathi-Brahmani Plain, Brahmani-Ajay Plain, Ajay-Silai Plain, Damodar Terminal Fan and that of Barind Tract (Lower Level) (QGWB4 and QGWB3) and (c) poorly developed soils associated with young fluvial plains like Old Ganga Plain, Ganga Floodplain and Bhagirathi Plain (QGWB2 and QGWB1).

The lower autochthonous unit of Lateritic Upland soils represents intense weathering of ferralitisation stage of Duchaufour (1982). The upper allochthonous unit of lateritic soils represents eroded lateritic material from the hinterland and its emplacement in the topographically lower regions due to lowering of the msl as discussed below. This can be called as Laterite-Derived-Facies (LDF) after Valeton and Wilke (1993). Of course continuation of lateritisation caused induration of these soils.

The moderately developed soils are marked by clay illuviation and transformation of smectite and illite into interstratified clay minerals on a large scale. However, the soils of the Bhagirathi-Brahmani, Brahmani-Ajay and Ajay-Silai Plains are marked by the presence of vertic intergrade soils with high proportion of 2:1 interstratified minerals and smectite in the soil profile. Additionally they are marked by pedoturbation in the upper part and swelling and shrinking leading to formation of slickensides and stress-oriented coatings and the presence of sand grains with clay coatings in the Ap horizon, brought up from the Bt horizon. The presence of illuviation features and high amount of 2:1 swelling clays suggests fersialitisation stage of weathering of Duchaufour (1982). Two TL ages of samples from the base of shrinkage cracks in vertic intergrade soils are 500 yr and 1.5 ka. These are interpreted to represent time of turnover of the soils.

Formation of small amounts of chlorite and illite-chlorite in the surface horizons of QGWB3 soils together with common occurrence of gleyans and flood coatings suggest that illite is being transformed to chlorite through illite-chlorite (e.g. in Barind Tract) and chlorite-smectite (in Damodar Terminal Fan) by ferrolysis in a manner suggested by Brinkman (1969/1970, 1977).

The poorly developed soils of the young fluvial plains are marked by hydromorphism and slight clay illuviation.

6.6.2 Role of Paleoclimatic and Sea level Changes

The paleoclimatic and sea level changes seem to have played a significant role in the development of landforms and soils of the study area. From a review of the earlier work three major phases of sea level and climatic changes since Mid Pleistocene can be recognized from eastern coast of India:

i. The coastal regions experienced a major transgression during the Mid Pleistocene reaching level of +25 m (Merh, 1992). At this time (125 ka) a warm and humid climate prevailed in the area and it corresponds to the Last Interglacial in mid. latitudes (Mishra, in press). It was followed by a regression.

ii. According to Agarwal and Guzdar (1972 in Merh, 1992) and Burckner (1988 in Merh, 1992), the east coast was marked by a transgression at ca. 30 ka. Also, the sea level fell to -130 m in the Bay of Bengal at 22-18 ka (Johnson, 1975) during an arid phase corresponding to the Last Glacial Stage in the mid. latitudes.

iii. At 7-6 ka, transgression of sea swept many parts of the area (Banerjee and Sen, 1987) and sea level rose to 6-10 m above msl (Merh, 1992). This was also a time of onset of more humid and wetter climate. Since then sea level has receded to the present level.

The first phase saw deposition of the parent material for the Lateritic soils (QGWB5). Lateritization started with regression of the sea of this stage on the upland areas with a good drainage under a warm and humid climate. The low msl in the later part of this phase must have caused the formation of the LDF. In the second phase a small transgression at ca. 30 ka with associated rising groundwater must have accelerated lateritization of the autochthonous Lateritic soils in a manner suggested by Valeton and Wilke (1993). Regression at the end of this phase probably led to erosion and formation of Raghunathganj Surface/Soil with petrocalcic horizon during an arid phase. The third phase led to the deposition of sediments of the QGWB3 (Damodar Terminal Fan) and QGWB4 members. As the sea regressed during this phase, freshly deposited sediments were exposed on which pedogenic processes started, as a result soils are younger from west to east in the region east of the Lateritic Upland. This regression has also contributed at least partly to entrenchment of the courses of the Ganga, Damodar, Ajay and Brahmani rivers due to reduced msl.

The above discussion also implies the existence of another Quaternary cycle of lateritization different from the Early Tertiary 'Indian Cycle' identified by Valeton and Wilke (1993).

6.6.3 Role of Tectonics

The present region lies in one of the most seismically active zones of the world. Most of the study area overlies the Bengal Basin. Its contact with the Peninsular rocks is along the Chotanagpur Foothill Fault. Within the Basin, three major tectonic units are: Tectonic Shelf in the western part, Barind Tract Horst in the north and the Ganga Fluvio-deltaic Plain (GFDP) Graben in the eastern part. The Tectonic Shelf and Barind Tract Horst are separated by the Ganga-Padma Fault and the Damodar Fault separates the Tectonic Shelf and GFDP Graben. The Medinipur-Farakka Fault within the Tectonic Shelf separates the Lateritic Upland in the west from QGWB4 soils in the east. The Chotanagpur Foothill, Medinipur-Farakka and Damodar Faults are roughly N-S trending with significant reliefs of 250 m, 25 m and 6 m across them respectively and form step faults with eastern sides in each case being downthrown side.

The western boundaries of the (i) Lateritic Upland, (ii) BBP, BAP, ASP Plains and (iii) DTF units are marked by Chotanagpur Foothill, Medinipur-Farakka and Damodar Faults respectively (Fig. 2.9) and these faults were the areal limits of sediments deposited at different times indicating their activity at those times e.g.

1. Sediments deposited during transgression of 125 ka do not extend further west of the Chotanagpur Foothill Fault.

2. Transgression at 6-7 ka took place up to the Medinipur-Farakka Fault.

3. During regression after 6 ka, the Damodar Fault was active and had sufficient throw/relief so that the Damodar Rive constructed the Damodar Terminal Fan.

Thus the activity along faults affected sedimentation directly and pedogenesis indirectly.

The Lateritic soils (QGWB5) and the QGWB4 soils are presently 120-30 m and 50-20 m asl but the sea level rose to +25 m and +6 to 10 m above sea level during 125 ka and 7 ka transgressions respectively, suggesting that the Tectonic Shelf has been uplifted significantly more on the western side and less on the eastern side since 125 ka. The total uplift is probably accounted partly by relief/throw across the faults and partly by steep easterly slopes of the plains.

All the easterly flowing rivers in the Tectonic Shelf zone have shifted their courses towards the south within their floodplains indicating southerly tilting of the Shelf in the last 100's of years. Also, the Dwarkeshwar, Silai and Kasai rivers show annular drainage pattern indicating activity of some basal dome in this zone. Also, the courses of the rivers Ganga, Damodar and partly Bhagirithi are confined to faults.

As mentioned earlier the Barind Tract Horst has at least three erosional levels (with varying reliefs of 5 to 20 m) soils developed on each of them. These indicate tectonic uplift in at least three stages and these levels are similar to river terraces.

6.7 Conclusions

(1) Nine soil-geomorphic units were recognized and grouped into five soil-chronoassociation members (QGWB1 to QGWB5, with QGWB5 being the oldest).

(2) The ages of different soil-chronoassociation members are QGWB1: <500 yr; QGWB2: 1-1.5 ka; QGWB3: 3-4 ka; QGWB4: 5-6 ka and QGWB5: 22-125 ka.

(3) The Last Interglacial Stage (125-22 ka) was a period of warm and humid climate in the area and its beginning was marked by a major transgression. It was followed by a regression and a smaller transgression at ca. 30 ka. The Last Glacial Stage (22-18 ka) was a period of regression. Another transgression took place at 7 ka accompanied by the start of a warm and humid phase. Since then the sea has regressed.

(4) The soils formed during the Last Interglacial Stage show intense weathering of ferralitisation stage. The LDF soils were formed during later regressions. During 30 ka - 18 ka period, soils developed with a petrocalcic horizon under an arid climate. Soils developed since 7 ka have developed to fersialitisation stage. The younger soils have been affected by hydromorphism, ferrolysis and slight clay illuviation.

(5) The Quaternary cycle different from the already reported Early Tertiary "Indian Cycle" of lateritisation has been recognized.

(6) On the Tectonic Shelf different faults have been active since 125 ka controlling sedimentation and development of landforms, drainage and soils. Activity along faults controlled limits of sedimentation in the past. Differential uplift (higher on the west than in the east) caused steep easterly slopes and drainage. Recent reactivation of a subsurface dome in the southern part and generally southerly tilt caused development of annular drainage and southerly shifting of rivers respectively.

Episodic uplift of the Barind Tract gave rise to different levels with the varied degrees of soil development.

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APPENDICES

APPENDIX I

PARTICLE SIZE DISTRIBUTION OF SOIL PROFILES OF THE VARIOUS SOIL-GEOMORPHIC UNITS

Soil-geomorphic Units	Pedon	Depth	Horizon	Sand %	Silt%	Clay %	Texture	Clay Accumulation Index
Ganga Floodplain	L21	0-10	Ap	17.58	46.85	35.56	Sicl	ND
		10-22	A1	7.11	57.17	35.71	Sicl	
		22-55	C1	20.07	47.34	32.57	Sicl	
		55-85	C2	14.33	50.49	35.16	Clm	
		85-115	C3	23.69	39.67	36.62	Clm	
Old Ganga Plain	L2	0-18	Ap	28.51	65.54	5.95	Sil	58
		18-35	B1	20.21	70.77	9.02	Sil	
		35-75	II B2	22.69	71.17	6.13	Si	
		75-116	II B3	12.50	82.50	5.0	Si	
		116-150	II C	7.71	87.95	4.34	Si	
Bhagirathi Plain	L15	0-18	Ap	35.56	51.11	13.32	Lm	122
		18-31	B1	33.21	50.11	16.66	Lm	
		31-43	B21	29.80	52.51	17.68	Sil	
		43-64	B22	29.31	48.93	21.75	Lm	
		64-105	C1	27.29	56.95	15.75	Sil	
		105-130	C2	27.47	48.53	24.00	Lm	
Bhagirathi Plain	LC6	0-15	Ap	10.3	70.2	19.5	Sil	114
		15-32	B1	5.4	71.72	22.88	Sil	
		32-51	B21	5.2	65.70	30.1	Sicl	
		51-63	B22	13.3	61.40	25.3	Sil	
		63-85	C1	33.87	66.13	20.0	Sil	
Damodar Terminal Fan	LB3	0-12	Ap	39.19	43.90	16.90	Lm	433
		12-23	A1	38.89	45.51	15.58	Lm	
		23-33	B1	32.59	46.93	20.46	Lm	
		33-70	B21g	26.03	51.24	22.72	Sil	
		70-93	B22g	35.93	43.22	20.84	Lm	
		93-120	C	56.63	28.79	14.56	Salm	
Damodar Terminal Fan	LB4	0-17	Ap	34.89	38.22	26.87	Lm	545
		17-31	A1	28.45	53.81	17.72	Sil	
		31-47	B1	16.32	50.73	32.93	Sicl	
		47-72	B21g	14.43	54.38	31.17	Sicl	
		72-98	B22g	31.15	43.99	24.85	Lm	
		98-120	C	35.48	47.19	17.31	Lm	

Damodar Terminal Fan	LD3	0-20	Ap	12.28	69.29	18.42	Sil	199
		20-40	A1	2.39	93.22	4.38	Si	
		40-61	B1	1.84	75.57	22.58	Sil	
		61-80	B21tg	1.09	73.78	25.11	Sil	
		80-94	B22tg	4.29	65.23	30.47	Sicl	
		94-117	C1	9.31	66.33	24.34	Sil	
		117-151	C2	14.97	65.58	19.43	Sil	
Barind Tract	L1	0-15	Ap	8.86	77.84	13.30	Sil	114
		15-35	A1	21.07	75.21	3.73	Sil	
		35-65	B1	27.73	69.49	2.78	Sil	
		65-92	B2	17.20	73.58	9.22	Sil	
		92-120	C1	8.01	87.00	4.99	Si	
Barind Tract	LA1	0-26	Ap	49.57	47.46	2.97	Salm	392
		26-52	B1	50.44	42.65	6.91	Lm	
		52-72	B21	32.10	57.75	10.15	Sil	
		72-103	B22	26.36	58.64	15.0	Sil	
		103-144	C1	28.53	68.47	3.00	Sil	
		144-167	C2	25.09	68.15	6.76	Sil	
Ajay-Silai Plain	LD1	0-14	Ap	39.43	46.15	14.40	Lm	378
		14-29	A1	48.26	48.99	2.73	Salm	
		29-52	B1	39.82	38.07	22.09	Lm	
		52-99	B21t	45.15	35.31	19.52	Lm	
		99-120	B22t	36.98	44.01	18.99	Lm	
		120-198	C	63.67	22.62	13.69	Salm	
Ajay-Silai Plain	LD2	0-20	Ap	29.46	54.59	15.94	Sil	-
		20-35	B1	18.71	58.03	23.25	Sil	
		35-55	B21	16.29	53.11	30.58	Sicl	
		55-87	B22	26.67	46.64	26.67	Lm	
		87-100	B3	31.11	50.60	18.27	Sil	
Ajay-Silai Plain	L8	0-12	Ap	55.88	33.84	10.27	Salm	-
		12-20	A1	51.29	37.08	11.62	Salm	
		20-38	B1	35.73	45.53	18.72	Lm	
		38-65	B21	28.87	45.46	25.66	Lm	
		65-120	B22	34.26	35.20	30.52	Clm	
Ajay-Silai Plain	LB2	0-18	Ap	27.12	61.33	11.55	Sil	1062
		18-34	B1	22.90	50.72	26.37	Sil	
		34-88	B21	24.15	44.95	30.90	Clm	
		88-126	B22t	27.43	31.99	40.58	C	
		126-	C	19.31	56.49	24.19	Sil	

Ajay-Silai Plain	LB1	0-20	Ap	30.69	41.55	27.75	Lm	870
		20-36	B1g	25.69	42.87	31.43	Clm	
		36-58	B21g	18.82	44.54	36.63	Sicl	
		58-87	B22g	20.97	40.38	38.64	Clm	
		87-127	B23g	20.26	38.02	41.72	C	
		127-150	C	35.20	40.57	25.23	Lm	
Ajay-Silai Plain	LB11	0-20	Ap	23.94	32.41	43.64	C	1522
		20-38	A1	13.31	42.37	44.30	Sic	
		38-57	B1	18.81	37.39	43.78	C	
		57-83	B21t	9.94	42.58	47.47	Sic	
		83-117	B22t	11.96	34.52	53.50	C	
		117-151	C	34.66	40.23	25.11	Lm	
Brahmani-Ajay Plain	LC2	0-20	Ap	28.16	61.18	10.64	Sil	1564
		20-29	A1	30.21	56.98	12.80	Sil	
		29-44	B1	43.49	40.64	15.86	Lm	
		44-58	B21t	34.37	50.28	15.33	Sil	
		58-85	B22t	27.27	43.92	28.80	Clm	
		85-104	B23t	28.10	39.21	32.68	Clm	
		104-140	B3	35.34	33.12	32.53	Clm	
		140-160	C	34.02	53.87	12.11	Sil	
Brahmani-Ajay Plain	LC4	0-20	Ap	28.12	52.12	19.75	Sil	852
		20-58	B1	36.00	50.42	13.56	Sil	
		58-82	B21t	27.85	40.15	31.98	Clm	
		82-113	B22t	27.36	41.05	31.57	Lm	
		113-150	Km	36.20	47.60	16.20	LM	
Bhagirathi-Brahmani Plain	L12	0-10	Ap	29.70	55.00	15.30	Sil	1173
		10-22	A1	31.90	49.93	18.15	Lm	
		22-33	B1	21.97	47.04	30.98	Clm	
		33-61	B21t	26.05	39.10	34.83	Clm	
		61-118	B22t	24.54	41.61	33.83	Clm	
		118-130	C	58.88	22.59	18.52	Salm	
Bhagirathi-Brahmani Plain	L11	0-15	Ap	24.63	61.97	13.40	Sil	-
		15-22	A1	27.70	56.15	16.15	Sil	
		22-42	B1	19.00	52.11	28.90	Clm	
		42-80	B21	23.40	45.90	30.70	Clm	
		80-110	B22	20.50	48.60	30.90	Clm	
Lateritic Upland	LC1	0-45	C	53.90	31.80	14.30	Salm	ND
		45-96	II B	54.10	34.20	11.70	Salm	
		96-150	II B	45.00	45.40	9.60	Lm	
		150-220	II B	35.70	47.30	17.10	Lm	
		220-300	III Box1	40.90	37.50	21.60	Lm	
		300-340	III Box2	41.40	35.50	23.10	Lm	
		340-390	III Box3	66.10	13.80	20.10	Sacl	

Lateritic Upland	LB5	0-37	C	46.3	46.10	7.60	Lm	ND
		37-50	II Box1	44.3	38.80	16.90	Lm	
		50-105	II Box1	41.5	46.40	13.00	Lm	
		105-150	II Box1	35.4	53.10	11.50	Sil	
		150-250	II Box2	27.6	57.10	15.30	Sil	
		250-320	II Box2	29.2	52.10	18.70	Sil	
		320-360	II Box3	31.9	40.80	27.30	Clm	

APPENDIX II

VARIATION OF MAJOR OXIDES AND MOLAR RATIO WITH DEPTH IN VARIOUS SOIL-GEOMORPHIC UNITS

Depth (cm)	Horizon	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	MnO	K_2O	Na_2O	Molar Ratio SiO_2/R_2O_3 *
OLD GANGA PLAIN											
PEDON L2											
0-18	Ap	62.49	17.33	5.19	0.16	0.83	0.73	0.30	2.80	0.15	4.3
18-35	B1	60.08	18.35	6.23	0.32	0.91	0.77	0.51	2.70	0.15	4.1
35-75	II B2	63.08	19.37	5.27	0.39	0.89	0.63	0.49	2.1	0.10	3.9
75-116	II B3	64.29	17.33	5.19	0.32	0.97	0.58	0.43	2.3	0.13	4.8
116-150	II C	65.50	18.35	7.27	0.32	0.81	0.56	0.32	2.14	0.07	4.3
BHAGIRATHI PLAIN											
PEDON L15											
0-18	Ap	66.76	18.09	3.11	0.27	0.96	0.59	0.21	2.29	0.13	4.8
18-31	B1	63.07	17.99	6.76	0.10	0.80	0.61	0.16	2.13	0.05	4.7
31-43	B21	64.47	18.87	7.58	0.45	0.81	0.59	0.31	2.12	0.03	4.3
43-64	B22	60.64	19.25	7.57	0.23	0.910	0.81	0.51	2.42	0.05	4.2
64-105	C1	65.50	17.33	6.23	0.16	.86	0.64	0.29	2.08	0.09	4.7
BHAGIRATHI-BRAHMANI PLAIN											
PEDON L12											
0-10	Ap	69.72	13.91	5.29	0.07	0.61	0.50	0.04	1.92	0.15	6.1
10-22	A1	73.13	13.73	5.61	0.09	0.60	0.52	0.09	1.83	0.07	6.7
22-33	B1	74.97	15.92	5.63	0.54	0.60	0.51	0.13	1.96	0.08	5.8
33-61	B21t	72.19	15.31	6.33	0.34	0.85	0.63	0.24	2.31	0.09	5.6
61-118	B22t	67.01	18.32	6.90	0.30	0.93	0.64	0.32	2.50	0.89	4.4
BRAHMANI-AJAY PLAIN											
PEDON LC2											
0-20	Ap	70.71	13.87	5.12	0.09	0.71	0.50	0.03	1.88	0.10	6.9
20-29	A1	74.17	13.63	5.57	0.12	0.70	0.50	0.08	1.84	0.08	7.7
29-44	B1	76.90	15.80	5.60	0.65	0.91	0.50	0.14	1.70	0.08	6.5
44-58	B21t	73.20	15.28	6.42	0.38	0.71	0.51	0.11	1.91	0.06	6.3
58-85	B22t	67.80	18.35	6.88	0.34	0.85	0.88	0.26	2.10	1.74	5.0
85-104	B23t	68.34	18.98	6.94	0.60	0.91	0.62	0.22	2.15	0.26	4.8
104-140	B3	65.77	19.94	7.57	0.75	0.95	0.63	0.33	2.17	0.17	4.2

* $R_2O_3 = Fe_2O_3 + Al_2O_3 + TiO_2$

AJAY-SILAI PLAIN

PEDON LB11

0-20	Ap	68.59	18.67	6.48	0.74	0.83	0.53	0.05	1.87	0.05	4.9
20-38	A1	61.30	20.95	6.44	0.83	0.90	0.54	0.04	1.94	0.02	3.9
38-57	B1	60.36	23.41	6.75	0.97	0.94	0.53	0.03	1.89	0.01	3.6
57-83	B21t	59.87	23.26	7.18	1.06	0.94	ND	0.04	1.92	ND	3.4
83-117	B22t	64.47	22.93	6.57	1.15	1.06	ND	0.03	1.88	ND	4.0
117-151	C	64.22	23.62	7.25	1.07	1.14	0.73	0.03	2.10	0.04	3.7

PEDON LD1

0-14	AP	77.90	14.22	5.01	0.84	0.73	ND	0.08	1.42	ND	7.2
14-29	A1	78.49	12.56	4.09	0.43	0.70	ND	0.02	1.16	0.04	8.2
29-52	B1	74.23	15.74	5.49	0.70	0.72	ND	0.03	1.40	0.06	6.5
52-99	B21T	73.34	16.84	6.05	0.74	0.72	ND	0.08	1.51	0.04	5.6
99-120	B22T	68.72	19.29	6.09	1.38	0.82	ND	0.070	1.80	0.07	4.6
120-198	C	78.63	13.46	5.30	0.55	0.72	ND	.05	1.24	0.04	7.7

PEDON LD2

0-20	Ap	64.89	21.54	6.73	1.12	1.13	0.65	0.15	2.43	0.94	4.0
20-35	B1	62.62	22.91	7.34	1.61	1.28	0.64	0.17	2.31	0.76	3.6
35-55	B21	57.77	23.83	7.72	1.42	1.35	0.96	0.17	2.37	0.67	3.2
55-87	B22	61.37	23.95	7.79	1.59	1.31	0.97	0.23	1.96	0.67	3.3
87-100	B3	60.33	24.20	7.45	1.62	1.23	0.78	0.17	2.03	0.66	3.3

PEDON LB1

0-20	Ap	71.28	17.34	4.72	0.39	0.78	0.42	0.06	2.10	0.09	5.8
20-36	B1g	69.28	19.46	5.01	0.78	0.83	0.55	0.08	2.19	0.02	5.0
36-58	B21g	69.58	19.06	4.85	0.61	0.83	0.53	0.05	2.18	0.18	5.0
58-87	B22g	57.34	23.67	3.66	0.55	0.95	0.50	0.04	2.33	0.22	3.7
87-127	B23g	58.71	22.58	8.78	0.10	0.97	0.51	0.09	2.34	0.38	3.6

DAMODAR TERMINAL FAN

PEDON LB4

0-17	Ap	65.38	18.95	5.59	1.00	0.87	0.68	0.06	3.01	0.94	4.5
17-31	A1	65.09	21.57	6.68	0.89	0.97	0.54	0.10	3.09	0.82	4.2
31-47	B1	64.85	21.74	6.77	ND	1.08	0.50	0.07	3.19	0.75	4.2
47-72	B21g	61.21	22.68	7.05	0.73	1.09	0.52	0.09	3.04	0.24	3.8
72-98	B22g	63.00	22.00	7.02	0.44	1.11	1.03	0.14	3.12	1.05	3.9
98-120+	C	62.30	21.75	6.79	0.38	1.14	1.01	0.07	3.13	1.12	4.1

PEDON LD3

0-20	Ap	61.80	22.47	6.94	1.27	1.44	0.72	0.10	2.50	0.82	3.7
20-40	A1	60.55	22.97	7.07	1.47	1.32	0.60	0.12	2.40	0.64	3.4
40-61	B1	59.79	23.72	7.55	1.48	1.38	0.80	0.25	2.35	0.71	3.3
61-80	B21tg	54.12	24.09	8.34	1.70	1.36	0.67	0.20	2.37	0.57	3.0
80-94	B22tg	57.34	24.24	7.64	1.73	1.32	0.58	0.10	2.42	0.61	3.1
94-117	C1	53.94	24.24	7.91	1.46	1.31	0.53	0.1	2.50	0.65	3.2
117-151	C2	56.49	24.65	7.88	1.26	1.25	0.60	0.22	2.40	0.75	3.0

BARIND TRACT

PEDON LA1

0-26	Ap	57.13	26.27	7.18	0.88	1.18	0.59	0.16	2.84	0.30	3.1
26-52	B1	58.73	25.93	6.78	0.80	1.33	0.54	0.07	2.92	0.34	3.3
52-72	B21	61.52	24.69	6.51	0.05	1.19	0.53	0.07	3.27	0.31	3.7
72-103	B22	60.02	25.85	6.49	1.00	1.17	0.46	ND	2.90	0.32	3.3
103-145	C1	61.80	25.44	6.47	0.83	1.11	0.45	0.04	2.80	0.26	3.4
145-167	C2	60.64	25.11	6.99	0.85	1.12	0.43	0.08	ND	0.35	3.4

LATERITIC UPLAND

PEDON LC1

0-16	C	63.33	10.59	4.39	4.20	0.01	ND	0.05	1.86	ND	5.8
16-45	C	69.46	10.20	2.38	4.99	0.01	ND	0.06	1.16	ND	6.8
45-220	II B	73.00	8.96	2.92	4.37	ND	ND	0.07	1.14	ND	7.6
220-300	$IIIBox_1$	69.05	10.17	2.85	2.49	ND	ND	0.04	0.79	ND	8.2
300-340	$IIIBox_2$	66.17	15.33	3.45	4.43	0.02	ND	0.02	0.84	ND	4.8
340-390	$IIIBox_3$	53.98	15.94	5.02	2.40	0.05	ND	0.04	2.48	ND	4.1

PEDON LB5

0-37	C	64.73	12.91	1.91	3.81	0.09	ND	0.05	1.40	ND	5.8
37-90	II Box_1	57.87	15.71	3.85	3.58	0.14	ND	0.11	1.38	ND	4.6
90-150	II Box_1	55.40	15.39	4.44	3.52	0.15	ND	0.08	1.38	ND	4.2
150-210	II Box_2	53.37	12.64	9.00	2.74	0.06	ND	0.11	1.17	ND	4.2
210-250	II Box_2	46.59	16.76	9.33	3.23	0.06	ND	0.14	1.16	ND	3.0
250-320	II Box_2	37.74	13.24	18.33	2.64	0.03	ND	0.20	0.70	ND	2.2
320-360	II Box_3	55.38	14.75	5.3	2.96	0.02	ND	0.03	1.17	ND	4.4

APPENDIX III

VARIATION OF CLAY MINERALS WITH DEPTH IN VARIOUS SOIL-GEOMORPHIC UNITS

Soil-Geomorphic Units	Pedon	Horizon	Depth (cm)	Kaolinite (%)	Illite (%)	Inter stratified minerals (%)	Smectite (%)	Chlorite (%)
Bhagirathi Plain	L15	Ap	0-18	27.6	20.2	35.2	17.0	-
		B1	18-31	29.5	37.4	27.0	6.1	-
		B21	31-43	33.9	23.0	35.1	8.0	-
		B22	43-64	32.0	26.6	31.1	10.3	-
		C	64-105	30.6	32.5	30.6	6.3	-
Damodor Termonal Fan	LB4	Ap	0-17	35.4	33.1	28.0	-	3.5
		A1	17-31	38.2	28.0	32.3	-	1.5
		B1	31-47	40.0	25.5	33.0	-	1.5
		B21g	47-72	30.3	23.5	46.2	-	-
		B22g	72-98	21.4	17.4	61.2	-	-
		C	98-120	15.3	35.0	49.7	-	-
	LD3	Ap	0-20	24.9	34.3	38.3	-	2.5
		A1	20-40	25.3	31.7	39.9	-	3.1
		B1	40-61	31.5	32.3	36.2	-	-
		B21tg	61-80	34.5	25.3	40.2	-	-
		B22tg	80-94	33.4	18.5	48.1	-	-
		C1	94-117	26.6	39.4	34.0	-	-
Barind Tract	LA1	Ap	0-26	5.1	24.5	63.4	-	7.0
		B1	26-52	6.0	25.8	63.2	-	5.0
		B21	52-72	6.5	38.3	55.2	-	-
		B22	72-103	7.2	46.0	46.8	-	-
		C1	103-145	16.0	65.0	17.3	-	-
Bhagirathi Brahmani Plain	L12	Ap	0-10	44.1	27.0	18.0	10.9	-
		A1	10-22	40.4	22.4	25.2	12.0	-
		B1	22-33	42.2	24.7	20.3	12.8	-
		B21t	33-61	41.3	22.7	21.0	15.0	-
		B22t	61-118	23.7	11.6	48.0	16.7	-
		C	118-130	15.9	29.8	34.1	20:3	-

Brahmani Ajay Plain	LC2	Ap	0-20	19.2	53.8	27.0	-	-
		A1	20-29	18.4	46.2	35.4	-	-
		B1	29-44	13.3	41.3	45.4	-	-
		B21t	44-58	9.7	30.2	60.1	-	-
		B22t	58-85	5.5	25.1	69.4	-	-
		B23t	85-104	5.7	20.1	74.2	-	-
		B3	104-140	5.6	19.6	74.8	-	-
		C	140-160	4.2	35.3	60.5	-	-
Latiritic Up Land	LC1	C	0-16	59.0	18.5	22.5	-	-
			16-45	41.6	44.4	14.0	-	-
		II B	45-150	45.8	42.7	11.5	-	-
			150-220	70.0	20.4	9.6	-	-
		III BOX1	220-300	63.8	20.6	15.6	-	-
		III BOX2	300-340	82.6	13.5	3.9	-	-
		III BOX3	340-440	89.0	11.0	-	-	-
Ajay Silai Plain	LB1	Ap	0-20	12.5	52.5	35.0	-	-
		B1g	20-36	14.7	54.8	30.5	-	-
		B21g	36-58	18.1	40.2	41.7	-	-
		B22g	58-87	22.3	38.5	39.2	-	-
		B23g	87-127	20.9	40.8	38.3	-	-
		C	127-150	8.1	50.3	41.6	-	-
Old Ganga Plain	L2	Ap	0-18	17.5	55.3	17.1	6.2	3.9
		B1	18-35	14.3	49.6	22.7	8.1	5.3
		II B2	35-75	11.8	47.6	25.6	7.1	7.9
		II B3	75-116	15.1	49.3	23.7	6.5	5.4
		II C	116-150	15.9	58.1	16.1	5.1	4.8

APPENDIX - IV

DESCRIPTION OF TYPICAL THIN SECTIONS

1 OLD GANGA PLAIN

(i) Thin Section No. L2/3; Horizon : II B2; Depth : 35-75 cm

Macroscopic Characteristics

Olive (5 YR/3) moist, silt loam, weakly developed fine subangular blocky structure, very friable, nonplastic, many fine roots.

Microstructure

The soil material is weakly pedal. The voids are mostly packing voids and intergrain channels with a few vughs and vesicles.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 30/70

(a) Coarse Fraction

The coarse fraction consists mainly of sub-rounded quartz of 50-75 μm, size and shows mainly monic to chitonic related distribution. Other minerals are mica (mostly muscovite) about 10%, K-feldspars about 10%. Micas show weakly altered flakes of 30-50 μm which are oriented parallel to each other. Other constituents of coarse fraction include a few rock fragments, heavy minerals and opaques.

(b) Fine Fraction/Groundmass

Mainly mineralic matters of fine micaceous nature. It consists of very fine silt and speckled clay. Stipple-speckled b-fabric is commonly observed in this thin section.

Pedofeatures

Sesquioxide accumulation with diffuse external boundary are commonly observed. A few voids are completely filled with reworked soil material. Shells and snails are quite common in this horizon.

(ii) **Thin Section No.** L2/5 **Horizon :** II C; **Depth :** 116-150 cm

Macroscopic Characteristics

Olive (5y 4/3) moist, silt, few fine faint mottles, weak fine subangular blocky, common very fine tubular pores, firm, patchy thin clay cutans.

Microstructure

Weakly developed subangular blocky structure. Moderately well sorted grains. Voids are mostly packing voids. Total void space is about 25%. Voids are unoriented.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 30/70

(a) Coarse Fraction

The coarse fraction consists of 70% subangular to subrounded 40-50 μm size quartz. Micas are about 5-10% usually fresh to slightly altered flakes. Feldspars up to 5%, mainly orthoclase. Other coarse materials observed include a few heavy minerals and opaques.

(b) Fine Fraction/Groundmass

Mainly mineral matter of micaceous nature, consists of impure clay and fine silt. Weak to moderate parallel striated b-fabric is commonly observed. Infillings of coarse material in voids are observed at places.

Pedofeatures

Illuvial clay pedofeatures are absent. Remnant of sedimentary layer is observed in the lower part of this thin section. Diffuse sesquioxide hypocoatings are observed around voids at a few places in the section.

2 BHAGIRATHI PLAIN

(i) **Thin Section No.** L15/4; **Horizon** B22; **Depth :** 43-64 cm.

Macroscopic Characteristics

Dark grayish brown (10YR4/2) moist, loam, few fine faint mottles, strong medium subangular blocky, mainly fine tubular pores, hard, firm, plastic, few very fine roots.

Microstructure

The soil material is weakly pedal with fine angular blocky structure. Voids are mainly vughs,vesicles and channels which are randomly distributed.

Basic Mineral Components C/F limit : 10μm ; C/F ratio : 40/60

(a) Coarse Fraction

The coarse fraction consists of mainly angular quartz of 50-100 μm size. Other minerals include fresh microcline and partially weathered micas. The C/F related distribution is monic to gefuric.

(b) Fine Fraction

Fine fraction consists mostly of clay size micaceous particles which show stipple-speckled b-fabric.

Pedofeatures

A few channel infillings by fine sorted silt size material is noted. Sesquioxide material occurs as hypocoatings and as mottles with diffuse external boundaries. Incomplete infillings of voids with mineral excrement indicates animal activity in the soil section. Illuvial clay features are very thin.

(ii) Thin Section No. L15/5; Horizon : C1 : Depth 64-105 cm

Macroscopic Characteristics

Dark brown to brown (10 YR4/3) moist, silt loam, common fine distinct mottles, strong medium subangular blocky, common very fine tubular pores, hard, firm, plastic.

Microstructure

The soil material is weakly pedal and the texture is finer than the overlying horizon. Voids are vesicles and vughs with rough surfaces.

Basic Mineral Components C/F limit : 10 μm ; C/F ratio : 40/60

(a) Coarse Mineral Fraction

The coarse mineral fraction consists of about 70% angular to subangular quartz with the most common size range 50-100 μm, orthoclase and microcline about 10% and partially altered mica about 5%. Other minerals are heavy minerals and opaques.

(b) Fine Fraction/Groundmass

Colourless to yellowish brown micaceous material in the groundmass. Some silty accumulation around voids. C/F related distribution is close porphyric, stipple-speckled b-fabric is common.

Pedofeatures

No illuvial clay features. Remnants of sedimentary layering are observed in lower part of the thin section. Sesquioxide occurs as hypocoatings and as diffuse nodules and mottles. Incomplete infillings of voids with animal excrements and soil material are observed in some parts of the section.

(iii) Thin Section No. L21/3; Horizon : C1; Depth : 22-55 cm

Macroscopic Characteristics

Light olive brown (2.5 Y 5/4) moist, silty clay loam, common fine distinct mottles, massive, common fine tubular pores, extremely hard, very firm, plastic, patchy thin clay cutans, few fine roots, a few semi-hard ferro-manganese concretions.

Microstructure

The soil material shows weakly developed subangular blocky structure, peds are weakly separated and occasionally partially accommodating ped faces are seen. Voids are mainly elongated rough to smooth walled channels, producing channel microstructure. Total estimated void space is about 15%. The voids are unoriented and show basic random distribution.

Basic Mineral Components C/F limit : 10 μm; C/F ratio : 35/65

(a) Coarse Fraction

The coarse fraction consists of subangular quartz up to 60%, ranging in size from 50-80 μm, randomly distributed in the groundmass. Fresh to partially weathered microcline 5%. Micas up to 5%. Other minerals include heavy minerals and opaques.

(b) Fine Fraction/groundmass

White to yellowish white fine silt and clay occurring as groundmass. Weak stipple-speckled b-fabrics are commonly observed which are randomly distributed.

Pedofeatures

Very thin (10-20 μm) hypocoatings of clay along voids. Small moderately impregnated ferruginous nodules diffuse mottles are commonly observed. Loose infillings and oriented clay in partly filled voids.

(iv) Thin Section No. L 21/4; **Horizon** : C2; **Depth** : 55-85 cm

Macroscopic characteristics

Light olive brown (2.5Y5/4) moist, clay loam, common fine distinct mottles, massive, few fine tubular pores, very hard, very firm, plastic, continuous thin clay cutans, few fine roots, a few semi-hard ferro-manganese concretions.

Microstructure

The soil material in the thin section is very weakly developed subangular blocky. Voids are mainly elongated rough walled channels. The total estimated void space is about 15%. The voids are unoriented and show basic random distribution.

Basic mineral components C/F limit : 20 μm; C/F ratio : 35/65

(a) Coarse Fraction

The coarse fraction consists mainly of subangular to subrounded quartz up to 60%, ranging in size from 50-100 μm. They are randomly distributed in the groundmass. Other minerals include K-feldspar 5% and micas up to 5%. Some heavy minerals and opaques are also visible.

(b) Fine Fraction/groundmass

White to yellowish white fine silt and clay occurring as groundmass. Weak stipple-speckled b-fabrics are common. Stress cutans along ped faces are observed in some parts of the thin section.

Pedofeatures

Thin (10-20 μm) hypocoatings along voids and diffuse sesquioxide nodules common. Sorted fine material around voids are observed at a few places.

3 BHAGIRATHI-BRAHMANI PLAIN

(i) Thin Section No. L 11/2; Horizon A1; Depth : 15-22 cm

Macroscopic Characteristics

Light brownish gray (2.5 Y6/2) dry, loam, common fine distinct reddish yellow (5 YR 6/8) mottles, moderate medium subangular blocky, mainly fine tubular pores, hard, firm, plastic, few fine roots, brown to black semi-hard ferro-manganese concretions (2-3 mm size).

Microstructure

The soil material in the thin section shows a pedal to weak subangular blocky structure. Peds are weakly separated. Randomly distributed elongated voids are quite common in the thin section. Occasionally, equant voids, channels and vughs are also observed.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 60/40

(a) Coarse Fraction

The coarse fraction consists of mostly angular to subangular quartz, ranging in size from 300-400 μm. occasionally fragments of feldspars and micas are also observed.

(b) Fine Fraction / groundmass

The fine fraction consists of yellowish brown specks of fine silt and clay size particles which are often stained by iron-oxide material. Grano-striated and poro-striated b-fabric are quite common in lower part of the thin section whereas in the upper part moderately developed mosaic to stipple-speckled b-fabric is more common. The C/F related distribution is porphyric.

Pedofeatures

No clay illuviation features are observed in this thin section. Faunal activity is very conspicuous. At places, the voids are completely filled with welded, angular mineral excrements and soil aggregates. A few small < 1 mm size rounded strongly impregnated sesquioxide nodules with sharp external boundaries are observed.

(ii) Thin Section No. L11/3; Horizon : B1, Depth : 22-42 cm

Macroscopic Characteristics

Dark grayish brown (2.5 Y4/2) moist, silty clay loam, few fine distinct reddish yellow (5 YR6/8) mottles, strong medium to coarse subangular blocky, few fine tubular pores, hard, firm, plastic, patchy thin clay cutans, few fine roots, common brown to black semi-hard ferro-manganese concretions (2-3 mm size).

Microstructure

Moderately developed coarse angular blocky soil structure. The peds are partially accommodating. Voids are mainly elongated channels: Total void space is about 10%. The voids show random distribution pattern.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 60/40

(a) Coarse Fraction

The coarse fraction consists mainly of quartz about 80%. Micas are about 5% and K-feldspars about 5%. Micas are partially altered. Other minerals occurring in minor amount are opaques and heavy minerals.

(b) Fine Fraction / groundmass

Mainly mineralic and some part organic in nature. It consists of impure ferruginous clay and fine silt. Grano-striated and poro-striated b-fabrics are common in thin sections. Weak, stress oriented clay coatings are seen at places.

Pedofeatures

Thin (30-40 μm) illuvial clay features are randomly distributed as coatings. Hypocoatings of sesquioxide are frequently observed. Depletion of iron oxide diffused mottles and stress coatings are also observed.

(iii) Thin Section No. L 12/4; Horizon : B21t; Depth : 33-61 cm

Macroscopic Characteristics

Olive brown (2.5 Y4/4) dry. common medium distinct brownish yellow (10 YR 6/8) mottles, clay loam, strong coarse subangular blocky, many very fine irregular pores, very hard, firm, very plastic, patchy moderately thick clay cutans, very few very fine roots.

Microstructure

Moderately to strongly developed subangular blocky structure. The peds are partially accommodating and separable. The peds are bounded by interconnected channel voids. The voids do not show any definite orientation and are randomly distributed. Channel and vughy microstructure is observed commonly. Chambers are also observed at a few places.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 60/40

(a) Coarse Fraction

Mostly angular to subangular quartz grains of size range 300-500 μm constituting 70-80% of the coarse fraction. They are randomly distributed. Weathering minerals like feldspar and mica are rare. Heavy minerals and opaques occur in less than 2%.

(b) **Fine Fraction/Groundmass**

Fine fraction consists of mostly fine silt and clay size materials. Clay occurs as groundmass and coatings along grains and voids. b-fabric development is moderate as stipple-striated b-fabric. Occasionally, weakly developed striated and grano-striated b-fabric. C/F related distribution is mainly porphyric.

Pedofeatures

Very thin (50 - 60 μm) illuvial clay features occur as coatings along grains and voids. Moderately to strongly impregnated iron-oxide mottles are observed commonly. Rounded sesquioxide concretions of diameter up to 1 mm constitute 1% of the area of the thin section. They have sharp external boundaries and contain angular quartz grains. Stress oriented coatings are observed occasionally in a zone devoid of other clay accumulation features. Loose infillings of voids with mineral excrements are also observed occasionally.

(iv) Thin Section No. L 12/5 : **Horizon** B22t; **Depth** : 68-118 cm

Macroscopic Characteristics

Strong brown (7.5 YR 5/6) dry, sandy loam, mainly medium vesicles, soft, friable, nonplastic.

Microstructure

Moderately to strongly developed subangular blocky structure with partially accommodating and separable peds. The voids are channels, chambers and vughs. The voids do not show any definite orientation and they are randomly distributed.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 60/40

(a) Coarse Fraction

Mostly quartz of 300 - 400 μm size constituting about 80% of the coarse fraction. Other minerals include flakes of weathered mica and resistant rock fragment caught up in the matrix. Some heavy minerals and opaques are also observed occasionally.

(b) Fine Fraction/Groundmass

Yellowish to dark brown due to staining of the groundmass with iron oxide material. The finer fraction consists of fine silt and impure clay. It occurs as groundmass and coatings along voids and grains. Moderately developed grano-striated and poro-striated b-fabrics are commonly observed throughout the section. C/F related distribution is mainly porphyric and enaulic.

Pedofeatures

Illuvial clay features, very thin (30-40 μm) coatings along voids and grains. Moderately to strongly impregnated iron-oxide mottles. Rounded sesquioxide nodules and concretions with sharp external boundaries are common. Features of iron accumulation due to alteration of biotite is observed at places.

4 BRAHMANI-AJAY PLAIN

(i) Thin Section No. LC2/3; Horizon : B1; Depth : 29-44 cm

Macroscopic Characteristics

Light grey (10 YR 7/1) dry, abundant medium prominent reddish yellow (7.5 YR 6/8) mottles, loam, strong coarse subangular blocky, very fine irregular pores, very hard, firm, plastic, patchy thin clay cutans, few very fine roots, silty coatings along ped faces.

Microstructure

The soil material shows moderately developed subangular blocky structure with ped faces are partially separated. Voids are mainly vesicles with some vughs and channels. Total void space is about 15%. The voids are unoriented and show basic random distribution.

Basic Mineral Components C/F limit 10 μm; C/F ratio : 60/40

(a) Coarse Fraction

The coarse fraction is mainly subangular to subrounded quartz of 75-100 μm size. Other minerals include partially altered orthoclase and plagioclase feldspars and micas. Some heavy minerals are also observed.

(b) Fine Fraction/Groundmass

Fine fraction consists mainly of yellowish brown micaceous material of fine silt and clay size particles. Some fine discretely mixed organic matter is also associated with it. Undifferentiated b-fabric is noted due to the presence of fine organic matter. Weakly developed stipple-speckled b-fabric is also observed at places. C/F related distribution is generally single spaced open porphyric.

Pedofeatures

Illuvial clay pedofeatures though present, are not very conspicuous. They occur as thin (40-50 μm) oriented speckled clay coatings along channels and voids. Small (< 1 mm) moderately impregnated sesquioxide nodules with clear to diffuse external boundaries are common. Iron-oxide depletion features are also observed at places in the upper part of the section.

(ii) Thin Section No. LC2/4; **Horizon** : B21t; **Depth** 44-58 cm

Macroscopic Characteristics

Light brownish grey (2.5 Y 6/2) dry, common medium distinct strong brown (7.5 YR 5/6) mottles, silt loam, strong coarse subangular blocky, common very fine tubular pores, very hard, firm, very plastic, patchy thin clay cutans along pores, common very few fine roots, concretions of 1-3 mm size are very common, silt/clay coatings along ped faces.

Microstructure

Moderately developed subangular blocky structure. Voids are mainly vughs and vesicles with some channels. Occasionally, a few chambers are also observed. The voids are unoriented and have the basic random distribution. Total estimated void space is 5-10%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 30/70

(a) Coarse Fraction

Coarse fraction consists mainly of 80% subangular to subrounded quartz. The most common size range is 25-75 μm occasionally up to 150-200 μm. Plagioclase is about 5% and mica (mostly muscovite) about 5%. Mica shows pellicular weathering in a few grains. Other minerals are heavy minerals and opaques.

(b) Fine Fraction/Groundmass

Mainly fine silt and clay size particles. The clay is impure and it is often punctuated by micro-contrasted organic particles of variable sizes. Weakly developed poro-striated and grano-striated b-fabric is observed frequently. C/F related distribution is close porphyric.

Pedofeatures

Thin (20-30 μm) silt and impure clay coatings along voids often masked by iron-oxide are common. Fragments of illuviated clay features (papules) embedded in soil matrix is seen at places. Subrounded impregnative ferro-manganese nodules of 1-3 mm size with sharp boundaries are commonly observed. Diffuse nodules are also observed frequently. Stress cutans with oriented clay domains are observed occasionally.

(iii) Thin Section No. LC2/5; **Horizon** : B22t; **Depth** : 58-85 cm

Macroscopic Characteristics

Light brownish gray (2.5 Y 6/2) dry, clay loam, mainly medium distinct strong brown (7.5 YR 5/6) mottles, strong coarse subangular blocky, extremely firm, very plastic, common very fine tubular pores, few very fine roots, often breaks along plains which consist of silty/clay material, ferro-manganese concretions of 1-2 mm size common.

Microstructure

Moderately developed subangular blocky structure with peds up to 5 mm size which are partially accommodated and weakly separable voids are mainly vughs and vesicles.

Basic Mineral Components C/F limit :20 μm; C/F ratio : 30/70

(a) Coarse Fraction

Poorly sorted grains with more than 80% of the coarse fraction consisting of subangular to subrounded quartz. Other major constituents are feldspars, mainly weakly altered orthoclase and some muscovite showing pellicular weathering. A few grains of hornblende and other heavy minerals are also observed.

(b) Fine Fraction/Groundmass

Yellowish brown colour silt and clay size particle often punctuated by micro-contrasted organic matter. Weakly developed speckled and reticulate b-fabrics are observed at a few places.

Pedofeatures

Thin (30-40 μm) ferruginous clay occurring as coating around voids and grains. Neoformed clay coatings of < 20 μm thickness are also seen commonly. Brown and black sesquioxide nodules with internal rings are often seen.

(iv) Thin section No. LC2/7, Horizon : B3; Depth 104-140 cm

Macroscopic Characteristics

Light brownish gray (2.5 Y 6/2) dry, clay loam, common medium distinct brownish yellow (10 YR 6/6) mottles, strong coarse subangular blocky, common very fine tubular pores, extremely firm, very plastic, common thin clay cutans.

Microstructure

Weakly developed subangular blocky structure. Voids are mainly vesicles with a few vughs. The estimated pore space is 10-15% of the total area of thin section. Voids are unoriented and have random basic orientation pattern.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 40/60

(a) Coarse fraction

More than 80% of the total coarse fraction is quartz. The most common size range is 50-100 μm. The larger grains are subangular and smaller ones subrounded. Opaques are about 5% and they are distributed throughout the section. Heavy minerals are also seen at places. Sorting is very poor.

(b) Fine Fraction/Groundmass

Mainly minerallic. It consists of clay with fine micaceous silt and iron oxide. Iron oxides show variable degree of impregnation giving rise to gray to yellowish brown colours. The speckled b-fabric is most common along with a few grano-striated which are seen occasionally. C/F related distribution is double spaced porphyric.

Pedofeatures

Very thin (< 20 μm) neoformed clay coatings along voids and grains. Rounded ferro-manganese nodules of 1-3 mm size, often assimilated with soil mineral mass, form about 10% of the total area of the thin section. Some irregular shaped sesquioxide nodules of varying impregnation are also seen.

(v) **Thin Section No.** LC 4/2; **Horizon** B1; **Depth** : 20-58 cm

Macroscopic Characteristics

Light yellowish brown (2.5 Y 6/4) dry, silt loam, moderate medium subangular blocky, common medium distinct strong brown (7.5 YR 5/6) mottles, common very fine tubular pores, very hard, very plastic, continuous thin clay cutans, few very fine roots.

Microstructure

Bridged to pellicular grain structure. Simple and complex packing voids of size range 50-100 μm. Voids are subrounded to irregular shaped often rough walled. The total void space is around 10% of the total area of the thin section.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 50/50

(a) Coarse Fraction

Coarse fraction consists of approximately 80% quartz of wide size range of 10-500 μm. The most commonly observed size range is 50-100 μm. The coarse fraction is randomly distributed and the sorting is moderate. Other major minerals include K-feldspar 5% and mica (muscovite) 5%. Heavy minerals and opaques occupy the rest of the area of thin section. All the minerals are fresh with little or no alteration.

(b) Fine Fraction/Groundmass

Yellowish brown colour fine silt and impure clay with micro-contrasted punctuations form the major component of fine fraction. The opaques are concentrated around pores and grain boundaries. Majority of the fines are isotropic. Undifferentiated b-fabric is very common. The fine fraction occurs as partial to complete coatings on grains and as bridges between grains of the soil aggregates. C/F related distribution is chitonic and single spaced porphyric.

Pedofeatures

Little or no illuvial clay pedofeatures. Subrounded typic ferro-manganese nodules of 2-3 mm size with sharp external boundaries, often assimilated with soil material.

(vi) Thin Section No. LC 4/3; **Horizon** : B21t; **Depth** : 58-82 cm

Macroscopic Characteristics

Olive (5 Y 5/3) dry, common medium distinct yellowish brown (10 YR 5/6) mottles, clay loam, strong coarse subangular blocky, very hard, very plastic, patchy thin silt/clay cutans, ferro-manganese concretions common.

Microstructure

Moderately to strongly developed subangular blocky structure. Ped faces are partially accommodating and incompletely separated. They have planar voids. Vesicles of 75-100 μm size are most common. Some vughs and planar voids at places. Occasionally channel voids in some parts.

Basic Mineral Components C/F limit ; 20 μm, C/F ratio : 40/60

(a) Coarse Fraction

Mostly single grain quartz of 75-100 μm size. Quartz forms about 80% of coarse fraction. Sorting is poor. Weathered plagioclase feldspars about 5%, muscovite 5%, biotite 2%, heavy minerals 2%. Opaques form < 1% of the total coarse fraction.

(b) Coarse Fraction/Groundmass

Mainly minerallic and partly organic in nature, mostly unsorted impure clay and fine silt. Usually anisotropic, with some part of the fraction isotropic due to fine discrete organic and ferruginous matter. Fine fraction occurring generally as groundmass and in the interstices of coarse grains. b-fabric is weak to moderate stipple-speckled and undifferentiated b-fabric. C/F related distribution is mainly porphyric.

Pedofeatures

Thick (60 μm) alluvial clay coatings around pores occur at a few places occupying < 1% of the total area of thin section. Also ferruginous clay coatings of 20-30 μm size occur as coatings around grains and voids. Deformed illuvial clay pedofeatures unrelated to voids are found embedded in the soil matrix at a few places.

Moderately to strongly impregnated ferro-manganese concretions constitute about 2% of the thin section.

(vii) **Thin Section No. LC 4/5; Horizon** : II Km; **Depth** : 113-150 cm

Macroscopic characteristics

Pale olive (5 Y 6/4) dry, loam, few fine faint mottles, strong subangular blocky structure, extremely hard, very plastic, continuous thin clay cutans, ferro-manganese concretions and lime concretions (1-2 mm) common.

Microstructure

Moderately to strongly developed subangular blocky structure. Ped faces are completely accommodating and separable. Inter-ped pores consist of planar voids with smooth walls. Intra-ped voids are mostly vughs and channels which are randomly distributed. Total estimated void space is 5-10%.

Basic Mineral Components C/F limit ; 20 μm; C/F ratio : 20/80

(a) Coarse Fraction

Single grain fine sand and silt. Quartz is about 80% of the coarse fraction, 20-50 μm in size, showing porphyric related distribution. Micas are about 10%, both biotite and muscovite showing intense weathering features. Heavy minerals and opaques constitute about 5%.

(b) Fine Fraction/Groundmass

Mainly minerallic and partly organic in nature. Yellowish brown colour clay with micro-contrasted particles. Micaceous silt and iron-oxide are also common. Strongly developed stipple-speckled and poro-striated b-fabrics. At places parallel striated and locally reticulate striated b-fabric is also observed. C/F related distribution is mostly single and double spaced porphyric.

Pedofeatures

Thin (20-60 μm) microlaminated impure clay coatings around grains and voids are seen which form more than 1% area of the thin section. Moderately to strongly developed crystallitic b-fabric due to impregnated microsparitic and micritic calcite in the groundmass. Calcite depletion features are also seen around voids. Alternate light and dark bands of calcite due to periodic staining by iron-oxide is observed. Mineral excrement features are also observed at a few places.

5 AJAY-SILAI PLAIN

(i) Thin Section No. LB1/5; Horizon : B23g; Depth : 87-127 cm

Macroscopic Characteristics

Gray (2.5 Y 6/0) moist, clay, few fine faint mottles, moderate coarse subangular blocky, very firm, very plastic, continuous thick clay coatings, ferro-manganese concretions (< 2 mm size) common.

Microstructure

Soil thin section shows moderately developed subangular blocky structure. Voids are vesicles with some channels and inter-ped planar voids. Peds are partially accommodating and weakly separable. Total estimated pore space is about 5-10%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 40/60

(a) Coarse Fraction

Mainly single grain fine sand size mineral grains. Subrounded quartz grains of 50-100 μm size form 70-80% of the coarse fraction. Partially altered K-feldspars and micas are present in minor quantities. Sorting is poor.

(b) Fine Fraction/Groundmass

Yellowish brown colour fine silt and clay occurring as coatings around voids and grains. Clay particles often show dotted appearance due to micro-contrasted organic particles. Mosaic-speckled b-fabrics are very common. Grano-striated and poro-striated b-fabrics is also observed occasionally. C/F related distribution is porphyric.

Pedofeatures

Textural pedofeatures include typic illuvial clay coatings about 30-40 μm size around voids. 5-10% area of the thin section is covered by ferro-manganese aggregate concretions of 50-100 μm size. They have clear external boundaries.

(ii) Thin Section No. LB2/4; Horizon B22t; Depth : 88-126 cm

Macroscopic Characteristics

Gray (5 Y 6/1) moist, clay, common medium distinct olive brown (2.5 Y 5/4) mottles, moderate medium subangular blocky, firm, very plastic, patchy moderately thick clay coatings, many ferro-manganese concretions (< 2 mm size).

Microstructure

Moderately developed subangular blocky structures. Planar voids, vesicles and channels are randomly distributed and unoriented. Total estimated porosity about 10%.

Basic Mineral Components C/F limit : 20 μm, C/F ratio 35/65

(a) Coarse Fraction

Generally poorly sorted. It consists mainly of quartz up to 70%, size 50-100 μm, they are subangular to subrounded in shape. They show open porphyric distribution. Other minerals include partially altered K-feldspars up to 5% and micas up to 10%. Heavy minerals and lithorelicts constitute the rest of the coarse fraction.

(b) Fine Fraction/Groundmass

Yellow to yellowish brown colour due to ferruginous matter. The finer fraction occurs as groundmass and coatings around voids and grains. Stipple-speckled b-fabric is common along with occasional appearance of poro-striated b-fabric. C/F related distribution is gefuric and porphyric.

Pedofeatures

Illuvial clay pedofeatures are present as 40-60 μm thick coatings around voids and grains. Fine silty accumulation is observed along planar voids. Strongly developed oriented domains of clay forming stress coatings are observed throughout the thin section. Typic, orthic ferro-manganese nodules with varying degrees of impregnation are widespread.

(iii) Thin Section No. LB11/2; Horizon A1; Depth 20-38 cm

Macroscopic Characteristics

Olive gray (5 Y 5/2) moist, silty clay loam, few medium distinct dark brown (7.5 YR 4/4) mottles, moderate medium subangular blocky structure, silt grains of gray colour along ped faces.

Microstructure

Soil thin section shows weakly to moderately developed subangular blocky structure. Inter-grain vesicles, channels and planar voids are common.

Basic Mineral Components C/F limit : 20 μm; C/F ratio 30/70

(a) Coarse Fraction

About 80% of coarse fraction is silt size (< 50 μm) quartz grains with K-feldspars and micas in minor quantities.

(b) Fine Fraction/Groundmass

Mainly mineralic in nature consisting of fine silt and clay. b-fabric development is weak. Stipple-speckled b-fabric is observed some times. C/F related distribution is porphyric and gefuric.

Pedofeatures

Illuvial clay pedofeatures are absent. Ferro-manganese concretions of irregular shape are observed in some parts of the section.

(iv) Thin Section No. LB11/5 : Horizon B22t; Depth : 83-117 cm

Macroscopic Characteristics

Light brownish gray (2.5 Y 6/2) moist, clay, moderate medium subangular blocky, extremely firm, many fine to coarse hard and semi-hard ferro-manganese concretions.

Microstructure

Moderate to strong subangular blocky structure. Voids are mainly vughs and channels. Total pore space is about 10%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio 40/60

(a) Coarse Fraction

Mainly single grain quartz (50-100 μm) up to 80%. Other mineral grains of the size of quartz include plagioclase feldspar grains which constitute 5% of the coarse fraction. Other minerals are mica up to 5%, heavy minerals and opaques. The coarse grains are unoriented and show basic random distribution.

(b) Fine Fraction/Groundmass

Colourless to yellowish, mainly of micaceous fine silt and clays. The b-fabric is well developed. Stipple-speckled and poro-striated b-fabrics are observed commonly. Impure clay occurs as coatings around voids and as ground mass. C/F related distribution is porphyric.

Pedofeatures

Clay illuvial pedofeatures are observed commonly. 40-50 μm thick ferruginous clay coatings are observed around pores. Typic, strongly impregnated sesquioxide nodules of 1-2 mm size are common.

(v) Thin Section No. LD1/3; Horizon : B1; Depth : 29-52 cm

Macroscopic Characteristics

Light brownish gray (2.5 Y 6/2) dry, loam, many medium distinct brown (7.5 YR 4/4) mottles, moderate medium subangular blocky, clay coatings along ped faces, a few medium (2 mm) size ferro-manganese concretions.

Microstructure

Weakly to moderately developed subangular blocky structure with partially accommodating faces. Mainly vesicles and channels, chambers at places. Total estimated void space is about 5%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 30/70

(a) Coarse Fraction

80% quartz with most dominant size range 40-80 μm. K- feldspar showing cross-linear weathering pattern form about 5% of the coarse fraction. Heavy minerals, rock fragments and opaques form rest of the coarse fraction.

(b) Fine Fraction/Groundmass

Yellowish brown colour fine silt and clay size particles occur as coatings around voids and grains. Clay particles are speckled and dotted in appearance due to presence of the punctuation of micro-contrasted organic pigments. Stipple-speckled and crystallitic b-fabric more common.

Pedofeatures

20-50 μm thick fine silt and impure clay coatings often stained by iron oxide. Nucleic sesquioxide nodules with quartz nucleus are moderately impregnated.

(vi) **Thin Section No.** LD1/4; **Horizon** B21t; **Depth** : 52-99 cm

Macroscopic Characteristics

Light brownish gray (2.5 Y 6/2) moist, loam, moderate medium subangular blocky, firm, slightly plastic,clay coatings along ped faces, common medium (2-4 mm) size ferro-manganese concretions.

Microstructure

Moderately to strongly developed subangular blocky peds. Inter-grain vesicles, channels and chambers common. Total estimated void space 15-20%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio 50/50

(a) Coarse Fraction

Single grain subangular to subrounded quartz of 150-200 μm size constitute more than 80% of total coarse fraction. Orthoclase feldspars with similar size range constitute about 5% and mica (mostly muscovite) about 2%. A few grains of heavy minerals together with rock fragments of granite and sandstone constitute rest of the coarse fraction.

(b) Fine Fraction/Groundmass

Yellowish colour fine silt and clay size particles with microcontrasted material are commonly seen giving rise to speckled aspect to the fine material. Some residue of roots partially replaced by mineral matter (organo-mineral matter). Fine opaques occur in inter-grain spaces as specks of microcontrasted matter. Stipple-speckled b-fabric is more common. Occasionally mosaic- speckled, porostriated and grano-striated. C/F related distribution is gefuric and porphyric.

Pedofeatures

Mostly clay coatings about 20 μm thick with no preferential coatings of walls. At places (< 1% of the total thin section area) 50 μm thick microlaminated coatings around voids. Ferruginous hypocoatings superimposed on clay coatings are often observed. Moderately impregnated rounded ferro-manganese concretions constitute < 1% of the thin section area.

(vii) **Thin Section No.** LD 2/1; **Horizon** : B1; **Depth** : 20-35 cm

Macroscopic Characteristics

Yellowish brown (10 YR 5/4) moist, silt loam, weak medium subangular blocky, patchy thin clay coatings, many fine roots.

Microstructure

Weak pedal compact grain structure. Simple packing voids and channels are common. Total estimated void space more than 20%.

Basic Mineral components C/F limit : 20 μm, C/F ratio : 70/30

(a) Coarse Fraction

Mostly quartz grains of 50-100 μm size constituting more than 80% of coarse fraction. Coarse fraction is moderately sorted. Feldspars form 5%. Heavy minerals, opaques and rock fragments constitute the rest of coarse fraction.

(b) Fine Fraction/Groundmass

Fine silt and clay size particles with microcontrasted organic matter. Fine fraction occurs mostly as groundmass and occasionally as thin coatings. Remains of root and bark in upper part.

Pedofeatures

Impure clay coatings about 20-30 μm in the lower part of thin section often masked by iron-oxide. About 50 μm thick microlaminated clay coatings along a crack is observed in the middle part. Also, matrix infillings of clay is commonly observed. Ferruginous hypocoatings are observed occasionally.

(viii) Thin Section No. LD 2/4 : Horizon B22; Depth : 55-87 cm

Macroscopic characteristics

Yellowish brown (10 YR 5/4) moist, silt loam, continuous thin clay coatings, ferro-manganese concretions are common, moderate medium subangular blocky.

Microstructure

Moderately to strongly developed subangular peds in top portion of the thin section with accommodating boundaries. Voids are randomly distributed vesicles and planar voids. Total void space is less than 10%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 40/60

(a) Coarse fraction

More than 70% of coarse fraction is subrounded single grain quartz ranging in size from 75 to 100 μm. Weathered biotite showing exfoliation is about 10%. A few grains of muscovite are also seen at places. Plagioclase feldspar 5%, weathered hornblende 5%. Heavy minerals and rock fragments make up the rest of the coarse fraction.

(b) Fine Fraction/Groundmass

Fine silt and clay size particles often masked by iron oxide. They occur as groundmass and also around voids. Stipple-speckled b-fabrics are common. At places parallel striated b-fabric. C/F related distribution is enaulic to close porphyric.

Pedofeatures

Illuvial clay pedofeatures are seen around voids. Matrix filling with clay and fine silt is also widespread. Reworked soil material stained by iron-oxide is seen at places. A thick micropan (0.5 mm) is seen in the soil matrix.

6 DAMODAR TERMINAL FAN

(i) **Thin Section No.** LB4/4; **Horizon** : B21g; **Depth** : 47-72 cm

Macroscopic Characteristics

Grayish brown (2.5 Y 5/6) moist, silty clay loam, many medium prominent yellowish red (5 YR 5/6) mottles, continuous moderately thick clay coatings, ferro-manganese concretions (2-5 mm) are common, weak medium subangular blocky structure.

Microstructure

Weakly developed subangular blocky structure with unaccommodating ped faces. Voids are mostly vughs and vesicles which are not interconnected and are randomly distributed.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 40/60

(a) Coarse fraction

70-80% of the coarse fraction is quartz ranging in size from 200-300 μm. Plagioclase feldspar with strained twin lamellae are about 5%. A few grains of microcline are also seen. Weakly altered mica showing exfoliation weathering pattern are observed at places. Rock fragments and opaques form rest of the fraction.

(b) **Fine Fraction/Groundmass**

Mostly mineralic with some organic matter. They are colourless to yellow and occur as coatings and groundmass. Weak to moderate reticulate and cross-striated b-fabrics are common. C/F related distribution is porphyric.

Pedofeatures

Very thin (20-30 μm) illuvial clay features together with thick (up to 50 μm) weakly oriented flood coatings. Biorelicts are seen in the upper part of the thin section. Small sesquioxide accumulation features with clear and diffuse external boundaries.

(ii) **Thin Section No.** LB4/5; **Horizon** : B22g; **Depth** : 72-98 cm

Macroscopic Characteristics

Grayish brown (2.5 Y 5/2) moist, loam, moderate subangular blocky structure, slightly hard, firm, plastic, ferro-manganese concretions less common.

Microstructure

Weakly to moderately developed subangular blocky structure with partially accommodating ped faces. Voids are vughs and vesicles. They are unoriented and have a basic random distribution pattern. Total estimated void space is about 15%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 50/50

(a) **Coarse Fraction**

Subrounded to subangular quartz of 100-150 μm size range constitutes 70% of the coarse fraction. Biotite grains of similar size range constitute 5-10% and show exfoliation. K-feldspar and plagioclase feldspar showing different alteration patterns 2-3%. Other minerals constitute hornblende, heavy minerals and rock fragments. The coarse fraction shows moderate sorting.

(b) **Fine Fraction/Groundmass**

Mostly mineral matter. Colourless to yellowish brown clay occurs as groundmass and coatings around voids and grains. Moderately developed cross-striated b-fabric and speckled b-fabric are common. Iron oxide staining is also very commonly observed.

Pedofeatures

Thin (20-30 μm) illuvial clay coatings and weakly oriented limpid clay coating (100 μm thick) forming flood coatings. Speckled to impure clay in groundmass. Small (< 1 mm) irregular ferro-manganese nodules with clear external boundaries common. Deformed and distorted papules in groundmass are observed occasionally.

(iii) Thin Section No. LD 3/2; **Horizon** : B1; **Depth** : 40-61 cm

Macroscopic Characteristics

Light brownish gray (2.5 Y 6/2) dry, silt loam, common faint mottles, weak medium subangular blocky, patchy thin clay coatings.

Microstructure

Weakly to moderately developed subangular blocky structure. Inter-grain channels and vesicles very common. A few large vughs.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 30/70

(a) Coarse Fraction

80% of the coarse fraction is quartz ranging in size from 50-100 μm. Plagioclase feldspar of similar size range up to 10%. Mica, mostly weathered biotite 3-5%. Other minerals include hornblende, heavy minerals and opaques.

(b) Fine Fraction/Groundmass

Mostly mineralic. Fine silt and clay size particles with micro-contrasted particles and often stained by iron-oxide. Small diffuse to moderately impregnated ferro-manganese concretions. Stipple-speckled and cross-striated b-fabric common. C/F related distribution is close porphyric.

Pedofeatures

Fine silt and clay occur as coatings and unrelated laminae in the groundmass. Pedorelicts and fragments of thick layered ferruginous clay coatings in the soil matrix. Small accumulations of sesquioxides with clear or diffuse external boundaries common.

7 BARIND TRACT

(i) Thin Section No. LA 1/4; Horizon : B21; Depth : 52-72 cm

Macroscopic Characteristics

Olive (5 Y 5/4) moist; few fine faint mottles, silty loam, moderately developed medium subangular blocky, very firm, plastic, patchy thin silt coatings on ped faces, moderate lime effervescence.

Microstructure

Moderately developed subangular blocky peds with partially accommodating boundaries, channels and vughs common. Occasionally planar voids. Voids are unoriented and randomly distributed. Total estimated void space < 10%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio 40/60

(a) Coarse Fraction

Quartz (100 - 500 μm size) constitutes about 60-70% of the coarse fraction. Mica consists of muscovite 10-15% and biotite 5% showing exfoliation due to weathering. Heavy minerals and opaques constitute the rest.

(b) Fine Fraction/Groundmass

Mainly clay size particles which occur as thin coating along channels and voids. Weak to moderate mosaic speckled and cross striated b-fabric distributed throughout the thin section. Also, monostriated and unistrial b-fabric at places. C/F related distribution is porphyric.

Pedofeatures

Pedofeatures unrelated to voids are more common. Illuvial clay pedofeatures are not very common. Occasionally thin (30-40 μm) clay coatings around voids are observed. Calcrete pedofeatures occur as moderately impregnated orthic calcareous nodules of > 2 mm size, hypocoatings and as complete infillings of voids. Broken papules and sesquioxide nodules with diffuse boundaries are also observed commonly.

(ii) Thin Section No. LA 1/5; Horizon : B22; Depth : 72-103 cm

Macroscopic Characteristics

Olive gray (5 Y 5/2) moist, few fine faint mottles, silty clay loam, moderate lime effervescence, many ferro-manganese concretions of 3 mm size, moderately developed subangular blocky structure.

Microstructure

Moderately developed subangular blocky structure. Voids are mainly channels and planar voids which are randomly distributed and unoriented.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 40/60

(a) Coarse Fraction

Coarse Fraction is moderately sorted and consists of 70% quartz of size range 50-100 μm. Other minerals are moderately altered micas 5%, feldspars 5% and heavy minerals and rock fragments constitute the rest.

(b) Fine Fraction

Mainly mineralic matter with some organic matter occurring as microcontrasted particles. Clay and fine silt size particles occur in clusters in several clay-rich domains. Also, there are occasional occurrence of thin clay coatings around root channels and planar voids.

Pedofeatures

Occasionally 30-40 μm thick illuvial clay pedofeatures around channels and planar voids. Papules derived from old soils are seen embedded in the soil groundmass commonly. Calcrete pedofeatures occur in different forms such as moderately to strongly impregnated orthic micritic modules of >2 mm size, hypocoatings and as complete infillings of voids. Digitate and aggregate ferro-manganese concretions are very common in the lower pat of the thin section. Locally ferruginous hypocoatings cover clay coatings and papules. The rounded ferro-manganese concretions with abrupt external boundaries contain soil material which are coarser than the surrounding groundmass. Isotubles and loose infillings of voids with mineral matter is also observed occasionally.

8 LATERITIC UPLAND

(i) Thin Section No. LC 1/2; Horizon : II B; Depth : 45-65 cm

Macroscopic Characteristics

Yellowish red (5 YR 5/7) moist, sandy clay loam, few faint yellowish red (5 YR 5/6) mottles, many medium to coarse vesicular pores, slightly hard, firm, slightly plastic, weakly cemented, a few hard ferro-manganese concretions (< 2 mm), irregular quartz grains (2 - 5 mm size) embedded in the matrix.

Microstructure

Crumby structure. Packing voids and vesicles common. Total estimated void space is more than 15%

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 80/20

(a) Coarse Fraction

Coarse fraction is poorly sorted. It consists of 80% quartz with most dominant size range of 500-600 μm. A few grains of plagioclase are also observed in the groundmass. Other minerals include hornblende, heavy minerals and opaques.

(b) Fine Fraction/Groundmass

Mainly mineral matter. Yellowish brown colour ferruginous clay occurs mainly as coatings around grains and voids. The b-fabric is stipple-speckled and the C/F related distribution is gefuric.

Pedofeatures

At places 100 μm thick illuvial clay coatings often masked by iron oxide. Also, ferruginous hypocoatings at places. Detached free-grain coatings and papules common. A few rounded ferro-manganese nodules with sharp external boundaries are observed in the groundmass. They contain quartz grains which have iron-oxide in the cracks (runiquartz). Pedorelicts and infillings of voids with fine matter is also observed. Ferro-manganese nodules with diffuse boundaries indicate their formation due to current pedogenic processes.

(ii) Thin Section No. LC 1/3; Horizon : II B; Depth : 65-150 cm

Macroscopic Characteristics

Yellowish red (5YR 5/7) moist, prominent yellowish red (5 YR 5/6) mottles, strong subangular blocky, firm and hard, moderately cemented, a few rounded hard ferro-manganese concretions embedded in the matrix.

Microstructure

Coarse subangular blocky, vesicles and channels more common. Total estimated void space is more than 15%.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 60/40

(a) Coarse Fraction

Single and compound mineral grains and rock fragments up to 2 mm in size. Dominantly single and polycrystalline quartz. A few grains of bleached biotite and heavy minerals are also observed. A few coarse quartz grains have veins which have coatings of iron-oxide (runiquartz). The whole of coarse fraction is very poorly sorted.

(b) Fine Fraction/Groundmass

Mainly mineral matters, yellowish brown clay size material often masked by iron-oxide. A few particles with dotted and speckled appearance. Reddish brown iron oxide material form zones. C/F related distribution is close to single spaced porphyric. The b-fabric of the micromass is undifferentiated to weakly stipple-speckled.

Pedofeatures

A few voids have clay coatings up to 100 μm thick. Limpid clay coatings along voids are also observed occasionally. The amorphous pedofeatures include brown and black colour, mostly rounded concretions of ferro-manganese which contain quartz and feldspar. A few voids have infillings of soil aggregates. Small discontinuous parallel striated b-fabrics at places.

(iii) **Thin Section No.** LB 5/ 2 **Horizon** : II Box_1; **Depth** : 37-50 cm

Macroscopic characteristics

Light gray (7.5 YR 7/0) dry, sandy loam, common coarse prominent red (10 R 4/6) mottles, strong subangular blocky, many medium to coarse vesicular pores, slightly hard, firm, slightly plastic, few fine roots, many hard black ferro-manganese concretions of $<$ 2 mm size.

Microstructure

Strong subangular blocky, vesicle and channels common. Occasionally chambers. Total estimated void space 15%.

Basic Mineral Components C/F limit : 20 μm, C/F ratio : 50/50

(a) Coarse Fraction

Coarse fractions are poorly sorted and consist of 50-100 μm size quartz. Other minerals in minor quantities are feldspars, micas and heavy minerals.

(b) Fine Fraction/Groundmass

Mainly mineral matters. Yellow colour clay size particles which are masked by dark brown colour iron-oxide material. C/F related distribution is close to single spaced porphyric. The b-fabric is weak stipple-speckled.

Pedofeatures

Thin (< 30 μm) ferruginous clay coatings along with accumulations of silt around voids, shaped mineral excrements partly filling irregular voids are common. Runiquartz is observed enclosed in ferro-manganese concretions. Illuvial clay pedofeatures are absent.

(iv) Thin Section No. LB 5/3; Horizon : II Box_1; Depth : 50-105 cm

Macroscopic Characteristics

Light gray (7.5 YR 7/0) dry, common coarse prominent red (10 R 4/6) mottles, slightly hard and indurated, moderately cemented, many hard, black ferro-manganese concretions.

Microstructure

Massive, vesicles and channels common. Occasionally chambers, total estimated void space > 20%.

Basic Mineral Components

(a) Coarse Fraction

Subangular to subrounded quartz constitutes more than 90% of the coarse fraction. Feldspars, mostly K-feldspars showing weak alteration about 5%, biotite with exfoliation features in minor amount.

(b) Fine Fraction/Groundmass

Clay size particles around voids and grains. Iron-oxide material occurs throughout the groundmass. Undifferentiated b-fabric due to masking of iron-oxide. C/F related distribution is porphyric.

Pedofeatures

Illuvial clay pedofeatures around grains up to 150 μm thick. Broken and deformed ferruginous clay and papules in the matrix. At places typic clay coatings along planar voids. Rounded ferro-manganese concretions occupy more than 50% area of the thin section. They are up to 4 mm in diameter and have sharp external boundaries. Loose infillings of irregular voids with mineral aggregates are common.

(v) **Thin Section No.** LD 5/4; **Horizon :** II Box_1; **Depth :** 50-160 cm

Microstructure

Pisolitic structure widespread. Almost whole of the thin section is covered by ferro-manganese concretions and masked by reddish brown colour iron-oxide material. Chambers and vughs common.

Basic Mineral Components : C/F limit : 20 μm; C/F ratio : 30/70

(a) Coarse Fraction

A few quartz grains and K-feldspars are seen embedded in the ferro-manganese concretions.

(b) Fine Fraction/Groundmass

Clay and iron-oxide material are the dominant constituents of the fine fraction. They occur as coatings along void, grains and in the inter-concretion spaces. Undifferentiated b-fabric throughout the section due to masking of groundmass with iron-oxide. At places stipple-speckled b-fabric. C/F related distribution is porphyric.

Pedofeatures

Ferruginous clay features widespread. At places void infillings with yellow colour limpid clay up to 100 μm thick are observed. Microlaminated oriented ferruginous clay coatings 150- 300 μm thick observed around voids and grains. Free-grain coatings up tp 300 μm are widespread. Irregular ferro-manganese concretions with sharp external boundaries are present throughout the thin section. Clay hypocoatings around the channels are also observed at places.

(vi) **Thin Section No.** LC1/6; **Horizon :** III Box_3; **Depth :** 340-440 cm

Macroscopic Characteristics

Reddish yellow (7.5 YR 6/7) lithomarge, vermicular with subangular blocky structure, many medium to coarse vesicular pores, loose to slightly hard, firm, plastic, a few quartz grains (> 1 cm) embedded in the matrix, a few concretions, some white patches at places.

Microstructure

Coarse subangular blocky structure, total estimated void space more than 20% vughs and channels common.

Basic Mineral Components C/F limit : 20 μm; C/F ratio : 20/80

(a) Coarse Fraction

Mostly quartz (about 90%) of 20-40 μm size. A few larger grains up to > 1 cm size. Larger grains seem to be broken. Weathered and altered K-feldspars about 5%. Biotite showing alteration and exfoliation feature.

(b) Fine Fraction/Groundmass

Mainly mineralic. Clay and iron-oxide materials occurring around voids and grains and also as infillings. They are randomly distributed. Poro-striated and grano-striated b-fabric common.

Pedofeatures

Clay illuvial pedofeatures very extensive and dominant. They occur as infillings and microlaminated coatings of 200-300 μm thickness. Ferruginous coatings are also observed occasionally. At places oriented limpid clay coatings are also seen. Free-grain clay coatings are widespread. A few irregular ferro-manganese concretions are observed which are distributed throughout the thin section.