EARLY CRETACEOUS ALLUVIAL PALAEOSOLS (KIRKWOOD FORMATION, ALGOA BASIN, SOUTH AFRICA) AND THEIR PALAEOENVIRONMENTAL AND PALAEOCLIMATOLOGICAL SIGNIFICANCE

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ABSTRACT

The Kirkwood Formation in the Bushman's River area of the Algoa Basin is characterised by a number of fining-upward cycles. These have been interpreted as indicating deposition in a dynamic aggrading meandering river system with the channel deposits (conglomerates grading upwards into sandstones) fining upward into the overbank deposits (mudrocks). Channel, channel-margin and overbank deposits were recognised.

The three mudrock sequences logged comprise compound pedofacies sequences of multistorey, simple and cumulative palaeosols. Distinctive palaeopedological features, such as root traces and pedotubules, soil horizons and structures, mottles, and iron-rich and calcareous glaebules and calcareous hardpan lenses and layers were used to identify a number of palaeosols within the mudrock sequences. Each mudrock sequence comprises multistorey entisol, inceptisol, alfisol, ultisol, aridisol and vertisol profiles at different stags of pedogenic maturity. The entisols and inceptisols are relatively immature profiles formed close to the meandering river channel and are classified as channel-margin palaeosols. The ultisols, alfisols, aridisols and vertisols are more mature and formed at some distance from the channel. They are classified as proximal floodbasin or distal floodbasin palaeosols depending on their maturity, distance from the channel and grain-size.

Slickensides, desiccation cracks, and iron-rich concretions occur , indicating multiple cycles of wetting and drying. A low water-table beneath the floodplain is indicated by both the prominent maroon-brown colouration of the mudstones, caused by oxidation during deposition, and the general lack of evaporites in the sequence. Calcretes comprising calcic and petrocalcic horizons are very common in the lower mudrock sequence, rare in the middle mudrock sequence and relatively common in the upper mudrock sequence. The calcretes generally consist a nodular zone which may, in some cases, be capped by a thin hardpan layer. The calcic palaeosols commonly show stages of carbonate accumulation which indicate at least 10 000 years of formation. The lack of calcrete formation in some of the profiles may indicate frequent flooding and high sediment accretion rates or a decrease in the influx of Ca^{2+}-rich aeolian dust into the depositional basin. Clay alluviation is common in many of the profiles and soil structures are commonly well developed.

The palaeosols are interpreted as having formed on an aggrading floodplain in a warm to hot (25-30°C), semi-arid climate with a low but seasonal rainfall (100-500mm per annum).

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INTRODUCTION

1.1 Introduction

Sedimentology concerns the processes, environments and products of sedimentation, whereas palaeopedology concerns soil formation (pedogenesis) on the sediments between depositional events. Both approaches contribute to the understanding and interpretation of ancient terrestrial environments (Retallack, 1983a). Palaeosols are defined as old, fossil or relict soils and/or soil horizons which have been buried and which are no longer undergoing pedogenesis (Smith, 1990; Soil Classification Working Group, 1991). They commonly occur in sedimentary sequences but until recently, have been known by more common, non-genetic terms including: red beds, variegated beds, ganister or cornstone. When dealing with sediments, ancient conglomerates and sandstones closely mirror their modern counterparts, resembling hardened gravels and sands (Retallack, 1990). Fossil soils do not resemble the modern sediments and rocks which they were generally compared with in the past, thus the similarities to modern soils generally went unrecognised (Retallack, 1990).

Problems with the identification of palaeosols in sedimentary sequences include: the alteration of the soils after burial due to diagenetic effects; the confusion of boundaries between palaeosols due to stacking and overprinting/overlapping of successive palaeosols in the sedimentary sequences; and the application of inappropriate models to the interpretation of these rocks (Retallack, 1990). With respect to the latter, problems arise due to the varying interpretations of fundamental concepts in modern soils, which differ widely between the fields of engineering, agriculture, geology and soil science.

There is often confusion about the meaning of the term "soil". From a palaeopedological perspective, soils can be defined as the "material forming the surface of a planet or similar body and altered in place from its parent material by physical, chemical or biological processes" (Retallack, 1990, p. 9). Palaeosols can be recognised in outcrop of ancient sedimentary sequences by the presence of preserved pedogenic features such as irregular tubular structures (roots and/or burrows, colour banding and mottling, calcareous and iron-rich nodules and calcareous hardpan lenses and layers, soil structures such as peds and cutans, and destroyed primary sedimentary structures by pedoturbation (Blodgett, 1988; Retallack, 1983a).

Soils forming on aggrading floodplain sediments are more likely to be preserved than those forming on degrading pediplains. Deposition of flood basin sediments in an alluvial system is episodic and short-lived when compared with the time period between depositional events. Pedogenic alteration of the alluvial parent material occurs during periods of non-deposition. Subsequent flooding and associated sedimentation may result in the complete burial of the soil profile, halting pedogenesis. Cyclic repetition of deposition followed by pedogenesis on an aggrading alluvial floodplain results in multistorey sequences of stacked soil profiles (palaeosols in the ancient sedimentary sequences) (Kraus, 1987). Because of the good preservation potential of soils formed on alluvial floodplains, palaeosols preserved in ancient floodplain sequences have been extensively studied and described.

Palaeosols are windows to the past and can be used to indicate past controls on pedogensis, including the nature of the parent material, vegetation, topographic relief, climate, rates of sedimentation, time of formation and position on the floodplain relative to the position of the channel. Palaeohydrological features, including the position of the groundwater table and the permeability and porosity of the original soils, can often be determined from palaeosols.

1.2 Geological Setting

The Mesozoic sediments in the Southwestern and Southeastern Cape Provinces are virtually confined to a series of fault-controlled depositional basins in the Cape Fold Belt, and extend some 700km from near Port Elizabeth in the east to Worcester in the west (Hill, 1972; Dingle, 1978; McLachlan and McMillan, 1976; SACS, 1980). The largest Mesozoic outlier produced by onshore erosion is the Algoa Basin in the Eastern Cape, which extends northwards from Port Elizabeth to the foothills of the Suurberg-Klein Winterhoek range (Haughton, 1969; Dingle, 1978) and has a landward extend of 4000km^2 (Hill, 1972; Winter, 1973; McLachlan and McMillan 1976; Truswell, 1977; Tankard et al., 1982). Figure 1 shows the Algoa Basin in relation to other Mesozoic Basins in the Southern Cape.

Tankard et al. (1982) described the basin as comprising a series of half-graben which are further dislocated by normal block faulting. According to Dingle et al. (1983), the Algoa Basin is a composite structure composed of three curved half graben, two of which (the Coega and Sundays River Troughs) have offshore extensions. Figure 2 illustrates the dominant controlling structural features in the Algoa Basin. The Sundays River Trough, in the northern section of the basin, stretches from just offshore in the south eastern part of Algoa Bay to the northwest panhandle (Dingle et al., 1983). Controversy has raged as to the existence of a southward-throwing fault, the Zuurberg Fault, on its northern boundary. Hill (1972) found no evidence for the fault, whereas Lock et al. (1975) believed that the northern margin of the basin is bounded by a series of small southward-throwing fractures. Winter (1973), using evidence of regional dips away from the Addo Fault and seismic evidence from the Sundays River Trough, concluded that the Addo Fault is the major controlling structure in the northern basin and that the Zuurberg Fault represented an ancient fracture, reactivated when it became the hinge line of the Algoa Basin in Cretaceous times. The Zuurberg Fault forms a prominent feature on the northern margin of the basin and further work needs to be done to determine its importance as a controlling factor in the basin history.

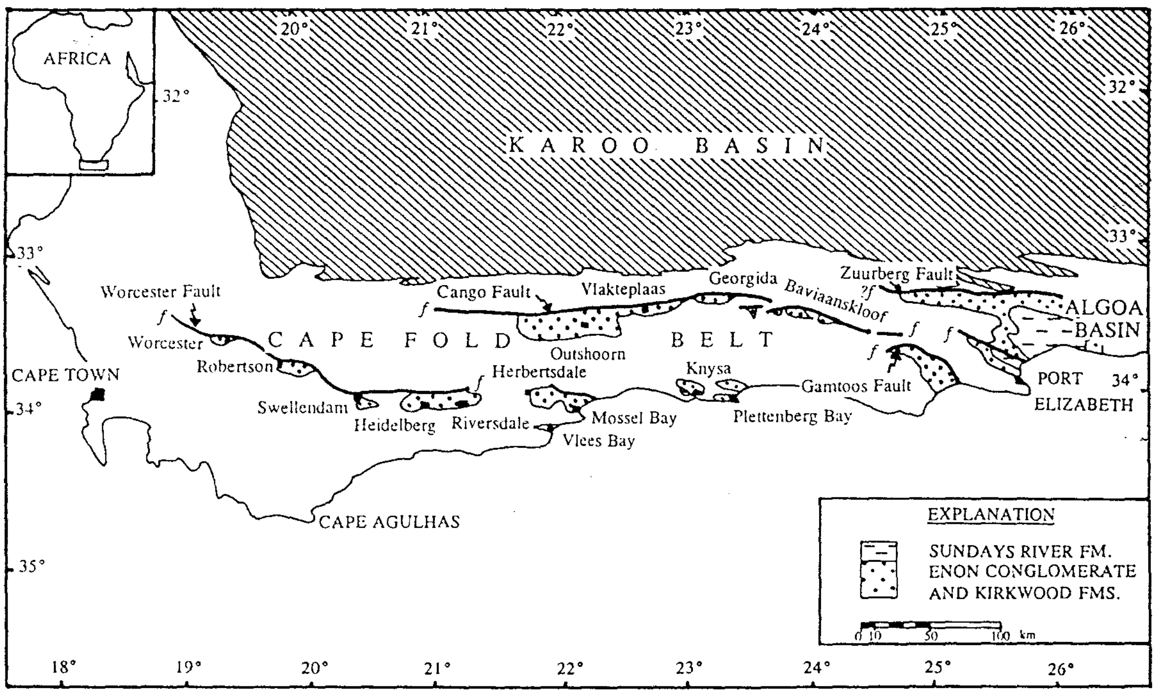


Figure 1. Plan showing the spatial relationship of the Algoa Basin to other Mesozoic basins in the South-Eastern and -Western Cape Provinces (modified from McLachlan and McMillan, 1976, p.197).

Most faults in the basin, partially controlled by the structure of the Cape Fold Belt (Winter, 1973), have an approximate east-west trend and were contemporaneous with sedimentation, as suggested by the variations in thickness of the basin sediments (Rich et al., 1983). The basin floor has a complex topography as a result of faulting and tilting (Dingle et al., 1983) and comprises mainly highly folded Palaeozoic rocks of the Cape Supergroup

(Winter, 1973). Along the northern margin of the basin the Permo-Carboniferous Dwyka Group, of the Karoo Supergroup, locally forms the floor (Winter, 1973). The volcanic rocks of the Suurberg Group crop out along the northern and north-western basin margins and unconformably overlie the basement (SACS, 1980).

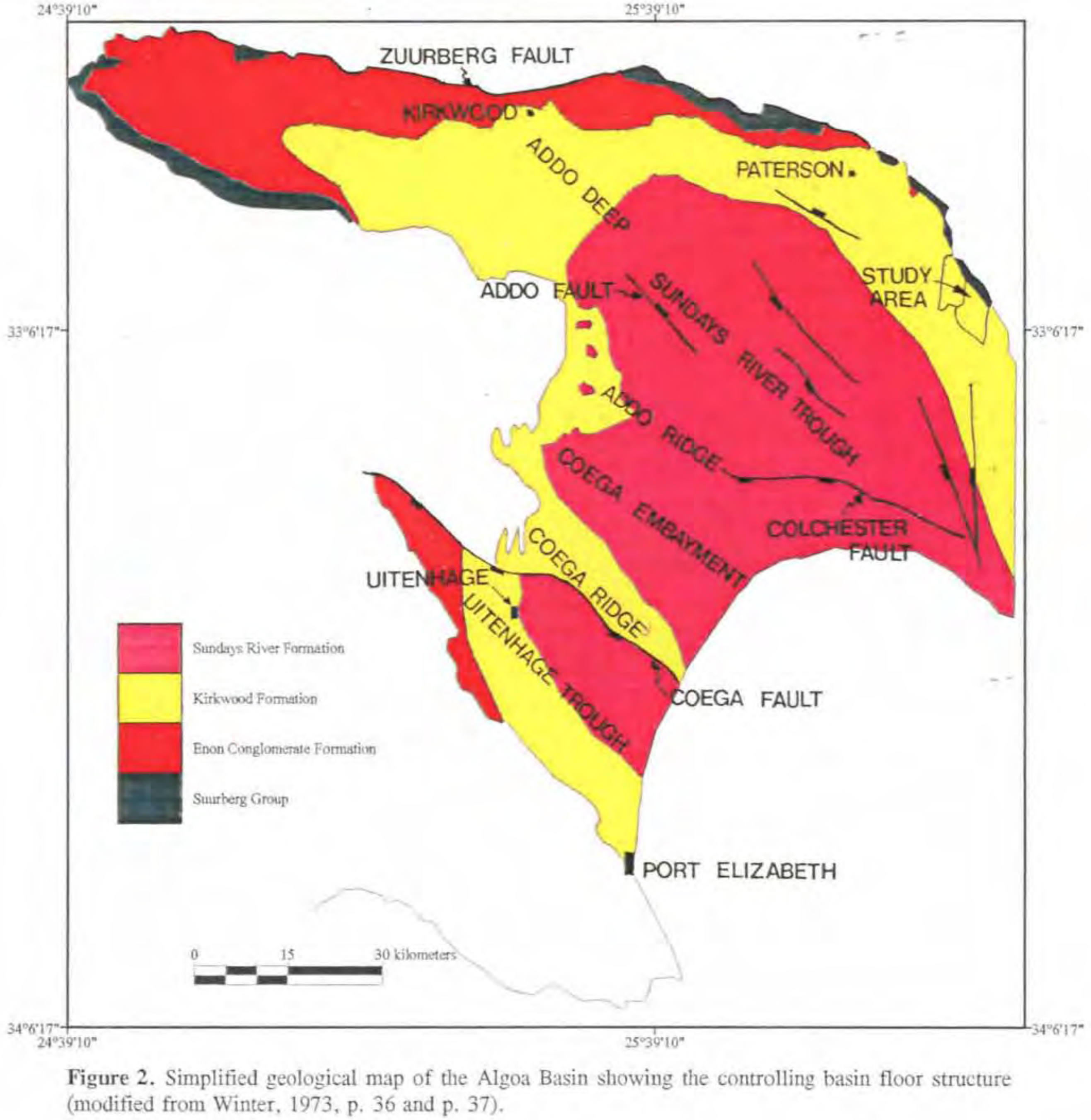


Figure 2. Simplified geological map of the Algoa Basin showing the controlling basin floor structure (modified from Winter, 1973, p. 36 and p. 37).

The Mesozoic sediments within the Algoa Basin are collectively referred to as the Uitenhage Group, which reaches its maximum onshore development in the Algoa Basin

(Figure 2) (McLachlan and McMillan, 1976). Outcrops are generally poor with large areas covered by dense thorn scrub and Tertiary to Recent sediments. However, good exposures can be found in the valleys of the Swartkops, Coega, Sundays and Bushmans Rivers (McLachlan and McMillan, 1976). SACS (1980) subdivided the Uitenhage Group into three formations; the basal Enon Conglomerate Formation, the Kirkwood Formation, and the topmost Sundays River Formation.

1.2.1 Suurberg Group

The Suurberg Group (Figure 2) discordantly overlies the Cape and Karoo Sequences and is in turn overlain by the Uitenhage Group. Outcrops of the Suurberg Group, found in close proximity to the Zuurberg Fault, are confined to the northern margin of the Algoa Basin and have not been reported from elsewhere in the south-eastern Cape Province (Hill, 1972; McLachlan and McMillan, 1979). Hill (1972) divided the Suurberg Group into three conformable formations. The lowermost Slagboom Formation comprises breccias (probably volcanic) and conglomerates (Hill, 1972; SACS, 1980). The middle Coerney Formation comprises tuffs and thin tuffaceous sandstones with minor small pebble conglomerates and agglomerates (Hill, 1972; SACS, 1980), and is overlain by the Mimosa Formation which is characterised by basalts with subordinate dolerite dykes and thin interbedded tuffs (Hill, 1972; SACS, 1980). The volcanics of the Suurberg Group were extruded locally along the Zuurberg Fault which acted as a conduit for the lavas (Winter, 1973). McLachlan and McMillan (1976) suggested that the group marks the early extensional faulting stages which resulted in the formation of the Algoa Basin.

1.2.2 The Enon Conglomerate Formation

The Enon Conglomerate (Figure 2) has a conformable contact with the underlying Suurberg volcanics in places (Hill, 1972), however, McLachlan and McMillan (1979) concluded that there was a considerable hiatus between the two. The Enon sediments crop out along the northern margin of the basin, and have been found near Uitenhage in the Elands River valley (Shone, 1976). In the type sections, in the vicinity of the Enon Mission Station east of Kirkwood, the conglomerates are approximately 300m thick, although basement topography may allow for even greater thicknesses (up to 700m?) in places in the Sundays River Trough (Dingle et al., 1983). The formation consists of various types of coarse, poorly-sorted conglomerates interbedded with subordinate lenticular red, yellow, and green sandstones and predominantly red-brown claystones (Winter, 1973). The Enon Conglomerate is thought to represent braided alluvial fan deposits, formed in a high energy fluviatile and terrestrial environment (SACS, 1980).

1.2.3 The Kirkwood Formation

The nature of the contact between the Enon and Kirkwood Formations is transitional and interfingering, both laterally and vertically (Winter, 1973, 1979; McLachlan and McMillan, 1976, 1979; Dingle et al., 1983). The Kirkwood Formation (Figure 2), previously known as the "Wood Beds and Variegated Marls" by Atherstone (1857), Haughton (1928) and Engelbrecht et al. (1962), crops out in the Glenconnor panhandle and over most of the northern part of the Algoa Basin, from Kirkwood to the Bushmans River area (Shone, 1976), and attains a maximum thickness of 2210m (Winter, 1973). It is subdivided into three members (SACS, 1980); the basal Swartkops Member comprises non-fossiliferous sandstones and is part fluvial and part estuarine in origin (Winter, 1973; SACS, 1980). This is succeeded by the Colchester Shale Member consisting of dark grey shales, siltstones and minor sandstones, with the presence of marine fossils indicating an estuarine brackish water environment (Winter, 1973; SACS, 1980). The remaining youngest part of the Kirkwood Formation has no separate name; it is characterised by fining upward cycles of subordinate conglomerate and grit lenses (Hill, 1972), overlain by yellow, yellow-brown, white and pale grey interbedded sandstones and pebbly sandstones (Shone, 1976; SACS, 1980; Dingle et al., 1983), and capped with bioturbated red-brown and green-grey mudstones and siltstones (Shone, 1976; SACS, 1980; Dingle et al., 1983). It is thought to represent sediments deposited in a continental fluvial environment (SACS, 1980). Numerous plant fossils and invertebrate and reptilian remains have been found in the Kirkwood Formation and are reviewed by McLachlan and McMillan (1976). The area studied during this project occurs in the Bushmans River valley where the upper part of the Kirkwood Formation is exposed.

1.2.4 The Sundays River Formation

The contact between the Kirkwood and Sundays River formations may be interfingered or unconformable (Winter, 1973, 1979; McLachlan and McMillan, 1976). The Sundays River Formation (Figure 2) is well exposed at a number of localities within the

Algoa Basin along the Sundays River, and attains a maximum thickness of approximately 2000m near the coast to the east of Colchester (Dingle et al., 1983). It comprises grey claystones, siltstones and sandy claystones with subordinate interbedded and nodular limestones and sandy limestones, and grey sandstones (SACS, 1980; Dingle et al., 1983). The formation is rich in marine fossils and has been subdivided into the Amsterdamhoek, Soetgenoeg, Addo, and Vetmaak Members (SACS, 1980). The Sundays River Formation sediments were deposited in a shallow-water marine to estuarine environment (McLachlan and McMillan, 1976).

1.2.5 The Age of the Uitenhage Group

The ages of the Mesozoic sediments in the Algoa Basin are difficult to determine accurately as the lithofacies are generally continental and non-marine with only rare interfingered marine units (Dingle, 1978), but it is generally accepted that they straddle the late Jurassic/early Cretaceous boundary (Dingle, 1978). McLachlin and McMillan (1976, 1979) report that a single basalt sample taken from the Mimosa Formation was tentatively dated at 162 $\pm$ 7My, which agrees with Hill's (1972) conclusion that the Cape folding predated the Suurberg volcanism. The Enon Formation can therefore be provisionally placed in the Upper Jurassic (SACS, 1980).

Based on palynological identifications, Winter (1973) dated the Kirkwood Formation as possibly late Jurassic to early Cretaceous, although comparison of ostracod remains with those from Malagasy indicated an early Late Jurassic age, most probably Callovian (Dingle and Klinger, 1972). McLachlan and McMillan (1976) used plant fossils to place the upper part of the Kirkwood Formation at Lower Valanginian, extending back into the Upper Jurassic. Further work on material from the Colchester Member of the Kirkwood Formation revealed a similarity to the Wealden Facies flora from the Northern Hemisphere, leading McLachlan and McMillan (1976) to conclude that the sediments were of latest Jurassic age. However, according to Tankard et al. (1982), the plant fossils in the Kirkwood Formation are Lower Cretaceous rather than Upper Jurassic. McLachlan and McMillan (1979) assessed palaeontological evidence from the Sundays River Formation and assigned a conservative age of Upper Valanginian to Hauterivian. Thus the age range for the Uitenhage Group may tentatively be regarded as Berriasian to Lower Valanginian for the Enon and Kirkwood

Formations, and Upper Valanginian to Hauterivian for the Sundays River Formation (Tankard et al., 1982).

1.3 Background and Aims of the Study

In 1845 Dr W.G. Atherstone and Mr A.G. Bain discovered fossil bones and part of a tooth-bearing jaw, of what they called "Cape Iguanodon", in the Bushmans River area (Atherstone, 1857). They named the discovery site Iguanodon Hoek although the name was never formally adopted. In 1853, Bain sent the fossil bones to the Geological Society of London to Sir Richard Owen who identified the specimen as *Anthodon serrarius* (Owen, 1876). Broom (1910) recognised that the teeth of the lower jaw resembled those of a stegosaur and renamed the specimen *Palaeoscincus africanus*. Schwarz (1913) revisited the site and found more bones, including two heavy limb bones (a femoral head and the head of a tibia). He retained the name *Anthodon serrarius*. Most recently, Galton and Coombs (1981) studied the jaw in detail, confirming its identity as that of a stegosaurian dinosaur, and naming the specimen *Paranthodon africanus (Broom)*. In 1991, staff of the Albany Museum (Grahamstown), the Port Elizabeth Museum, and Rhodes University Department of Geology initiated a project to try and find the original locality, Iguanodon Hoek, in an attempt to recover more bone material. Some bone material was indeed found in the mudrock facies of the fluviatile Kirkwood Formation in the Bushmans River area at a site that is thought to be close to that discovered by Atherstone and Bain. As part of the project, it was decided to collect sedimentological data in an attempt to reconstruct the palaeoenvironment and palaeoclimate existing at the time the dinosaur was alive.

The mudrock sequences in the study area bear a close similarity to banded "redbed" sediments exposed in the Badlands of South Dakota, USA in which numerous palaeosols have been identified (Retallack, 1983b). This prompted further investigation, as palaeosols are useful in the determination of palaeoenvironments and palaeoclimates.

On the basis of numerous palaeopedological features observed in the three mudrock sections studied, the palaeosol horizons and profiles identified from these, and the interrelationships between the mudrock, sandstone and conglomerate facies, it is possible, using modern analogues, to provide an interpretation of the palaeoenvironment and palaeoclimate at the time of deposition of the sediments. Various factors contributed to the formation of and types of palaeosols that developed on the overbank deposits of an alluvial system. Consideration of these factors enables interpretation of the palaeoenvironment. The different types of palaeosols identified form under different climatic conditions and thus the changes in the palaeoclimate with time can be observed.

Thus the aims of the present study are to describe the physical properties of the conglomerate facies, sandstone facies and the palaeosols in the mudrock facies, and to use the characteristics of the palaeosols identified, together with the interrelationships between the three facies, to reconstruct the palaeoenvironment and palaeoclimate, and to identify any changes in rates of deposition and palaeoclimate with time. The study provides an interpretation of the palaeoenvironment and palaeoclimate in the study area only.

1.4 Study Area

The study area is located within the Bushmans River valley, approximately 60 kilometres south-west of Grahamstown, just off the main road (N2) to Port Elizabeth. It is situated close to the boundary between the Woodbury and Bushmans River Farms, on the southern side of the Bushmans River. The terrain is rugged, with the hills, cliffs, gullies, and river valleys covered in thick thorn scrub. Outcrop is generally poor and discontinuous, with the best exposures occurring in the dry Bushmans River bed, in a few cliffs, and in numerous erosional gullies. Lithologies of the upper Kirkwood Formation are found in the study area, which is situated close to the northern margin of the Algoa Basin. The strata dip at approximately 10° towards the southwest and are truncated unconformably towards the top of the valley walls by horizontal beds of the mid-Miocene to late Pliocene Alexandria Formation. Recent calcrete, alluvium, scree and gulley wash cover large parts of the valley floor, the steep hill slopes and the hill tops. Figure 3 shows the locality of the study area and its position within the Algoa Basin.

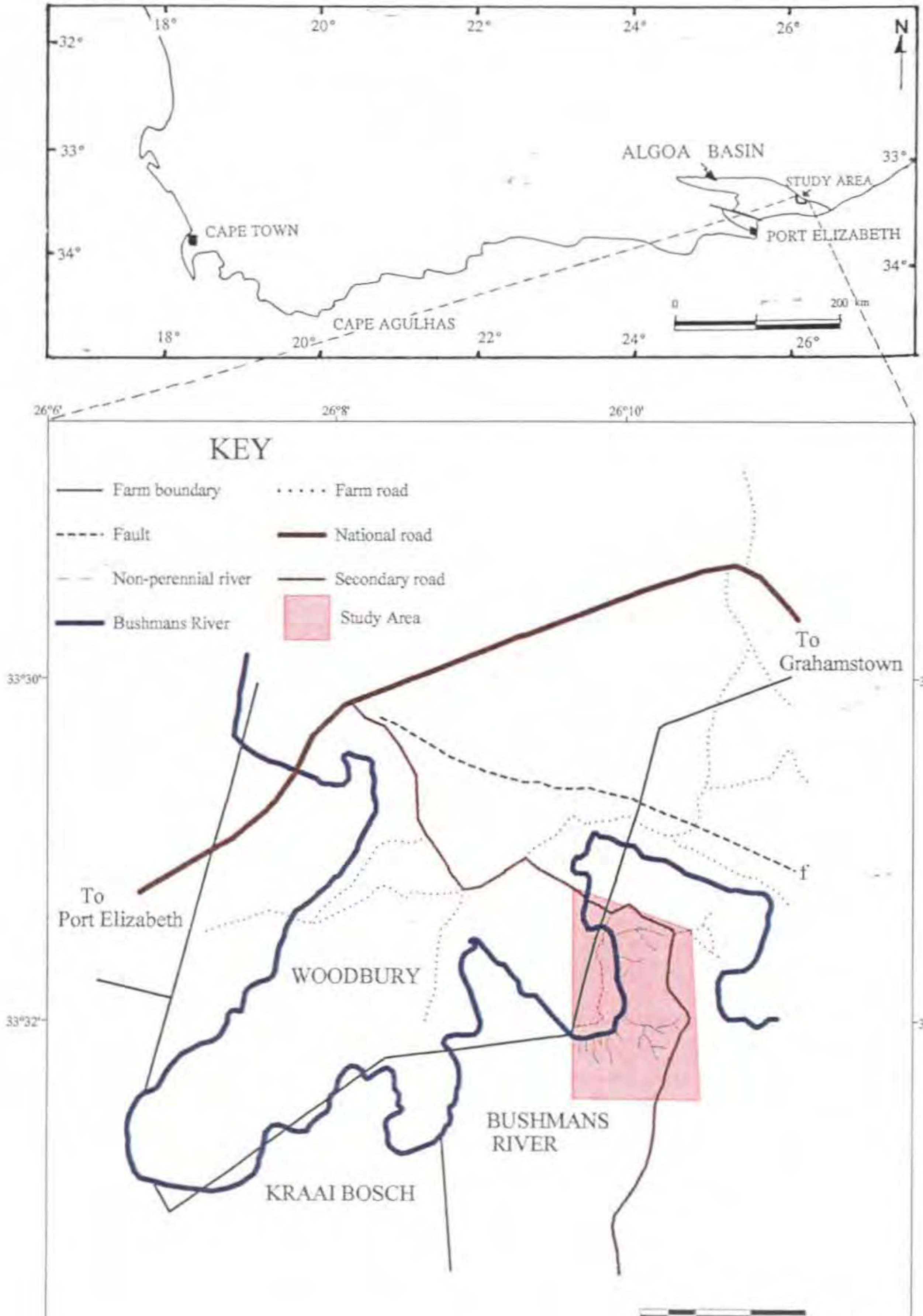


Figure 3. The locality of the study area and its position within the Algoa Basin.

CHAPTER 2
METHODS OF STUDY

2.1 Field Study and Collection of Data

Approximately nine months were spent in the field, during which time 470m of the upper Kirkwood Formation sediments exposed in the study area were logged. A number of fining-upward sequences, comprising a subordinate conglomeratic facies, a sandstone facies and a mudrock facies, were identified. Three mudrock sequences, of 57.51 m, 39.44 m and 59.11 m respectively, were logged on a cm scale and numerous diagnostic palaeopedological features were observed.

Palaeosols are difficult to recognise in outcrop and thus a standard form of horizon description, similar to that of Retallack (1983b; 1988, p. 18) was adopted to ensure thorough observations and the recording of all important palaeopedological data. Table 1 outlines the format followed for the descriptions of the palaeosol horizons. Grain size was estimated using a grain size comparison chart.

Because of the highly weathered nature of the rock, trenches were cut into the cliff and gully faces to expose fresh rock. The colours of the fresh rock were recorded within minutes of exposure to maintain consistency, as the colours fade substantially within a few hours. The weathering colours were recorded and changes in weathering colour were often used to determine the positions of the horizon contacts. The carbonate content of the palaeosols was determined by observing and recording the degree of effervescence or reaction to dilute (10%) hydrochloric acid, using the scale described in Table 2. The significance of black organic root traces preserved on some of the joint planes is unknown but it is believed that they post-date the original pedogenesis. The presence and orientation of organic matter was noted. The contrast, abundance and size of the colour mottles, papules and glaebules, and root traces and crystal tubes observed were recorded using the classes defined in Table 3. Mottles are important as they may indicate hydromorphy. Although glaebules and papules are found in marine sedimentary rocks as well as soils and thus, found by themselves, are of little use, it is important to record their presence. The nature and arrangement of root traces and crystal tubes, after roots and rootlets, were recorded as they aid in the determination of the palaeoenvironment and palaeoclimate. The presence of drab haloes associated with root traces was noted. Relict sedimentary structures present in some of the palaeosols are useful in determining the maturity of the palaeosols and the rate of sedimentation. Table 4 was used in the classification of soil peds and the presence and nature of cutans bounding the peds was noted. The distribution, abundance and orientation of gypsum pseudomorphs, iron-rich nodules and concretions, and carbonate nodules, concretions and hardpan lenses, were recorded as they are important in the naming of the horizons and in the determination of the palaeosol types. Oxidised, reduced, and alkaline soils can be identified from the composition of the nodules, concretions and hardpan lenses. The sharpness and lateral continuity of the contact with underlying horizons was described using the classes in Table 5.

The horizon nomenclature used for the palaeosols is descriptive rather than genetic. Horizons are labelled with letters and are defined on the basis of the materials that constitute them. Table 6 shows the horizon nomenclature used, and includes both the old terminology and the new terminology proposed by the U.S. Department of Agriculture's Soil Survey Manual (Guthrie and Witty, 1982). A distinctive feature of the new scheme is its recognition of "accumulations of carbonate, clay, sesquioxides and humus as equally valid indicators of B horizons" (Retallack, 1988, p. 8).

The palaeosol horizons observed in the field were labelled using the shorthand system in Table 6. Graphical logs (APPENDIX 3) of the sections were constructed from the descriptions to provide a visual representation and to aid in the interpretation of the palaeosols. Descriptions of all the horizons logged are provided in APPENDIX 2. The horizon nomenclature helped in the later interpretation of the types of palaeosols present. They were classified according to US Soil Taxonomy, the classification put forward by the Soil Conservation Service of the United States Department of Agriculture, as presented by Retallack (1990).

2.2 Thin Sections

Oriented thin sections were made of samples from certain horizons in the different profiles to confirm features observed in hand specimens and to determine the general characteristics of the horizons. The samples are extremely friable and thus they had to be impregnated with resin before sectioning. The method of impregnation was as follows:

1) small oriented blocks of the sample were cut (dry cutting without using coolant).

2) The blocks were placed into small trays (formers) and covered with a mixture of

Micromount E Resin and Hardener.

3) The trays were placed in an evacuation chamber which was then sealed.

4) Air was pumped out of the chamber to create a vacuum. As the air was removed, bubbles formed on the upper surfaces of the blocks. This process was continued for between 3 and 5 minutes.

5) The pump was then switched off and air allowed back into the chamber, resulting in the dissolution of the bubbles.

6) Steps 4 and 5 were repeated until no bubbles formed on the block surfaces, indicating impregnation. This process took approximately 1 hour.

7) The blocks in the resin were then allowed to dry.

8) Thin sections were then made following standard procedures.

The thin sections were of value in the detection of microscopic features and fabrics, and in the determination of the compositions of the nodules and concretions.

2.3 Problems encountered

Outcrop is generally poor in the study area with suitable exposures occurring only in the dry Bushmans River bed, in a few cliffs and in numerous erosional gullies. Although an almost continuous vertical section could be logged through the Kirkwood Formation exposed in the study area, the lateral continuity of the exposures along strike is poor, with most outcrops less than 20m to 30m wide. Lateral variation in the nature of the sediments and the types of palaeosols is therefore difficult to determine. The contact zones between the sandstone facies and the overlying mudrock facies are preferentially weathered and the exact nature of these contacts could not be determined.

Exposures of the mudrock facies occur in steep-sided gullies, and are rarely more than 25m in lateral extent. The rock is highly weathered and most of the sections were exposed by digging beyond the weathered veneer, which is up to 0.7 m in places. The sediments are generally soft and poorly cemented making them susceptible to weathering, pedogenesis (modern) and erosion. Many of the softer, more clayey horizons could not be sampled for thin sectioning as they were too friable. Samples taken for thin section study were often very friable and soft and had to be impregnated with resin.

Younger sediments and developing soil profiles, including calcretes, cover the palaeosols, resulting in overprinting of the palaeosols closest to the present land surface

(Figure 4). This proved to be one of the greatest problems encountered in the study area. Extreme care was taken not to confuse features of the present soils and those resulting from diagenesis with those of the palaeosols. When the origin or approximate age of features observed could not be determined, they were excluded from the log descriptions and ignored as pedogenic indicators in the identification and classification of the palaeosols.

Figure 4. Overprinting of the palaeosols closest to the present land surface by modern pedogenesis and calcrete formation

The modern calcretes are relatively thin and poorly cemented, and follow the present land surface, generally occurring on the flat hill crests and truncating the older mudrocks, sandstones and conglomerates which dip by approximately 10° to the south west. The calcrete is generally powdery or soft and poorly cemented. The carbonate hardpan layers, lenses, and glaebules observed in the mudrocks (particularly the lower mudrock sequence) follow the strike of the palaeosol horizons and are interpreted as having formed at the same time as the palaeosols.

Roots from the vegetation covering the gully walls and adjacent hill tops and slopes, penetrate many of the palaeosol profiles, resulting in alteration of the sediments in direct contact with the roots. These modern roots are easily identified. In addition, black root traces, which often have powdery organic or fleshy (woody) root material preserved, occur preferentially along the joint planes but do not penetrate the mudrocks. Although the exact age of these roots could not be determined, they are interpreted as originating from root systems younger than those preserved in the palaeosols but slightly older than the modern root systems.

It is more difficult to differentiate between pedogenic and diagenetic features. Many of the palaeosols in the study area display reddened horizons. Horizonation is easily discernible and the reddening is therefore interpreted as being the result of pedogenesis (see section 4.4).

The classification of the palaeosols using modern classification schemes is difficult as they cannot easily be applied to older soils (palaeosols) which have undergone burial or diagenesis; and the excessive terminology does not aid understanding. However, in this thesis an attempt is made to apply, as best one can, the classification scheme of the USDA Soil Taxonomy (Soil Survey Staff, 1975), (See section 5.1).

Table 1. Format followed for the description of the palaeosol horizons (modified from Retallack, 1988, p. 18).

+0 m; ..... (description of sediments directly overlying palaeosol) ..... contact to

-0 m; ..... (description of topmost horizon of palaeosol, using format below) ..... contact to

-(depth to top of horizon) m; horizon designation (Table 6); rock type (e.g., silty claystone, siltstone); fresh colour, weathering colour; reaction with dilute (10%) hydrochloric acid (Table 2); presence of black organic flakes; presence of lithorelicts; colour mottling (Table 3); burrows (Table 3); glaebules and papules; crystal tubes; nature of root traces (Table 3); relict sedimentary features; soil structure or other features (Table 4); nodules, concretions and/or hardpan lenses; nature of contact (Table 5) to

-(depth to top of horizon) m, horizon designation .....

Note: In the field, it is best to write longhand paragraphs on each horizon and to include any interpretations made.

Table 2. Scale of acid reaction to approximate carbonate content of palaeosols (From Retallack, 1988, p. 14).

Carbonate Content	Reaction with Dilute Acid
Non-calcareous	Acid unreactive; often forms an inert bead
Very weakly calcareous	Little movement within the acid drop, which could be flotation of dust particles as much as bubbles
Calcareous	Numerous bubbles, but not coalescing to form a froth
Strongly calcareous	Bubbles forming a white froth, but drop of acid not doming upward
Very strongly calcareous	Drop vigorously frothing and doming upward

Note: this table was developed by Retallack from an original scale proposed by Birkeland (1984).

Table 3. Size, abundance, and contrast of mottles in palaeosols (From Retallack, 1988, p. 18).

Category	Class	Features
Contrast	Faint	Indistinct mottles or glaebules visible on close examination: both mottles and matrix have closely related colours
	Distinct	Mottles are readily seen, with the colour different from that of the surrounding matrix
	Prominent	Mottles are obvious and form one of the outstanding features of the horizon; their colour differs markedly from that of the matrix
Abundance	Few	Mottles occupy less than 2% of the exposed surface
	Common	Mottles occupy about 2 to 20% of the exposed surface
	Many	Mottles occupy more than 20% of the exposed surface. This class can be subdivided according to whether (a) the mottles are set in a definite matrix, or (b) the sample is almost equally two or more kinds of mottle
Size	Fine	Mottles less than 5 mm diameter in greatest visible dimension
	Medium	Mottles between 5 and 15 mm in greatest dimension
	Coarse	Mottles greater than 15 mm in greatest dimension

Note: These terms are little modified from those of Soil Survey Staff (1975). They may also be used for describing pedotubules and glaebules.

Table 4. Classification of soil peds (From Retallack, 1990, p. 40; simplified from Soil Survey Staff, 1975; Birkeland, 1984).

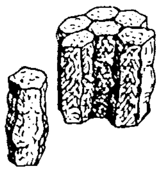
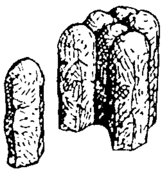
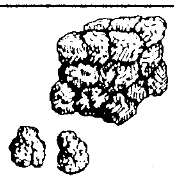
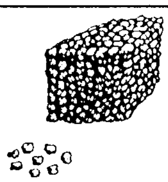
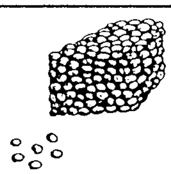
TYPE	SKETCH	DESCRIPTION	USUAL HORIZON	MAIN LIKELY CAUSES
PLATY		tabular and horizontal to land surface	E, Bs, K, C	initial disruption of relict bedding; accretion of cementing material
PRISMATIC		elongate with flat top and vertical to land surface	Bt	swelling and shrinking on wetting and drying
COLUMNAR		elongate with flat top and vertical to land surface	Bn	as with prismatic but with greater erosion by percolating water, and greater swelling of clay
ANGULAR BLOCKY		equant with sharp interlocking edges	Bt	cracking around roots and burrows; swelling and shrinking on wetting and drying
SUBANGULAR BLOCKY		equant with dull interlocking edges	Bt	as for angular blocky, but with more erosion and deposition of material in cracks
GRANULAR		spheroidal with slightly interlocking edges	A	active bioturbation and coating of soil with films of clay, sesquioxides and organic matter
CRUMB		rounded and spheroidal but not interlocking	A	as for granular; including fecal pellets and relict soil clasts

Table 5. Sharpness and lateral continuity of palaeosol horizon boundaries (From Retallack, 1988, p. 14)

Category	Class	Features
Sharpness	Abrupt	Transition from one horizon to another completed within 20 mm
	Clear	Transition completed within 20-50 mm
	Gradual	Transition spread over 50-150 mm
	Diffuse	One horizon grading into another over more than 150 mm
Lateral Continuity	Smooth	Horizon boundary forms an even plane
	Wavy	Horizon boundary undulates, with pockets wider than deep
	Irregular	Horizon boundary undulates, with pockets deeper than wide
	Broken	parts of the adjacent horizon are disconnected, e.g., by deep and laterally persistent clastic dykes in Vertisols

Note: This table is slightly modified from the one of Birkeland (1984).

Table 6. Descriptive shorthand for labelling palaeosol horizons (From Retallack, 1988, p. 13).

Category	New Term	Description	Old term
Master Horizons	O	Surface accumulation of organic materials (peat, lignite, coal), overlying clayey or sandy part of soil	O
	A	Usually has roots and a mixture of organic and mineral matter; forms the surface of those palaeosols lacking an O horizon	A
	E	Underlies an O or A horizon and appears bleached because it is lighter coloured, less organic, less sesquioxidic, or less clayey than underlying material	A2
	B	Underlies an A or E horizon and appears enriched in some material compared to both underlying and overlying horizons (because it is darker coloured, more organic, more sesquioxidic or more clayey) or more weathered than other horizons	B
	K	Subsurface horizon so impregnated with carbonate that it forms a massive layer	K
	C	Subsurface horizon, slightly more weathered than bedrock; lacks properties of other horizons, but shows mild mineral oxidation, limited accumulation of silica, carbonates, soluble salts or moderate gleying	C
	R	Consolidated and unweathered bedrock	R
Gradations Between Master Horizons	AB	Horizon with some characteristics of A and B, but with A characteristics dominant	A3
	BA	As above, but with B characteristics dominant	B1
	E/B	Horizon predominantly (more than 50%) of material like B horizon, but with tongues or other inclusions of material like an E horizon	A&B
Subordinate Descriptors	a	Highly decomposed organic matter	-
	b	Buried soil horizon (used only for pedorelict horizons with palaeosols; otherwise redundant)	b
	c	Concretions or nodules	cn
	e	Intermediately decomposed organic matter	-
	f	Frozen soil, with evidence of ice wedges, dykes, or layers	f
	g	Evidence of strong gleying, such as pyrite or siderite nodules	g
	h	Illuvial accumulation of organic matter	h
	i	Slightly decomposed organic matter	-
	k	Accumulation of carbonates less than for K horizon	ca
	m	Evidence of strong original induration or cementation, such as avoidance by roots in adjacent horizons	m
	n	Evidence of accumulated sodium, such as domed columnar peds and halite casts	sa
	o	Residual accumulation of sesquioxides	-
	p	Ploughing or other comparable human disturbance	p
	q	Accumulation of silica	si
	r	Weathered or soft bedrock	ox
	s	Illuvial accumulation of sesquioxides	ir
	t	Accumulation of clay	t
	v	Plinthite (in place, pedogenic laterite)	-
	w	Coloured or structural B horizon	-
	x	Fragipan (a layer originally cemented by silica or clay, and avoided by roots)	x
	y	Accumulation of gypsum crystals or crystal casts	cs
	z	Accumulation of other salts or salt crystal casts	sa

Note: This table has been adapted for use with palaeosols from one by Guthrie and Witty (1982), showing proposed terminology from the new edition of the USDA *Soil Survey Manual*, compared to that of the 1951 edition. Some of the subordinate descriptors are considered more important than others; these letters (a,e,i,h,r,s,t,v,w) should all be written first after the master horizon if in combination with other letters and should not be used in combination with each other.

CHAPTER 3
LITHOFACIES

3.1 Lithofacies found in the Study Area

A number of fining-upward cycles (Appendix 1) were identified in the exposures of upper Kirkwood Formation in the study area. These comprise a conglomeratic facies, a sandstone facies and a mudrock facies. The succession exposed is generally continuous, however, thick modern soils have developed on some of the finer-grained units, destroying and covering the original sediments. The gaps in the exposure are marked as scree-gaps on the log (Appendix 1).

3.1.1 Conglomerate Facies

The conglomerate facies generally forms the basal unit/s of a number of fining-upward cycles with the thickness and proportion of conglomerate within each cycle gradually decreasing upwards. The conglomerates are generally clast supported and poorly sorted. Some subordinate lenses of matrix-supported conglomerate occur, the matrix comprising a calcite-cemented grit. The clasts are mostly subangular to subrounded although some are more subangular. There is a decrease in clast size upward through the sequence with clasts in section A averaging -5.5ϕ - -6.5ϕ and in section F averaging -4.0ϕ - -5.0ϕ. Clast size and abundance appears to dependent on clast composition, with the largest and most common clasts being pink and white quartzite, white vein quartz, red sandstone, chert, and agate. Less common clasts comprise brown khaki shale, red, yellow and pink devitrified tuff, amygdaloidal and vesicular basalt and brown fine-grained sandstone. Small clasts of red and green jasper are rare, but small clasts of black shale are quite abundant and an exception to the rule.

The conglomerates generally appear massive although they may show crude bedding, trough cross-bedding, and crude fining-upward trends within the beds (Figure 5). The conglomerate layers are interbedded with thin trough cross-bedded lenses of grit and medium- to coarse-grained sandstone. Pebbles often mark the bases of some trough cross-beds and occasional one-pebble thick (pebbles average -2.0ϕ - -4.5ϕ), imbricated layers mark any laminations present (Figure 6). Some of the lenses contain randomly oriented pebbles and concentrations of wood chips and charcoal pebbles.

Fossils are rarely preserved in the conglomerates but logs of fossil wood, wood chips and fragments, and charcoal chips are found. The charcoal chips are generally concentrated in specific beds. Bored logs (Figure 7) and concentrations of wood chips (Figure 8) are present in the basal conglomerate of section E (Appendix 1). The femur of a large sauropod dinosaur (Figure 9) was found by Abson (1993) in a grit lens in the section E basal conglomerates. Mud-rafts, mud-chips, and occasional concretions are also present in the conglomeratic facies.

Figure 5. A typical conglomerate showing crude fining upward trends and crude bedding. Note the interbedded sandstone-grit lenses. (Basal conglomerate, section A, Appendix 1)

Figure 6. Lenticular sandstone with imbricated, thin, one-pebble thick layers (a) marking laminations (Basal conglomerates, section C, Appendix 1).

Figure 7. A fossilised log showing evidence of boring. From the conglomerate facies exposed in section E, Appendix 1.

Figure 8. Concentration of wood chips (w) within the basal conglomerate (section A, Appendix 1).

Figure 9. The femur of a large sauropod dinosaur found in a grit lense towards the base of the conglomerates in section E, Appendix 1.

3.1.2 Sandstone Facies

Sandstones occur interbedded with the conglomerate facies and with the mudrock facies but the majority of the sandstones overlie the conglomerate facies. Although fine-, medium-, and coarse-grained subfacies can be identified (Abson, 1993), there are no clear-cut boundaries between the different grain sizes as the subfacies generally grade into each other.

The coarse-grained subfacies comprises grits and medium- to coarse-grained sandstones, varying in colour from yellow orange-brown, to grey-yellow and grey, to olive. The coarse-grained subfacies is commonly found interbedded with the conglomerates, however, a 16.0 m thick coarse-grained sandstone occurs in Section E (Appendix 1). The coarse-grained sandstones commonly fine upwards into medium-grained sandstones, and show trough cross-bedding, planar bedding and laminations, and cross-laminations. One-pebble thick, imbricated pebble layers (including charcoal pebbles) mark some of the trough bases, the trough cross-beds and the planar laminations (Figure 10). The grit layers contain randomly-oriented pebbles and show parallel laminations, occasionally marked by thin imbricated pebble layers. Wood chip and charcoal pebble lenses (Figure 11) and fossilised wood logs (Figure 12) occur, with the coarse-grained sandstone in section D yielding abundant fossilised wood relative to the other wood-bearing horizons. Spherical and cylindrical nodules and concretions are often present in this subfacies (Figure 13 a and b), while differential weathering, due to the solution of calcite cement present in irregular patches, gives the sandstones a pitted appearance (Figure 14).

The medium-grained subfacies comprises fine- to medium-grained sandstones, varying from yellow-brown and grey-brown to olive green-brown in colour. The thickest medium-grained sandstones occur in sections E and F. Such sandstones are generally massive or cross-laminated, but rare trough cross-bedding has been observed. Combinations of the different sedimentary structures also occur. Single-pebble and thin grit layers are interbedded with the medium-grained sandstones marking the bases of some trough cross-beds. Wood-chip and charcoal pebble conglomerate lenses, charcoal pebbles, fossilised logs of wood, spherical and cylindrical concretions and nodules, randomly oriented pebbles, and mud-chip layers are all present (Appendix 1).

The fine-grained subfacies comprises fine-grained sandstones fining upward to siltstones usually occurring interbedded with the mudrock facies, but it is also found directly

Figure 10. One-pebble thick, imbricated pebble layers mark the bases of troughs, and some trough cross-beds or laminations and planar laminations (Basal sandstone, section E, Appendix 1).

Figure 11. Wood-chip and charcoal-pebble lens within the basal sandstones of section E, Appendix 1.

Figure 12. A large fragmented log of fossilised wood approximately 5.5 m long within the coarse-grained sandstone, section E, Appendix 1.

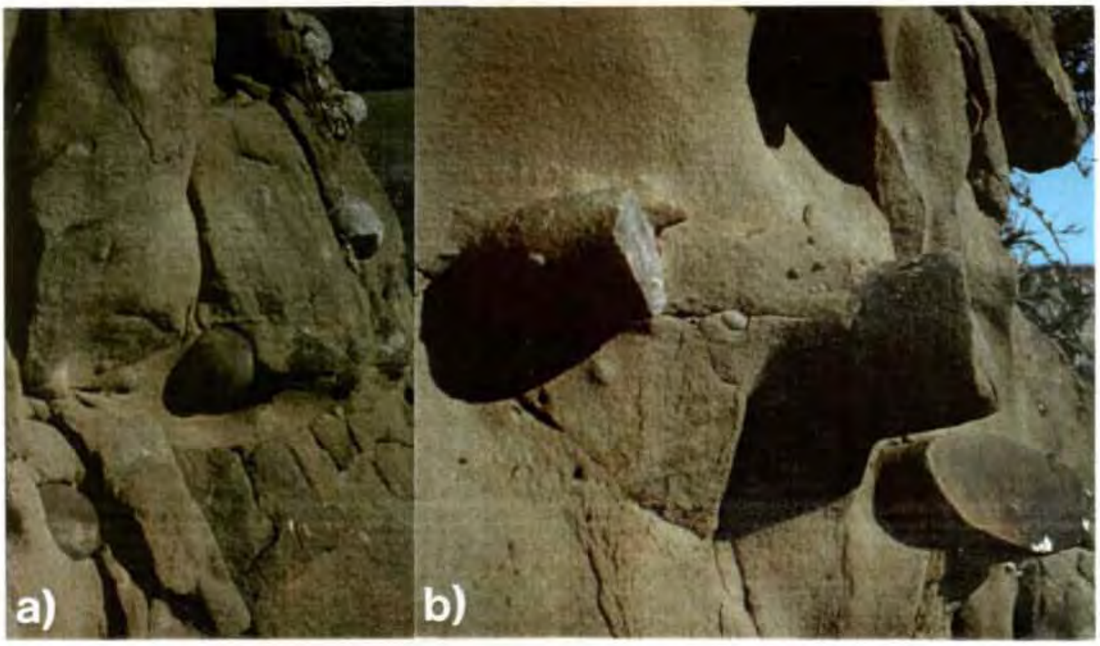


Figure 13 a) Spherical and **b)** cylindrical nodules within the sandstones of section D, Appendix 1

Figure 14. Pitted sandstones exposed in section D (Appendix 1) due to preferential weathering.

Figure 15. Well-cemented fine-grained sandstone lenses form positive weathering features in the river bed (Sandstone beds in section A, Appendix 1).

below the mudrock facies (e.g. Section D). The fine-grained sandstones vary in colour from olive-grey, olive-green and green-grey, to light orange and orange-yellow, to orange maroon-brown and maroon brown. They are generally massive but planar laminations have been observed. Well-cemented (calcite cement) lenses of fine-grained sandstone are more resistant to erosion and form positive weathering features (Figure 15). Fossilised wood, wood-chip and charcoal chip conglomerate lenses, and individual charcoal pebbles are found, as well as some spherical concretions and nodules, mud chips, mud-chip layers, and mud rafts.

3.1.3 Mudrock Facies

The mudrock facies comprises siltstones, claystones, and subordinate fine sandstones and varies in colour from shades of green, green-grey, and grey to shades of maroon-brown, maroon, brown, and red-brown. Occasional horizontal laminations and rare convolute laminations are the only sedimentary structures observed in these beds. Numerous stacked palaeosols have been identified within this facies and the features, descriptions and classifications of these are discussed later (see Chapters 4 and 5).

Figure 16. Well preserved relict laminations from the lower mudrock sequence, section B, Appendix 1.

3.2 Lithofacies interpretation

Most authors (Winter, 1973; Lock et al., 1975; McLachlan and McMillan, 1976; Shone, 1976; Truswell, 1977; Dingle, 1978; Tankard et al., 1982; Dingle et al., 1983) agree that the Kirkwood Formation sediments were deposited in a continental fluviatile (meandering river) environment. Kirkwood sedimentation commenced at the close of the Jurassic with the onset of subsidence along east-west trending faults, caused by regional tensional stresses (Shone, 1976). The bedding thickness distributions of the Kirkwood sediments, together with the absence of evidence for widespread unconformities or periods of non-deposition, are interpreted as indicating almost continuous sedimentation (Shone, 1976).

Bridge and Leeder (1979) identified two main facies groups in alluvial successions. The first facies group comprises sheet or ribbon-like bodies of generally porous and permeable sandstones and conglomerates with internal structures indicating deposition in river-channel bars. The second facies group comprises mudstones, siltstones and thin sandstones, generally showing low porosity and permeability. The internal structures of these sediments, together with peat accumulation and evidence of sheet flooding, indicate overbank deposition. Evidence for periodic exposure includes root traces, burrows, and soil formation. The geometry and relative proportions of the coarse and fine members in the fluvial system varies, depending on the "manner in which an aggrading river channel migrates laterally across its flood plain" (Bridge and Leeder, 1979, p. 618).

Similarly, Dingle et al. (1983) identified two facies in the Kirkwood Formation: an arenaceous pebbly facies (coarse member) representing point bar and channel fill deposits; and an argillaceous facies (fine member) representing flood plain muds. The two facies were deposited contemporaneously on valley floors "at the foot of Enon piedmont and alluvial fan deposits" (Dingle, 1978, p. 413).

A general log of the Kirkwood Formation exposures in the study area (Appendix 1), shows a number of fining-upward sequences. A typical sequence comprises a conglomeratic facies fining upwards into a sandstone facies, which in turn fines upwards into the mudrock facies. Crude upwards fining is observed within the conglomeratic facies and generally well-defined upwards fining is observed within the sandstone facies. Some of the sequences are incomplete, either due to non-deposition of the missing facies or due to erosion of the finer-grained facies prior to deposition of the overlying coarse-grained sediments.

There is a general decrease in the proportion of the conglomeratic facies, with respect to the sandy and muddy facies, upwards through the Kirkwood succession. The proportions of sand and mud appear variable. The decrease in conglomerates upwards may indicate: 1) a general decrease in flood intensity over a long period of time; 2) a retreating source area as erosion cuts back into the hinterland, resulting in a gradual change from proximal to more distal environments of deposition (with respect to the source); and 3) a general change from a relatively wet to a more arid climate with time. These three factors are interdependent and probably acted together to cause the observed general decrease in conglomeratic facies proportions.

The fining-upwards sequences exposed in the study area show similarities to sequences exposed in meandering river deposits, characterised by fining-upward gravel and sand deposits capped by finer-grained sediments (Reid and Frostick, 1994). Meandering river deposits (Figure 17) are generally divided into three groups: a) channel deposits which include channel lags and point bars; b) bank or channel-margin deposits, deposited on the river banks during flood events, including levees and crevasse splays; and, c) overbank or flood plain deposits, including flood basin and/or flood plain deposits, abandoned channel (channel-fill) deposits and backswamp and/or marsh deposits (Visher, 1972; Friedman and Sanders, 1978; Reineck and Singh, 1980; Daniels and Hammer, 1992). Final plugging of the channel occurs after abandonment as a result of flood plain deposition and channel-fill is therefore discussed as an overbank deposit (abandoned channel deposits). The differentiation between the flood bank and overbank deposits may be difficult to discern and in some instances, even absent.

The sedimentary deposits observed in the study area can be divided into channel deposits, channel-margin deposits and overbank deposits.

3.2.1 Channel deposits

Channel deposits are extremely diverse and may show rapid changes in character, both vertically and laterally (Daniels and Hammer, 1992). In general, fluvial depositional systems are aggradational but localised progradation and lateral accretion may occur in certain environments (Galloway and Hobday, 1983). Meandering river channel-deposits are generally thought to result from lateral accretion due to lateral migration of the channel, which is the locus of deposition and the most important and diagnostic feature of the aggrading alluvial surface (Reineck and Singh, 1980; Galloway and Hobday, 1983).

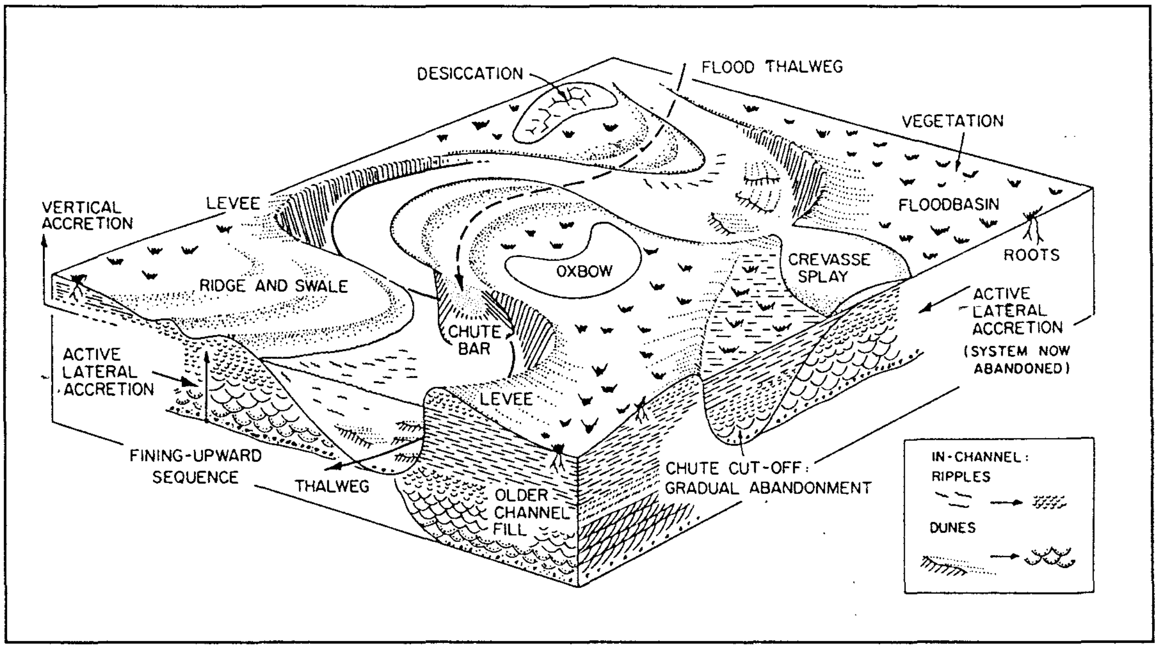


Figure 17. Block diagram showing the morphological elements of a meandering river system (from Walker and Cant, 1984, p. 72).

As mentioned above, channel deposits comprise channel lags and point bars (Figure 17). Several authors, including Allen (1965), Bridge and Leeder (1979), Reineck and Singh (1980), Galloway and Hobday (1983), Arche (1983), and Collinson (1986), discuss the mechanisms of lateral channel migration and distribution of sediment within the channel in some detail.

In general, rivers transport large amounts of sediment, either as bedload (material saltating or rolling along the river bed) or suspended load (very fine-grained material carried in suspension) (Reineck and Singh, 1980). Channel deposits predominantly comprise arenaceous coarse member sediments, resulting from the deposition of the bedload.

In the study area, channel lag and point bar deposits were identified.

A. Channel lag deposits

The coarsest material (bedload) in the river channel is transported intermittently by the river, for short distances only, during peak flood which is when the highest discharge occurs (Allen, 1965; Walker and Cant, 1979; 1984). Generally, the coarse materials are sorted and left as residual accumulations which become concentrated as channel lags by normal stream action (Happ, 1940; Reineck and Singh, 1980). The channel lags are generally deposited in a lenticular fashion on the channel floor (thalweg), which is the deepest part of the channel (Figure 17) (Allen, 1965; Reineck and Singh, 1980; Galloway and Hobday, 1983). They commonly occur on or just above the basal erosion surface and comprise coarse bedload conglomerates, gravel and sand. Waterlogged plant debris including large logs, and wood and charcoal chips, and locally-derived mudclasts and blocks eroded from the banks and bottom of the channel may also be included (Walker and Cant, 1979; 1984; Reineck and Singh, 1980; Cant, 1982; Galloway and Hobday, 1983). The conglomerates deposited as channel lags may range from clast-supported, matrix-free conglomerates, through clast-supported gravels with an interstitial sandy matrix, to sandy conglomerates with dispersed clasts (Cant, 1982).

Shone (1976) and Abson (1993) interpreted the conglomerate facies found in the Kirkwood Formation as channel lag deposits. In the study area, typical channel lag deposits occur at the bases of most of the logged sections (Appendix 1). They generally consist of conglomeratic layers and lenses, with clasts of both intrabasinal and extrabasinal origin, interbedded with thin gritty to coarse-grained sandstone lenses. The conglomerates are generally massive although they may show crude bedding, trough-cross bedding, and crude fining-upward trends within the beds. Logs of fossilised wood, mud clasts and blocks, and rare large pieces of bone also occur within the channel lag deposits, together with concentrations of wood and charcoal chip conglomeratic material. The latter generally occur as thin lenses towards the top of the conglomerate layers. Smaller channel lag deposits including thin pebble layers and lenses, and wood-chip and charcoal chip layers and lenses, also occur, interbedded with coarse-grained sandstones (within the sandstone facies).

Channel lag deposits may be separated by layers and lenses of finer grained sediment which are deposited by waning floods. These finer grained deposits have a low preservation potential as they are generally removed by subsequent scour action (Collinson, 1986). They may also be rare if there is a lack of fines in the sediment supply or, if only a small percentage of fine material is available, most or all of it is absorbed into the conglomerate framework rather than forming interbeds (Collinson, 1986). The grit and coarse-grained sandstone lenses interbedded with the channel lag deposits in the study area were probably deposited by waning flood currents. They may also have been deposited as advancing point bars.

Some of the conglomerate layers in the study area are fairly thick, show imbrication of pebbles and crude megacross-stratification, and may be interbedded with grit and coarse-grained sandstone lenses (basal conglomerates of section A and C, Appendix 1). Arche (1983) observed similar conglomerates on terraces of the Jarama River near Madrid, Spain and according to him they were deposited as coarse-grained point bars in a meandering river system, with the conglomerates being moved by lateral shifting of the active channel, especially during floods. As the flood waters waned, the conglomeratic point bars became fixed and sand was deposited on their downstream sides (Arche, 1983). This could account for the formation of grit and coarse-grained sandstone interbeds in some of the conglomerates observed in the study area (Abson, 1993).

The conglomerates were therefore probably deposited in a meandering river system as channel lags and coarse-grained, laterally migrating point bars.

B. Point bar deposits

Point bars are one of the most important sites of deposition in a meandering river channel, with most of the point bar sediment being deposited during floods, especially as the flood waters start subsiding (Reineck and Singh, 1980). The point bar deposits, which are discontinuous and lenticular in nature, generally overlie the channel lag deposits although, in some cases, the basal point bar deposits may be interbedded with several channel lag deposits (Figure 17) (Reineck and Singh, 1980). The point bar deposits are generally composed of the coarsest material available in the stream system, other than that deposited as channel lags. Classic point bar deposits show fining-upwards sequences, reflecting the wide range in the grain size of the sediment available (Reineck and Singh, 1980). Pebbles, drifted plant material and mud clasts may be incorporated into the point bars (Reineck and Singh, 1980).

The erosion of sediment from the outer convex sides of meander loops and the deposition thereof on laterally -accreting point bars, on the concave sides of each bend in high sinuosity rivers, is related to the helical flow pattern in the channel (Allen, 1965; Miall, 1977; Walker and Cant, 1979; Reineck and Singh, 1980; Galloway and Hobday, 1983). The resultant point bar sequence may be as thick as the depth of the channel (Reineck and Singh, 1980). The movement of sediment up and out of the channel onto the point bar results in a vertical decrease in grain-size (Galloway and Hobday, 1983). Thus, in high sinuosity rivers, lateral accretion on the point bars results in the formation thick, fining-upwards sandstone deposits. The fining-upwards cycle that starts with channel lag deposits overlain by point bar deposits may be capped, in the older sections, by fine-grained sandstone to mudrock levee and flood plain deposits, the latter completing the cycle (Miall, 1977). The mechanics of lateral accretion and point bar deposition are discussed by several authors including McGowen and Garner (1970), Reineck and Singh (1980), Arche (1983), Galloway and hobday (1983), and Miall (1992).

In an ideal point bar sequence observed in high sinuosity river deposits, large scale cross-bedding (megaripple-bedding) is dominant in the lower part (Reineck and Singh, 1980; Galloway and Hobday, 1983). The cross stratification indicates dune migration due to the movement of bedload (sand) across the lower and midbar surfaces (Galloway and Hobday, 1983). The thickness and size of the bed-sets generally decreases upwards, and scour-and-fill structures may be observed (Reineck and Singh, 1980). Above the zone of megaripple-bedding is a zone of ripple and climbing ripple stratification overlain by a zone of tabular and planar stratification (Reineck and Singh, 1980; Galloway and Hobday, 1983). The latter (upper) zone is characteristic of the finer-grained upper point bar sequence and is interpreted as indicating reduced flow velocities and shallow water depth, with deposition of the point bar occurring during the last phase of a receding flood (Reineck and Singh, 1980; Galloway and Hobday, 1983). The ideal point bar sequence is often capped by channel margin (levee) or overbank (flood plain) silty and clayey layers (Reineck and Singh, 1980).

Examples of point bar deposits have been identified in all the logged sections (Appendix 1). In Sections A and C (Appendix 1), the basal conglomerates are thicker than would be expected if they had been deposited as channel lag deposits. The coarse-grained point bars observed in the study area show very crude fining upwards if at all and may show large chute bars across the top. The conglomerates were probably deposited from coarse bedload during peak flood discharge.

According to Cant (1982) fluvial deposits form in areas where there is an elevated source area in close proximity to a shallow basin above sea level. These conditions commonly occur in fault- bounded basins. The Algoa Basin is believed to be such a fault-bounded basin, with tensional stresses causing subsidence of the basin along east-west trending faults (Shone, 1976). If there is rapid uplift in the source area or rapid subsidence in the basin, it could lead to "increasingly coarser sediment being shed farther into the basin" (Cant, 1982, p. 117). Thus, rapid subsidence along faults in the Algoa Basin could have resulted in increasing coarse bedload, resulting in thicker conglomeratic sequences (coarse conglomeratic point bars) further into the basin.

The conglomerates are often overlain by and interbedded with, coarse-grained sandstones, deposited by waning flood waters. These deposits are generally thin and show planar cross and tabular stratification. Lateral shifting of the active channel resulted in the deposition of the thicker conglomeratic sequences and with time, lateral migration of the channel resulted in the conglomerates being covered by finer point bar, levee and flood plain deposits. Channel lag deposits are common in most of the logged sections in the study area and are commonly overlain by sandier point bar deposits (Appendix 1).

Point bar sequences exposed in the study area generally show a typical fining-upwards point bar sequence with channel lags at the base overlain by coarse-grained sandstones with megaripple-bedding, which are in turn overlain by finer-grained sandstones and siltstones showing planar and ripple-cross bedding. Channel-margin and overbank deposits cap the fining-upward sequences. Thus, evidence of lateral migration of the channel and lateral accretion of point bar deposits is seen in virtually all of the logged sections (Appendix 1).

In streams with varied discharge, minor channels may develop across the tops of the point bars, ending in chute bars at the downstream end (Cant, 1982). Generally, chutes and chute bars form during floods, when flood waters tend to flow across the point bar surfaces, dividing the flow into two threads; one flows in the established channel (thalweg) and the other flows across the point bar surface, forming a chute (Cant, 1982; Galloway and Hobday, 1983; Collinson, 1986). The chutes, eroded into the upstream end of the point bar, funnel significant amounts of coarse material out of the channel onto the point bar (Galloway and Hobday, 1983). They vary in shape and are characteristically lined with gravel and lag material similar to that deposited in the main channel (Galloway and Hobday, 1983; Collinson, 1986).

The depth of the chute generally decreases in a downstream direction, eventually giving way to chute bars, which consist of bed-load material deposited as the flow spreads out at the end of the chute channel. The chute bar deposits are thickest at the downstream end of the chute, thinning into the deep main channel (Galloway and Hobday, 1983). Chutes are characterised by large scale sedimentary structures and coarse-grained deposits on the upper surfaces of the point bars (Galloway and Hobday, 1983). Examples of chute complexes can be seen in sections A and F (Appendix 1) where coarse-grained deposits containing imbricated pebble layers, mud-rafts and mud-pebbles, and sometimes charcoal and wood chips, overlie typical point bar deposits. These deposits are similar to those described by Galloway and Hobday (1983).

The point bar deposits observed in the study area generally conform to the ideal point bar sequence and commonly overlie channel lag deposits. Chutes and chute bars occur in some sequences and rare coarse-grained point bars have been identified in the thicker conglomeratic facies. The point bar sequences show evidence of lateral accretion and typically fine upward into channel-margin and overbank deposits.

3.2.2 Channel-margin deposits

Some bed-load and a high proportion of suspended load is deposited along the channel margins during flooding as waters overflow the banks or funnel through local breaches (Galloway and Hobday, 1983). Flow onto the flood plain is generally unconfined, and together with the decrease in flow velocity, results in rapid deposition of the coarser sands and silts close to the channel. Only the very fine-grained suspended load is transported into the flood basins (Galloway and Hobday, 1983; Collinson, 1986). The resultant sedimentation along the channel margin results in the formation of natural levees, which bound the channel, and crevasse splays, which extend on to the flood plain through breaches in the river bank and levees (Reineck and Singh, 1980; Galloway and Hobday, 1983).

A. Natural levee deposits

Natural levees are wedge-shaped ridges of sediment bordering stream channels and are best developed on the concave erosional banks of meanders (Figure 17) (Allen, 1965; Reineck and Singh, 1980, Collinson, 1986). On the convex bank, levees are rarely well developed and grade into the upper point bar sediments (Allen, 1965). Levees generally show their greatest elevation close to the edge of the channel, generally resulting in steep high banks, and from there they slope gently into the flood basin, away from the river channel (Allen, 1965; Reineck and Singh, 1980).

Levees are built up by the deposition of coarse- to fine-grained sand, silt and some clay along the channel margins as decelerating, suspended-load rich waters spill over the banks during flooding (Allen, 1965; Reineck and Singh, 1980; Galloway and Hobday, 1983). The rate of deposition, the amount of sediment deposited and the grain-size of the sediment all decrease away from the channel margin (Reineck and Singh, 1980). The coarsest sediment is deposited closest to the channel and the finer material further down the levee, some distance from the stream (Allen, 1965). With each successive flood, increments of sediment are added to the levee so that they may eventually become major topographic features on the generally featureless alluvial plain (Galloway and Hobday, 1983). Between floods, the levees may undergo pedogenesis and/or erosion by rainfall.

The levee deposits are generally finer grained than the point bar deposits, however, they may be compositionally similar to upper point bar sediments (Reineck and Singh, 1980). The internal sedimentary structures are also similar to those in the upper point bar and reflect rapid deposition, multiple waning flow cycles, shallow flow depths, and intermittent periods of subaerial exposure (Galloway and Hobday, 1983). They include small-ripple cross-bedding, climbing ripple lamination, horizontal bedding, wavy and planar lamination, and parallel laminated mud layers (Reineck and Singh, 1980; Galloway and Hobday, 1983). Localised soft-sediment deformation and scour-and-fill structures also occur (Galloway and Hobday, 1983). Evidence of repeated wetting and drying of the levee deposits includes the formation and preservation of desiccation cracks and pedogenic carbonate and iron oxide nodules and concretions (Reineck and Singh, 1980; Galloway and Hobday, 1983). Further evidence of pedogenesis includes colour mottling and root-disturbed zones (Reineck and Singh, 1980; Galloway and Hobday, 1983). Some of the larger levee deposits may support vegetation and plant debris and organic matter may be incorporated into the levee sediments (Reineck and Singh, 1980).

Levee deposits have been identified in the logged sections A, B, E and F in the study area (Appendix 1). They comprise fine-grained sands and silt and generally show parallel, horizontal (planar) lamination. In sections B, E and F, pedogenic features including desiccation cracks, root traces and burrows, colour mottles, carbonate and iron nodules, and palaeosol horizons, are common and several palaeosol profiles were identified. The levee deposits preserved in the study area commonly overlie point bar deposits and are in turn overlain by flood plain deposits .

B. Crevasse splay deposits

During high floods, breaches in the levees or isolated low channel bank sections may funnel the flow from the channel, along distinct pathways (crevasses), to the flood plain

(Allen, 1965; Reineck and Singh, 1980; Galloway and Hobday, 1983). A system of distributive channels may develop on the upper slopes of the levee as the floodwaters deepen the course of the crevasse. The repeatedly dividing crevasses extend across the levee deposits to the lower reaches of the levees and the flood basin where deposition takes over from erosion, and a narrow to broad tongue-shaped mass of sediment or crevasse splay, tapering in the flood basin direction, is deposited (Figure 17) (Allen, 1965). Splays build up by progradation and aggradation and may extend well into the flood basin, covering several kilometres in rivers prone to flooding (Reineck and Singh, 1980; Galloway and Hobday, 1983).

Crevasse splays are internally heterogeneous, reflecting their formation by "multiple flood events, shallow flow conditions, and rapid sedimentation rates" (Galloway and Hobday, 1983, p. 64). Although crevasse splay sediments have a highly variable grain-size, they are generally finer-grained than associated channel sediments, and coarser-grained than associated levee sediments (Reineck and Singh, 1980; Galloway and Hobday, 1983). Fossil remains and drifted plant material may also be incorporated into the crevasse splay deposits (Reineck and Singh, 1980). Small-scale cross-bedding, horizontal bedding, climbing-ripple and ripple lamination, planar, wavy and medium-scale trough cross-lamination, mud drapes, graded beds, and local scour-and-fill structures are common (Reineck and Singh, 1980; Galloway and Hobday, 1983). Palaeosols, with root-disturbed zones and evidence of oxidation and leaching, may develop on the exposed levee surfaces.

Crevasse splay deposits have been identified from logged sections B, D, E and F in the study area (Appendix 1). They comprise medium- to fine-grained sandstones and may show small scale cross-bedding and planar bedding and laminations. In section D (Appendix 1), an excellent example of a crevasse splay deposit, containing a concentration of mudchips, fossilised wood, and pebble lenses, was identified, and in section F, typically graded beds are prominent in one of the crevasse splay deposits.

In sections B, E and F, pedogenic features, including root traces and burrows, carbonate nodules, and palaeosol horizons, are common and several palaeosol profiles were identified. The crevasse splay deposits preserved in the study area are commonly interbedded with and/or overlie distal levee deposits. They are overlain by flood basin deposits or by subsequent crevasse splay and levee deposits.

3.2.3 Overbank deposits

Overbank deposits, comprising predominantly fine silts and clays (mudrocks), form away from the channels and beyond the levees (Reid and Frostick, 1994). Fine suspended load sediment only reaches the overbank interchannel areas during floods (Galloway and Hobday, 1983). In the interchannel (overbank) areas, sedimentation rates are low and inconsistent. Pedogenic processes, bioturbation (burrowing) and plant growth rework the sediments, destroying the original sedimentary structures. Overbank deposits include channel-fill deposits of abandoned channels and flood plain deposits.

A. Channel-fill deposits

When stream channels are abandoned, either by stream cut-off or by avulsion, subsequent sedimentation results in the formation of channel fill deposits (Reineck and Singh, 1980). Allen (1965) and Reineck and Singh (1980) give detailed accounts of the mechanisms involved in avulsion and channel cut-off. Cut-off occurs whenever the stream can shorten its course, with the frequency of cut-off increasing with channel sinuosity (Allen, 1965). Avulsion occurs when a stream abandons either part or the whole of a meander belt for a new course at a lower level on the flood plain (Allen, 1965). There are two types of cut-off: 1) chute cut-off occurs when "a stream in a meander loop shortens its course by cutting a new channel along a swale of a point bar" (Reineck and Singh, 1980, p. 293); and 2) neck cut-off occurs if a "stream cuts a new channel through the narrow neck between two meander loops" (Reineck and Singh, 1980, p. 293). Plugging of the abandoned channel proceeds gradually. After chute cut-off, the active channel gradually becomes narrower and shallower as plugging by bed load sediments proceeds (Allen, 1965). Neck cut-off results in the abandonment of meander loops and the rapid formation of "ox-bow" lakes as the ends of the abandoned channel are plugged by bedload sediments. Some of the channel cut-offs may become lakes, receiving water from overbank flood events. The initial sedimentation after both chute cut-off and neck cut-off is fairly rapid, however, in the later stages, the rate of sedimentation in the cut-off lakes is very slow (Allen, 1965; Reineck and Singh, 1980). The gradual deposition of suspended material, predominantly clayey sediments and organic matter, from overbank flows continues until filling is complete, and produces a sequence of clayey sediments in the form of clay plugs (Reineck and Singh, 1980). The ratio of sand to mudrock in the channel-fill deposits varies. Channel-fill deposits resulting from chute cut-off are generally short and less curved than the larger and strongly curved deposits resulting from neck cut-off (Reineck and Singh, 1980). Sandy units in the channel fill deposits may show cross-bedding while the muddy sediments are generally thinly laminated, with the laminations reflecting differences in colour, grain size and composition (Reineck and Singh, 1980).

Channel-fill deposits are very similar to flood plain deposits and it is often difficult to distinguish between the two when outcrop is limited. In the study area, possible channel-fill deposits occur in logged sections B, E, and F (Appendix 1). They are characterised by medium- to fine-grained sandstone deposits overlain by planar-laminated mudrocks, comprising predominantly interlaminated silty claystone and clayey siltstone.

B. Flood basin deposits

The flood basins, located adjacent to active or abandoned stream channels, are the lowest-lying part of a river flood plain and are generally poorly drained, flat, and featureless (Figure 17) (Reineck and Singh, 1980). Flood basin aggradation occurs when flood waters overflow the channel banks and spill across the interchannel areas (Reineck and Singh, 1980; Abson, 1993). The overbank flow contains mostly suspended sediment which settles from the flows, following the deposition of the coarser bedload on levees and crevasse splays (Reineck and Singh, 1980). The sediments tend to fine away from the channel and only major floods would result in the deposition of more than a few centimetres of sediment (Collinson, 1986). In general, sedimentation and post depositional changes on the flood basin depend on the climate and the distance from the active channel (Collinson, 1986). The rate of deposition in the flood basin is very slow, and aggradation occurs through vertical accretion, characterised by vertical deposition and upward growth (of the flood basin), by deposition of sediment from suspension (Allen, 1965; Reineck and Singh, 1980). Lateral accretion may occur in the flood basin but it is generally not common (Allen, 1965).

Flood basin sediments generally comprise fine silt and clay (mudrocks) (Reineck and Singh, 1980). They are characterised by parallel, finely laminated mudrocks, sometimes interrupted by sandier layers. Flood basin sediments commonly dry out between floods, resulting in oxidation to a reddish colour. Pedogenesis (soil formation) occurs and several palaeosols can be identified in ancient flood basin deposits. Pedogenic features such as root traces and burrows, desiccation cracks, colour mottling and colour banding, horizonation, the presence of iron-rich nodules and carbonate nodules and hardpan layers are often observed. In semi-arid to arid areas, large thicknesses of windblown silt may accumulate on the flood basin, sometimes forming the bulk of the deposits (Collinson, 1986).

The thick red (maroon-brown) mudrock sequences observed in the study area (sections B, E, and F, Appendices 1,2 and 3) are interpreted as flood basin deposits, interbedded with channel-fill, levee and crevasse splay deposits. They generally comprise finely laminated mudrocks and palaeosols (see chapters 4, 5 and 6).

CHAPTER 4
FEATURES OF THE PALAEOSOLS

Previous studies of the Kirkwood Formation have largely ignored the apparently massive and featureless mudrock sequences, classifying them simply as overbank deposits. However, numerous palaeosols have been identified and classified through detailed logging of the mudrocks exposed in the study area.

The recognition of distinctive pedogenic features is critical to the classification and interpretation of palaeosols. Features such as root traces, burrows and pedotubules, and soil structures (peds and cutans) are the most diagnostic in the identification of palaeosols. Other important pedogenic features include mottles, colour banding (horizonation), glaebules and hardpan layers of varying composition, desiccation cracks, slickensides and fossils. Care was taken to distinguish between the palaeosol pedogenic features and the features related either to subsequent diagenesis or to modern pedogenesis.

The pedogenic features are not only useful in the identification of soil horizons and the identification and classification of palaeosols, but also aid the interpretation of the hydrological, chemical, climatic and depositional conditions which prevailed at the time of pedogenesis.

4.1 Root Traces

Fossil root traces are one of the most diagnostic features used to identify palaeosols, distinguishing them from unaltered sedimentary deposits, volcanic flows, or zones of faulting (Bown and Kraus, 1981; Bown, 1982; Retallack, 1983b; Mount and Cohen, 1984; Sigleo and Reinhardt, 1988; Retallack, 1990). Root traces are evidence that "the rock was exposed to the atmosphere and colonised by plants, and thus a soil by almost anyone's definition" (Retallack, 1988, p. 2). The top of a palaeosol is often taken as the surface from which root traces emanate, with concentrations of other trace fossils such as burrows also being used. Together they record modification of surface sediments during periods of non-deposition or reduced deposition (Bown and Kraus, 1981; Retallack, 1990).

Well-preserved plant remains are often found in strongly reduced soils where the lack of oxygen precludes aerobic microbial activity (Retallack, 1990). Organic material will rarely be preserved in oxidised well-drained soils as it is decomposed and recycled by aerobic microbial decomposers (Retallack, 1988, 1990). Thus, in oxidised soils, the presence of branching root traces provides evidence that the soils did once support life (Retallack, 1990).

Organo-sedimentary structures produced by roots have been termed "rhizoliths" by Klappa (1980), who defined the term to include "accumulation and/or cementation around, cementation within, or replacement of, higher plant roots by mineral matter" (Klappa, 1980, p. 615). He identified five basic types of rhizoliths: root moulds; root casts; root tubules; rhizocretions *s.s.*; and root petrifications (Klappa, 1980). When the organic material making up the root decays, the tubular voids and/or channels (Brewer, 1964; Fastovsky and McSweeney, 1987; Retallack, 1988) left behind are termed root moulds (Klappa, 1980). Root casts are preserved when root moulds are filled by cements, such as crystalline sparry or drusy calcite, and/or single or several generations of sediments such as clay, silt, or sand (Klappa, 1980). The sediments may be washed into the root moulds from above or may come from collapsed void walls (Cohen, 1982). Cohen (1982) and Mount and Cohen (1984) distinguished five non-genetic categories for root cast morphologies (Table 7): horizontal planar root mats; vertical root casts; horizontal root casts; diagonal root casts; and root balls.

Table 7. Five non-genetic rhizolith or root cast configurations. (From Cohen, 1982, p. 404-406; Mount and Cohen, 1984, p. 265-266).

Rhizolith Morphology	Description
Horizontal root mats	Interwoven root casts (each less than 5 mm in diameter) lying within a larger rhizocretionary root mat. Mats form laterally continuous beds.
Horizontal, discrete roots	Irregular, horizontal to subhorizontal root casts and rhizocretions, less than 20 mm in diameter.
Vertical, discrete roots	Straight, vertical rhizocretions and root casts that reach diameters as large as 100 mm
Diagonal discrete roots	Straight, diagonal rhizocretions and root casts dipping from approximately 15-75°. Occur primarily at points of bifurcation of vertical roots.
Root ball	Irregular, globular rhizocretions encasing vertical and horizontal roots.

Root tubules are cemented cylinders which form around living or decaying roots, and rhizocretions *s.s.* are pedo-diagenetic accumulations of mineral matter, often accompanied by cementation, around roots (Klappa, 1980). Root petrifications are formed when the organic matter comprising the root is replaced by mineral matter and the anatomical features of the roots are preserved (Klappa, 1980).

Root traces generally branch and taper downwards, and are randomly oriented, distinguishing them from other trace fossils such as burrows. Compaction of the surrounding sediments results in the longitudinal "creasing" of the root traces, giving them an irregular "concertina-like" appearance (Retallack, 1988, p. 2).

Often it is impossible to distinguish between root traces and burrows, and thus the non-genetic term pedotubule is used. Brewer (1964, p. 236) defines this as:

> "a pedological feature consisting of soil material (skeleton grains or skeleton grains plus plasma, as distinct from concentrations of fractions of the plasma) and having a tubular external form, either single tubes or branching systems of tubes; its external boundaries are relatively sharp. Tubular form, in this context, means that the feature as a unit, or its impression in the enclosing soil material, has a relatively uniform cross-sectional size and shape, most commonly circular or elliptical; that is, the impression of the pedotubule conforms to the definition of channels."

Pedotubules can be subdivided into more specific groups depending on their internal fabric and their contrast with the surrounding soil material composition (Table 8).

Other processes can produce features similar to root traces (Brewer, 1964; Retallack, 1983b). Spring pits and cylindrical structures are produced by ascending water currents in sandy material, and pit and mound structures are produced by gas bubbles ascending through the sediment (Brewer, 1964). Fulgurites are produced when lightning strikes loose dry sand and are characterised by glassy rims (Brewer, 1964; Retallack, 1983b).

Former drainage, vegetation types, and originally-indurated parts of palaeosols may be determined from the arrangement of fossil root traces (Klappa, 1980; Semeniuk and Meagher, 1981; Cohen, 1982; Mount and Cohen, 1984; Retallack, 1988, 1990). Root traces may indicate the depth of the ancient water table as, unless special aeration structures are present, the roots do not penetrate the water table (Cohen, 1982; Retallack, 1988, 1990). Deeply penetrating roots are present in most root systems, indicating that the water table is well below most soils (Retallack, 1983b). In waterlogged soils, the root traces spread out laterally (tabular), whereas well-aerated soils may be deeply penetrated by root traces (Cohen, 1982; Mount and Cohen, 1984; Retallack, 1990). In dry, or seasonally dry climates, root patterns are irregular as the vegetation, typified by a few trees scattered among widespread scrub and/or grass, is sparse and clumped. Both deeply penetrating roots and near-surface finer roots are present with the former active during the dry seasons and the latter active during the wetter parts of the year (Retallack, 1983b, 1990). Root traces tend to avoid impermeable horizons and hard parts of the soils such as nodules and cemented horizons (Retallack, 1990). However, many hard nodules and cemented horizons were originally unindurated chemical aggradations, easily penetrated by roots.

Table 8. Subdivision of pedotubules according to internal fabric and contrast with the surrounding soil material (Definitions from Brewer, 1964, p. 238-241, 256; Retallack, 1990, p. 48).

Distinguishing characteristic	Terminology	Description
Internal fabric	Granotubules	granular tubules filled with mineral grains and little clay
	Aggrotubules	pelletoidal tubules filled with pellet-like masses consisting of clay and clastic grains, usually the faecal pellets of soil invertebrates, but in some cases rounded soil peds
	Isotubules	clay tubules filled with mixed clay and mineral grains without any preferred direction
	Striotubules	meniscate tubules contain clayey and granular layers transverse to the long axis
Contrast with the surrounding material	Orthotubules	compatible tubules with composition and fabric similar to the matrix; they are recognised by slight differences in coloration or by distinctly stained margins
	Metatubules	mixing tubules with internal composition dissimilar to the surrounding soil material but similar to other parts of the profile
	Paratubules	exotic tubules comprising material unlike anything else in the profile; pellet filled tubules may be like this as pellets are seldom so abundant or well-preserved in a soil matrix as in burrows

Note: The various kinds of tubules can be compounded into descriptive categories, for example, metagranotubules are mixing granular tubules.

Several types of root traces occur in the mudrock sequences of the Kirkwood Formation in the study area. Very little to no organic matter is preserved, indicating generally well-drained, oxidised soils. The organic material may have been lost through erosion of the soil surface before burial or recycled by microbes situated at depth within the overlying soil. The traces lack glassy rims, typical of fulgurites, and are branching and tapering, making it unlikely that they were caused by lightning or ascending water currents or gas bubbles. Most of the root traces observed are irregular with moderate amounts of creasing, indicating compaction.

The most common root traces are preserved as clay-filled root casts (Figure 18) which are vertically to subvertically oriented and range in colour from shades of green, green-grey and blue-grey to shades of maroon, maroon-brown, maroon-red, red-brown and rust orange. These root traces are fine (generally less than 5 mm in diameter) and are concentrated towards the tops of the palaeosols. They appear to have been formed by a single generation or several generations of clay washing into root voids or moulds. The root casts show an irregular arrangement and can rarely be traced back to a main taproot, indicating that they represent the roots of plants smaller than trees. Metagranotubules of green-grey and maroon-brown sandstone and rare meta-isotubules of green-grey and maroon-brown siltstone and are preserved as root casts.

Some of the root voids are filled with white sparry calcite crystal tubes. Root tubules are observed in thin section and are characterised by submillimetre-size micritic tubules surrounding spar-filled cylindrical voids. The micritic root tubule probably formed while the root was still alive or during decay. Once the roots had decayed, the voids left behind acted as conduits for meteoric water, with further micrite precipitating due to evaporation in the vadose zone (Mount and Cohen, 1984). The micrite formed relatively impermeable tubules, inhibiting the diffusion of water away from the voids. This resulted in complete saturation and the eventual precipitation of sparry calcite in the voids or root moulds (Mount and Cohen, 1984).

Horizontally-oriented carbonate crystal tubes are preserved on the upper contact surfaces of some calcrete hardpan horizons, rarely penetrating through them (Figure 19). The roots avoided the hardpan layers, which were indurated at the time of soil formation. When the roots died and decayed, the voids remained and may have been used as channel ways for

Figure 18. Handspecimen showing a vertical clay-filled root trace within a laminated sandstone (Middle mudrock sequence, Cr horizon, 31.84 m from the top of the sequence, Appendices 2 and 3).

Figure 19. A horizontally oriented crystal tubes on the upper surfaces of hardpan layers (Lower mudrock sequence, K horizon, 25.84 m from the top of the sequence, Appendices 2 and 3).

percolating waters or for later roots (Semeniuk and Meagher, 1981). Micrite was gradually precipitated and the voids eventually plugged (Semeniuk and Meagher, 1981). The close proximity to the hardpan layers accounts for the presence of sufficient micrite in the soil waters. Root traces of varying types are preserved within some of the hardpan layers and nodules. When calcrete initially forms, it is either moist and plastic or moist-chalky. Roots penetrated the initially soft calcrete, and were preserved when the calcrete later became indurated.

Vertically-oriented taproots (generally less than 15 mm thick and of varying length with rare larger taproots less than 40 mm in diameter and traceable for 0.35 m) occur in the upper mudrock sequence (Figure 20) and have finer calcite- and clay-filled rootlets associated with them. The taproots are composed of micrite and are rich in sesquioxides, giving them a much deeper red colour than the surrounding soil matrix. Lighter grey pink micritic root casts have fewer sesquioxides. In thin section, the root cast is filled with patches of lighter and darker micrite and very thin irregular tubes of spar, indicating multiple phases of formation. The precipitation of micrite may occur in both the life and death stages of the roots, initially precipitating as a pore filling (Mount and Cohen, 1984). The precipitation of micrite occurs rapidly as the root dies and decays. In the final stage of decay, sparry calcite precipitates in the thin irregular voids left behind (Mount and Cohen, 1984).

The vertically-oriented taproot casts may be lined with dark maroon-brown stress argillans. It is thought that the roots exerted pressure on the walls, causing slightly denser packing of the soil matrix near the walls and striations in the plasma close to the walls (Brewer, 1964). Swell-shrink movements in the surrounding soil matrix in response to seasonal wetting and drying may have resulted in the formation of the stress argillans lining the root casts. The other root types already discussed also show rare development of stress argillans. Some brick red taproot casts are well-indurated but lack carbonate. They are predominantly made of clay and clayey siltstone cemented by sesquioxides.

Diffuse drab haloes separate many of the different types of root casts observed from the surrounding generally maroon-brown or red matrix. The pale green, blue-grey and white colours of the haloes are attributed to a greater proportion of reduced or ferrous iron relative to oxidised or ferric iron, or due to less total iron in the surrounding matrix. The origin of the haloes is uncertain and Retallack (1983b) has suggested five possible hypotheses for their origin. Hypothesis one suggests that they could be krotovinas which are tongues of drab material that have fallen down into burrows or root traces from bleached overlying horizons (Retallack, 1983, 1990). Hypothesis two suggests the reduction of iron, manganese, and sulphate by microbial activity around root traces waterlogged by a perched water table, that is, surface water gley. In hypothesis three, the drab haloes represent the rhizosphere, defined by Retallack (1983, p. 9) as "the chemical micro-environment established by the living root and its associated halo of mucigel, micro-organisms, and soil water." The roots are mildly reducing and complex organic molecules produced by the roots and organisms may reduce the iron and manganese in the rhizosphere by chelation (Retallack, 1983, p. 9). Hypothesis four suggests that the drab haloes are the result of groundwater gleying which occurs after burial and subsidence. Nitrate, manganese, iron and sulphate are reduced by the decay of roots and organic matter by anaerobic bacteria (Retallack, 1983, p. 9). Hypothesis five suggests the enhancement of the drab haloes by the process of diagenetic reddening in the surrounding rock (Retallack, 1983, p. 9).

Figure 20. Handspecimen of a large fossilised taproot found in the upper mudrock sequence (Bk horizon, 15.93 m from the top of the sequence, Appendices 2 and 3).

The contacts of the drab haloes in the Kirkwood palaeosols with the surrounding soil material are diffuse, ruling out hypothesis one. Hypothesis two may be applicable in some of the redder palaeosols where there is less carbonate and more clay. However, many of the drab haloes occur in palaeosols where there are calcic horizons and distinct A horizons, which, according to Retallack (1983b), are evidence against surface water gley. In general, hypotheses three, four and five are used to explain the origin of the drab haloes as they are mutually compatible and may have all contributed to the formation of the haloes. (Some of the drab haloes in the palaeosols of the study area were formed by surface water gley, whereas the majority were formed by rhizosphere chemistry, post-burial groundwater gley, and diagenetic reddening).

In some root horizons (rhizosphere) iron-rich rust orange and yellow concretions up to 10 mm in diameter, occur in association with the root traces. The iron in the rhizosphere is mobilised in the drab ferrous state, but becomes oxidised to yellow and red ferric oxides which form ferruginous rhizocretions in the vicinity of the roots (Bown, 1982). The presence of the rhizocretions indicates oxygenated, free-flowing water (Retallack, 1990).

There are a number of types of root traces in the study area and this chapter has dealt only with the appearance of these root traces and their formation. Their significance in the interpretation of the palaeoenvironment and climate will be discussed later.

4.2 Burrows and/or Pedotubules

Burrows are common tubular features of many soils and palaeosols, however, they are also common in marine environments and therefore the presence of burrows alone cannot be used to identify soil and palaeosol horizons. Together with root traces, they are important indicators of ancient land surfaces as they provide evidence that the sediment was colonised by organisms during periods of reduced or non-deposition. As mentioned in the previous section, it is often difficult to distinguish between burrows and root traces and therefore the non-genetic term, pedotubule, is used. Burrows are generally tubular and unlike most root traces, they do not branch and/or taper (Bown and Kraus, 1981; Retallack, 1983b).

The taxonomy of burrows is difficult to determine due to pedogenic and diagenetic alteration of the internal and external morphologies. Modern burrows occur in moist aerated sediments and therefore the presence of burrows in palaeosols can be taken to indicate previously unindurated parts of the soil profiles. Burrows generally occur above the water table as most soil animals are air-breathers and therefore burrows may be used to indicate depth to the water table (Braunagel and Stanley, 1977; Retallack, 1983b).

Burrows are preserved in a variety of substrates in the mudrock facies in the study area. The burrows do not taper or branch and are predominantly cylindrical and/or tubular in shape, although rare pouch-shaped burrows occur. They are generally vertically to subvertically oriented, with horizontally and randomly oriented burrows present in some horizons. They are rarely greater than 8 mm in diameter and are extremely variable in length. In some horizons, the burrows disturb and deform laminations indicating that the sediments were colonised during the last stages of, or soon after, deposition while the sediments were still moist and soft. They are also present in more mature palaeosol horizons, often in association with mottles (due to bioturbation) and numerous root traces.

The burrows are generally filled with maroon-brown and grey-brown clayey siltstone, siltstone, and very fine- to fine-grained sandstone. Green-grey silty claystone and clayey siltstone-filled burrows and rare sandy brown and maroon-grey burrows are also observed. The lack of internal features, such as meniscae, indicates that the burrows were most probably passively filled and no fossil remains were found in the burrows. Some of the burrows are lined with clay, suggesting that they served as pathways for downward percolating meteoric and flood waters which transported eluvial clay (Smith, 1990).

Approximately 16.23 m from the top of the lower mudstone sequence, large horizontally-oriented cylindrical, calcium carbonate- filled pedotubules are observed (Figure 21). It is possible that they represent large burrows as they show slight chamber development, follow a sinuous path and some striations are evident on their surfaces, possibly indicating scratch marks. However, the striations are linear and do not follow the sinuous path of the pedotubule in the section excavated, and therefore they cannot be used as definite evidence for a biogenic origin. Other evidence against the classification of the cylindrical pedotubules as burrows includes the lack of preserved internal structures and bone material. Cylindrical nodules, similar in appearance to these features, have been reported from other palaeosol sequences (Joeckel, 1991) and therefore the pedotubules in the lower mudstone sequence have tentatively been classified as cylindrical nodules (to be discussed later) rather than burrows.

The burrows in the study area are generally featureless and have tentatively been placed in the ichnogenus *Skolithos* due to their predominantly vertical to subvertical orientation and simple morphology. Rare, horizontally oriented burrows, similar to those described by Blodgett (1988) and Machin (1994) as the ichnogenus *Planolites*, occur. The burrows indicate well-aerated soils and generally low water tables, and together with root traces, are used to define the tops of palaeosols.

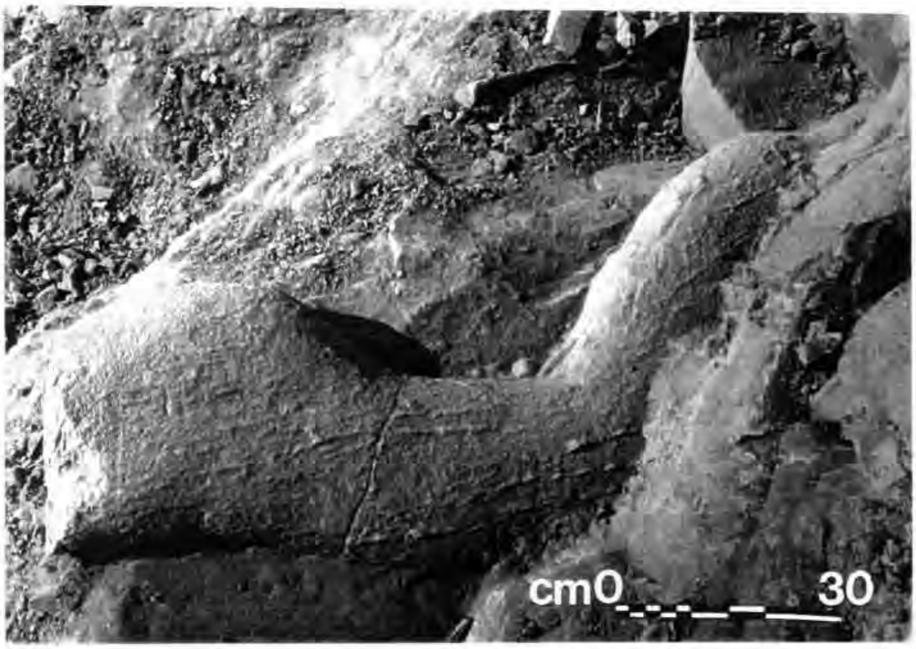


Figure 21. Horizontally oriented cylindrical calcium-carbonate filled nodule (pedotubule) from the lower mudrock sequence (Cr Horizon, 16.23 m from the top of the sequence, Appendices 2 and 3).

4.3 Mottles

Colour mottles occur in most palaeosols. Retallack (1988; 1990) defined mottles as:

irregularly-shaped aggregations or patches of material that are especially diffuse or weakly mineralised. The minerals are generally amorphous or very finely crystalline.

They may represent the early stages of nodule and/or concretion differentiation, but they generally occur as irregular patches of discolouration (Retallack, 1990). Mottles are classified in terms of size, visibility and abundance (Table 3).

Mottling may be related to faunal and floral bioturbation and associated decaying organic material (McBride, 1974; Blodgett, 1988), or to hydromorphy, that is, due to alternate wetting and drying of the solum (Walker, 1967; Bown and Kraus, 1981; Fastovsky and McSweeney, 1987; Retallack, 1988, 1990; Sigleo and Reinhardt, 1988; Smith, 1990;

Kraus and Aslan, 1993). Blodgett (1988) observed green and purple mottles occurring in association with root traces, and to a lesser extent, with burrows. He attributed the green pigment in the mottles to the presence of chlorite and illite and the removal of iron oxides and oxyhydroxides in reducing conditions, caused by the decay of organic matter. The purple pigment he attributed to coarsely crystalline hematite formed due to reaction with organic compounds from the roots (Blodgett, 1988).

Generally, mottles form due to hydromorphic processes, reflecting fluctuations in the water table, and/or episodic or seasonal soil saturation, or impeded drainage (Bown and Kraus, 1981; Kraus and Aslan, 1993). Iron and manganese are reduced and go into solution during periods of soil wetting (Bown and Kraus, 1981; Kraus and Aslan, 1993). The resultant compounds may be mobilised and leached from the soil or concentrated in more oxidised areas, such as voids and more permeable zones, as mottles (Retallack, 1990; Kraus and Aslan, 1993). As the soil dries, the compounds are reprecipitated and re-oxidised to oxides and oxyhydrates (Bown and Kraus, 1981). This process is known as gleying. Surface-water gley occurs when soils are waterlogged, due to the presence of impermeable layers, for prolonged or seasonal periods (Retallack, 1990; Kraus and Aslan, 1993). The impermeable layers, such as clayey soils, act as barriers to the downward percolation of water, and result in perched water tables (Retallack, 1990; Kraus and Aslan, 1993). Ground-water gley occurs when soils become seasonally or periodically waterlogged due to fluctuations in the ground-water table, and therefore the depth of the mottled zone depends on the amount of water table movement (Bown and Kraus, 1981; Retallack, 1990; Kraus and Aslan, 1993).

There are three main types of mottles in the study area. These include maroon-brown sandstone, siltstone and claystone mottles in green-grey and grey-brown sandstones and siltstones; green-grey sandstone, siltstone and claystone mottles in maroon-brown sandstones, siltstones and minor claystones; and grey-brown sandstone mottles in maroon-brown sandstones and siltstones.

Maroon-brown mottles in grey-green horizons, which form in response to gleying, have been described by Fastovsky and McSweeney (1987), Bown and Kraus (1981), Smith (1990) and Kraus and Aslan (1993). Oxidation of the soils occurs locally along cracks and/or channels of permeability during periodic drying of a normally saturated solum, resulting in irregular diffuse, maroon-brown mottles. Drying out may occur due to lowering of the water table and/or drying out of sediments between flood events. Maroon-brown mottles in grey-brown sediments may form as a result of local oxidation of iron in more permeable, coarser-grained parts of the horizon.

Green-grey mottles in maroon-brown horizons may have resulted from periodic surface-water gley, but are more likely to have formed as a result of the reduction of ferric iron in the presence of rapidly decaying organic matter. This explains the common association of green-grey mottling with floral bioturbation (root traces) and is similar to observations by Blodgett (1988).

Grey-brown mottles in maroon-brown horizons may be due to different states of oxidation of ferric iron, in response to slight differences in permeability of the sediments. In some cases, the mottled horizons reflect relatively deep contact zones between eluvial A horizons, which are being leached of iron (green-grey horizons), and illuvial B horizons, in which iron is precipitating (maroon-brown horizons).

From the types of mottling observed in the study area, it is evident that surface-water gley, due to perched water tables, did play a role in the formation of some of the green-grey pigmented horizons. However, some of these horizons may have formed as a result of gleization in low-lying areas where ponds of water remained as flood waters receded. If maintenance of water levels in the ponds is dependent on local ground-water table levels, seasonal fluctuations in response to rainfall could result in periodic drying out of the ponds. Localised oxidation would result in maroon-brown mottling in the predominantly green-grey horizons.

As most of the horizons in the mudrock facies are maroon-brown, indicating oxidation, it is thought that the water table was generally low. The presence of root traces, common in the maroon-brown horizons, suggests that some plant material would also have been present. As the plant material decayed, it resulted in localised reduction of the horizon, and the formation of green-grey mottles.

Collective evidence from root traces, colour banding and colour mottling indicates a generally low water table in the area at the time of soil formation. However, the presence of green-grey horizons and associated maroon-brown mottles indicate that perched water tables occurred locally and that the ground-water table, especially in low lying areas, was subject to seasonal fluctuations in response to rainfall.

4.4 Colour Banding

The palaeosols observed in the study area are characterised by strong colour banding. Similar colour banding has been reported from a number of alluvial sequences by Friend (1966), Neasham and Vondra (1972), McBride (1974), Braunagel and Stanley (1977), Bown and Kraus (1981), Retallack (1983b; 1990), and Driese and Foreman (1992). Factors influencing the colour of sediments and soils include the mineralogy and texture of framework grains, the presence or absence of interstitial matrix and organic matter, and the chemical form of iron and other compounds present (Pye, 1983).

The origin of red beds, which are common in both modern and ancient sediments, has been debated by several authors (Friend, 1966; Walker, 1967; McBride, 1974; Braunagel and Stanley, 1977; Bown and Kraus, 1981; Pye, 1983; Retallack, 1983b, 1990). McBride (1974), and Bown and Kraus (1981) have contrasted red, green, purple, olive, brown, and grey sediments and soils in an attempt to discover the causes and origins of the colours as well as the implications of environmental, climatic and diagenetic factors.

Pye (1983) distinguishes between *in situ* red beds, formed in place by direct precipitation or by weathering, soil formation and diagenesis, and detrital red beds, formed by erosion, transportation and re-deposition of existing red soils or sediment. The *in situ* red beds can be subdivided into pure chemical precipitates, diagenetic red beds, and pedogenetic red beds (Pye, 1983). Subaerial pedogenetic red beds show horizon definition within a weathering profile, whereas diagenetic red beds are not dependent on surface weathering processes, but are associated with migrating ground waters and the alteration of iron-bearing minerals.

Diagenetic red beds are further subdivided into eogenetic, mesogenetic and telogenetic types (Choquette and Pray, 1970). "Eogenesis involves changes in sediment character due to the action of surface related processes from the time of deposition until such time as the sediment body becomes more deeply buried. Mesogenesis refers to diagenetic processes operating at higher temperatures and pressures during deep burial (though not sufficiently extreme to cause metamorphism). Telogenesis involves changes when, after a period of burial, a sediment body is again exposed to near-surface processes by erosion of the overlying rocks" (Pye, 1983, p. 228). Pedogenetic and eogenetic red beds are most commonly found in alluvial deposits.

Most authors agree that the red pigment is due to haematite which may occur as well-or poorly-crystallised grains, amorphous grains, or as haematite stained grains and/or matrix. Bown and Kraus (1981, p. 10) attribute the red colouration to the "dominance of dehydrated ferric iron compounds (largely haematite) over hydrated ferric iron compounds (largely goethite) and manganese compounds, and a low incidence of organic carbon".

It was originally thought that the red pigment was inherited from transported lateritic material, eroded from red beds in source areas (Van Houten, 1948). However, no cases of modern red alluvium have been recorded, and it is thought that if there are known red beds in the source area, the eroded sediments become diluted with non-red sediments and are chemically altered and/or abraded during transportation (Van Houten, 1972; Walker, 1974). Modern alluvium is generally not red when deposited but drab greys, yellows and browns (Friend, 1966). More recently, the importance of syn- and post-depositional pedogenetic weathering and diagenesis in the formation of ancient red beds has been recognised, and two complementary models for the origins of red pigment in red beds have been developed (Pye, 1983). In the first model, Walker (1967) proved that haematite could form *in situ* and that haematite-stained haloes, evident around iron-bearing grains such as biotite, hornblende, epidote, magnetite, and illite, are formed from post-depositional intrastratal alteration of these grains. In the advanced stages of alteration and haematite formation, the haematite becomes concentrated in the interstitial clay matrix (Walker, 1967). The second model, preferred by Friend (1966) and McBride (1974), involves a combination of oxidation of ferrous iron, post-depositional ageing of brown detrital ferric iron, and/or pedogenesis under oxidising conditions.

Most red bed formations have associated non-red beds which include green, grey, purple, olive and yellow, orange, and brown beds. The origin of the green beds, which are most commonly associated with red beds, is controversial. Friend (1966), Neasham and Vondra (1972), McBride (1974), and Bown and Kraus (1981) agree that the green pigment is due to the reduction of ferric iron to ferrous iron, however there are differing opinions as to the processes involved.

Friend (1966) observed that green beds are associated with channel sandstones. He suggested that if sufficient plant debris was present in the channel sandstones, reducing conditions would develop, resulting in the formation of ferrous-organic complexes which are removed in solution, therefore decreasing the amount of iron in the sediments. Similarly, Walker (1967) observed a depletion of iron in green beds and attributed it to the leaching of ferrous iron by interstitial waters. Neasham and Vondra (1972) and Bown and Kraus (1981) noted that reducing environments occurred in areas of impeded drainage or in areas with water tables close to the depositional surface, and agreed that ferrous iron, resulting from the reduction of ferric iron, was leached from the soil, resulting in depletion of iron. Braunagel and Stanley (1977) also agree that there is a depletion of iron in green beds, but attribute the depletion to evaporation which results in the upward movement of water and minerals in the capillary zone above the water table, and in the leaching of lower horizons. McBride (1974) noted that iron is not always depleted in the green beds, and attributed the green pigment to the presence of iron in chlorite and illite, and to a lesser extent, to the absence of haematite.

In summary, most authors agree that the green pigment is due to the leaching of ferrous iron in a reducing environment, however, the process responsible depends on the individual study and the features observed.

Very little work has been done on the processes involved in the formation of purple, grey, yellow and olive, orange, and brown beds. According to McBride (1974), the purple pigment may be: a function of the amount of haematite that is present in the sediment; a result of colour mixing between green silicates and red haematite or between green hydrated ferric oxides red hydrated ferric oxides; imparted by manganese oxides or mixed manganese-iron oxides; or due to the grain size of the haematite. The purple pigment could also reflect a higher ratio of ferrous iron to ferric iron (Bown and Kraus, 1981).

Grey pigment is thought to be inherited from the abundant organic matter and plant material (Bown and Kraus, 1981). Olive and yellow beds reflect the mixing of hydrated and dehydrated ferric iron compounds (haematite, turgite, limonite, and goethite), with the hydrated compounds being more abundant (Bown and Kraus, 1981). The pigment could also be due to minor plant debris associated with iron in an intermediate state of oxidation (Bown and Kraus, 1981). McBride (1974) attributes the formation of olive and yellow beds to the mixing of green clay and black organic carbon.

The presence of lepidocrocite and moderate amounts of organic carbonate may result in orange beds (Bown and Kraus, 1981), whereas brown beds are due to the weathering of small amounts of goethite and haematite (McBride, 1974).

From the above, it is evident that the origins of pigment in red beds and associated non-red beds should be determined from the features observed in the palaeosols as all models suggested are possible.

In the field area, the exposures are predominantly maroon-brown (red) with associated green-grey horizons and minor associated purple-maroon, grey green-blue, grey-brown and sandy brown, olive grey-brown and olive sandy brown, grey, yellow-grey and olive-green horizons (Figure 22). There is no evidence to suggest that the maroon-brown pigment was inherited from the source area. The presence of drab yellow-brown sandstone facies horizons below the mudrock facies indicates that the alluvium deposited was not maroon-brown at the time of deposition, and that the colour banding was due to ancient soil formation involving *in situ*, post-depositional pedogenesis and possibly also early diagenesis, that is, eogenesis.

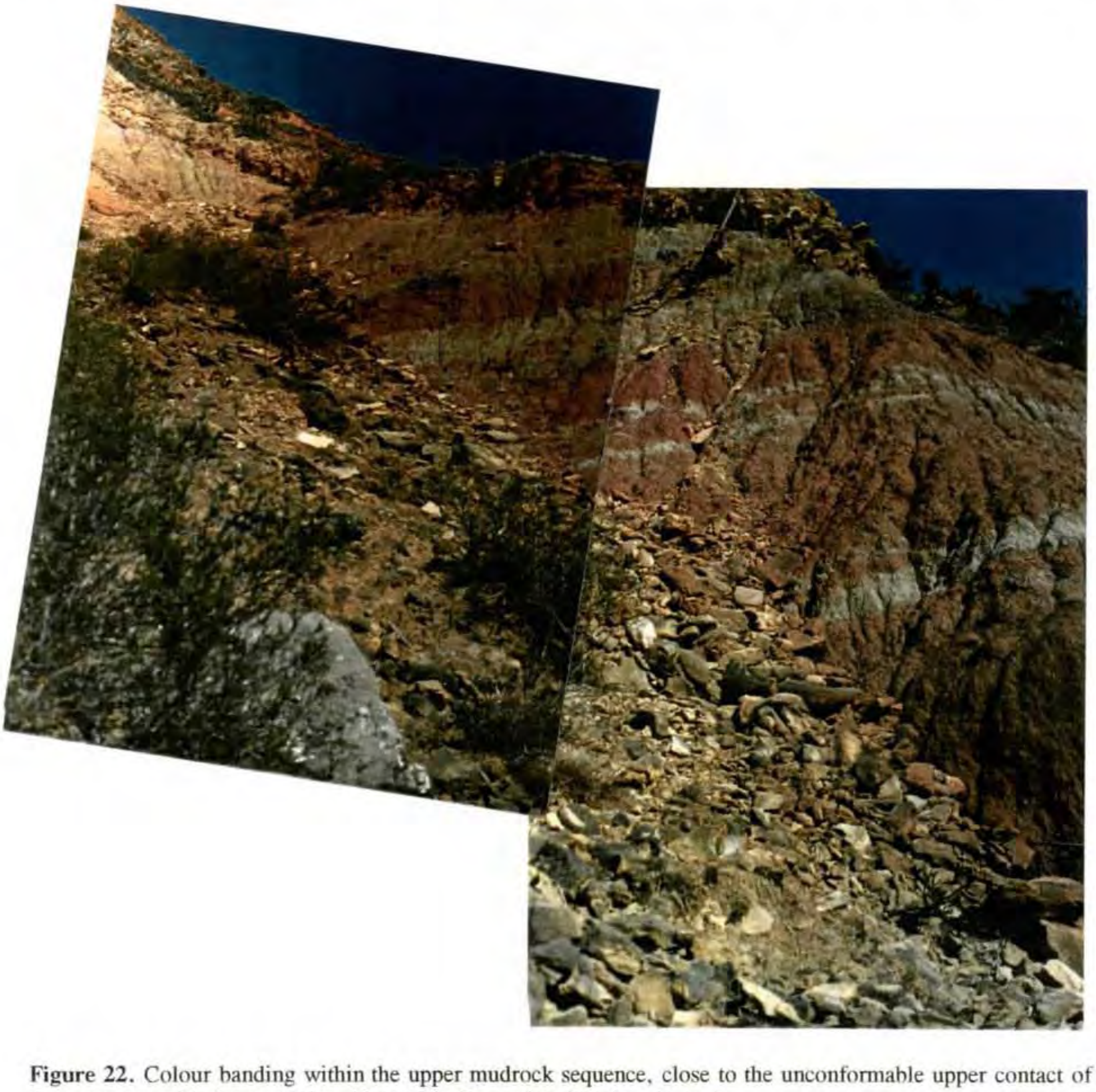


Figure 22. Colour banding within the upper mudrock sequence, close to the unconformable upper contact of the sequence with the overlying Alexandria Formation (Tertiary in age).

In the mudrock sequences, the maroon-brown layers occur as laminated sandstones, laminated clayey siltstones, non-laminated very fine-grained to fine-grained sandstones, and non-laminated siltstones and claystones. In thin section, the pigmentation is predominantly due to haematite-stained interstitial clay matrix. Most iron-bearing grains do not show alteration or the development of haloes and therefore it is unlikely that the pigment is due to intrastratal alteration. It is more likely that the pigment is due to pedogenesis under oxidising conditions and to a lesser extent, to oxidation of ferrous iron and post-depositional ageing of brown detrital ferric oxides. Purple-maroon horizons are also present, and the pigment is thought to be due to colour mixing between green and red hydrated ferric oxides, and to the presence of traces of organic material.

Green-grey layers occur as both claystones and medium-grained sandstones. Their colour is attributed to the reduction of ferric iron to ferrous iron in a reducing environment. It is possible that the green sandstones were originally closely associated with the channel and that they were below the water table for long periods. Reducing waters from the channel percolated through the sandstones, resulting in reduction of the iron and subsequent leaching, producing iron-depleted green beds. The ferric iron in green claystones is more likely to have been reduced due to waterlogging and surface- and ground-water gley. In lower lying areas of overbank deposits, such as in ponds, the sediments would be waterlogged for long periods of time and reducing conditions could be established, especially in the presence of some organic material. Reducing conditions could also be established in association with perched water tables beneath the floodplain sediments, or in areas of impeded drainage. Some of the green-grey claystones have blue tints which are due to the presence of minute particles of organic matter.

Sandy-brown, olive sandy-brown, olive grey-brown, and grey-brown sandstones of varying grain size are present. It is thought that they represent the original brown colour of the alluvium and that they have not been subjected to pedogenesis to any great extent. The grey pigment is probably due to organic matter preserved in the sandstones and the brown to weathering of small amounts of goethite and haematite. Yellow-grey sandstones may represent soils in which iron occurs in an intermediate oxidation state and in which small amounts of organic carbon are preserved. Olive green claystones are rare and are due to the mixing of green-grey claystone and black organic material.

The colour banding in the study area therefore depends on the oxidation and reduction potentials that prevailed at the time of pedogenesis, and to a lesser extent, on the amount of organic material preserved in the beds. The colours are a result of pedogenetic and eogenetic processes which were active in the post-depositional environment.

4.5 Glaebules and Hardpan Layers

4.5.1 Introduction

Glaebules are highly irregular to almost spherical concentrations of soil material with simple, distinctive mineralogical and chemical compositions (Brewer, 1964; Retallack, 1990). Nodules and concretions are the most common types of glaebules and are distinguished on the basis of their internal structures, which may reflect the way in which they were formed (Retallack, 1990). Nodules, thought to have formed from continuous growth, are internally massive whereas concretions display concentric layers, formed around a central point, plane, or line, by discontinuous often seasonal growth (Brewer, 1964; Retallack, 1990). Both nodules and concretions generally have sharp and distinct boundaries with the surrounding soil matrix.

Glaebules may be orthic, that is, formed *in situ* in the soil material by pedological processes, or they may be disorthic, that is, inherited pedological features which include relicts of parent rock and/or parent material, or the underlying material (Brewer, 1964). The nature of the glaebule contact with the surrounding soil matrix may indicate the degree of transport (Wieder and Yaalon, 1974). Orthic glaebules generally have diffuse contacts whereas disorthic glaebules have sharp contacts and have been moved in the soil profile by pedoturbation (Wieder and Yaalon, 1974). However, nodules with sharp boundaries need not necessarily have formed due to pedoturbation. They may represent originally diffuse nodules which have undergone multiple stages of formation and recrystallisation, or originally diffuse, partially lithified to lithified nodules that have inherited sharp boundaries due to differential compaction of the surrounding soil matrix (Blodgett, 1988). Allothic glaebules, which have been transported into the soil, have a composition different from that of the surrounding soil (Wieder and Yaalon, 1974).

The chemical composition of glaebules varies and reflects the availability of oxygen in the soils at the time of formation (Retallack, 1990). Permanently waterlogged soils have little oxygen and are characterised by the presence of pyrite, siderite, and marcasite, whereas better drained soils contain haematite and goethite nodules and concretions (Retallack, 1990).

Well-drained, oxidised, dry soils are characterised by calcareous nodules (Retallack, 1990).

4.5.2 Calcareous Nodules and Hardpan Layers

Calcareous nodules, including crystallaria and septaria, and hardpan layers are common in many soil profiles formed in semi-arid to arid areas, and are concentrated in calcic and petrocalcic horizons. Crystallaria comprise single crystals or arrangements of crystals, and septaria are characterised by wedge-shaped cracks filled with sparry calcite (Brewer, 1964; Blodgett, 1988).

Calcrete profiles are developed in stable, shallow subsurface environments and are characterised by accumulations of carbonate as nodules and hardpan and/or laminar horizons, in developing soil profiles (Francis, 1986). Calcium carbonate-cemented horizons are termed calcic horizons when the carbonate occurs as powder or isolated nodules, and petrocalcic horizons when the carbonate occurs as an extensively cemented, continuous brittle layer within the soil (Retallack, 1990).

A number of calcrete types have been identified by Netterberg (1980) and Goudie (1983): (a) Calcified soils, which are structureless and can attain great thicknesses, are soft loose soils weakly cemented by calcium carbonate (Goudie, 1983). (b) Powder calcretes, occurring in association with shales and mudstones, comprise loose calcium carbonate powder with rare visible soil particles and show no nodular development (Goudie, 1983). (c) Nodular calcretes, characterised by concentrations of carbonate-cemented soil (nodules) occur in a loose calcareous soil matrix (Goudie, 1983). The nodules, mostly comprising micrite or microspar with varying proportions of detrital grains, are generally discrete, vary in shape, and may be soft or very hard (Goudie, 1983; Blodgett, 1988). There is a general increase in size and abundance upwards. (d) Honeycomb calcretes, occurring as an intermediate stage between nodular and hardpan calcretes, are characterised by coalesced nodules (Goudie, 1983). (e) Hardpan calcretes occur as hard, generally indurated, sheet-like layers, often comprising "cemented honeycomb calcrete, cemented powder calcrete, brecciated host material re-cemented, coalesced horizontal nodules giving a pseudo-laminated horizon, or a case hardened calcic unit giving a petrocalcic horizon" (Goudie, 1983, p. 100). (f) Finely laminated, firm to hard, undulose sheet layers, characteristic of laminar calcretes (platy caliche or laminated crusts), are often found capping hardpan calcretes and are rarely greater than 0.25 m thick (Goudie, 1983). (g) Boulder calcretes are formed when hardpan and/or laminar calcretes undergo solution, resulting in large, rounded, very hard boulders (Goudie, 1983).

In thin section, the carbonates comprise varying proportions of detrital quartz and feldspar "floating" in a micrite or microspar cement (Blodgett, 1988). As carbonate levels in the sediment increase, the original clastic grains are pushed apart so that they eventually display no point-to-point contacts and they appear to float in the carbonate matrix (Goudie, 1983; Machette, 1985). Initially, void spaces in the soil are filled with precipitating carbonate, however, further accumulation of carbonate may occur resulting in the displacement and/or replacement of the original grains (Goudie, 1983). As the calcrete develops, calcite corrodes the clastic grains until, eventually, total replacement occurs (Goudie, 1983). Scalloped and modified grain boundaries are common and occur before the final stage of replacement (Goudie, 1983). Clotted textures (agglomeratic fabric of Brewer, 1964), common in calcretes, are characterised by dense patches of cryptocrystalline micrite in a microcrystalline matrix (Goudie, 1983). Crystic plasmic fabrics, commonly observed in calcretes, are characterised by discernable crystal outlines and occur due to the crystallisation of soluble fractions of plasma (Goudie, 1983; Allen, 1986; Retallack, 1990). The plasma of a soil material is defined as "that part which is capable of being or has been moved, reorganised, and/or concentrated by the processes of soil formation. It includes all the material, mineral or organic, of colloidal size and relatively soluble material which is not bound up in the skeleton grains" (Brewer, 1964, p. 12).

Gile et al. (1966) and Machette (1985) used the physical characteristics of pedogenetic calcium carbonate to develop a morphological sequence characteristic of calcic soils. The sequence involves six stages of carbonate accumulation that are partially dependent on the parent material of the soil (Table 9).

The stages of carbonate accumulation reflect increasing maturity of the soil profile from stage I to stage VI. Reeves (1970) used the stages of carbonate accumulation to identify young, mature, late mature and old age profiles.

In very weakly developed soils on non-gravelly materials, the carbonate (stage I of Gile et al., 1966, and Machette, 1985) occurs as faint coatings on grains, fine white powdery filaments, and as dispersed powdery nodules (Retallack, 1990). It is thought that at least 1000 to 2000 years must elapse before stage 1 carbonate accumulation is observed (Leeder, 1975).

Table 9. Stages of carbonate accumulation in palaeosols (from Retallack, 1988, p. 16)

Stage	Palaeosols developed in gravel	Palaeosols developed in sand, silt or clay
I	Thin discontinuous coatings of carbonate on underside of clasts	Dispersed powdery and filamentous carbonate
II	Continuous coating all around and in some cases between clasts: additional discontinuous carbonate outside main horizon	Few to common carbonate nodules and veinlets with powdery and filamentous carbonate in places between nodules
III	Carbonate forming a continuous layer enveloping clasts: less pervasive carbonate outside main horizon	Carbonate forming a continuous layer formed by coalescing nodules: isolated nodules and powdery carbonate outside main horizon.
IV	Upper part of solid carbonate layer with a weakly developed platy or lamellar structure capping less pervasively calcareous parts of the profile	
V	Platy or lamellar cap to the carbonate layer strongly expressed: in places brecciated and with pisoliths of carbonate	
VI	Brecciation and recementation as well as pisoliths common in association with the lamellar upper layer	

Note: This table includes modifications (Machette, 1985) to the scheme proposed by Gile et al. (1966).

With time, concentrations of authigenic carbonate result in the formation of discrete nodules in weakly developed non-gravelly soils (stage II of Gile et al., 1966, and Machette, 1985) (Retallack, 1990). The nodules may be slightly to extremely hard and some may be indurated (Gile et al., 1966). They may be spherical, ellipsoidal, tuberose and/or cylindrical, and irregular, with the smaller nodules generally tending towards higher sphericity (Retallack, 1990; Smith, 1990). The number and size of the nodules characteristically increases upwards (Goudie, 1983). The soil matrix surrounding the nodules may be calcareous or non-calcareous in parts (Gile et al., 1966).

In moderately developed soils (stage III of Gile et al., 1966, and Machette, 1985), nodules grow larger and eventually coalesce to form a carbonate-impregnated horizon or hardpan (Goudie, 1983; Retallack, 1990). This horizon is known as the K horizon, although it is often subdivided into K1, K2 and K3 horizons. Gile et al. (1966, p. 350) define the K2 horizon as "containing 90% or more, by volume, of material with K-fabric" where K-fabric is a diagnostic soil fabric in which "fine-grained authigenic carbonate occurs as an essentially continuous medium. It coats or engulfs, and commonly separates and cements skeletal pebbles, sand, and silt grains" (Gile et al., 1965, p. 74). K1 and K3 horizons are transitional and may be absent. They are defined as "containing 50% or more, by volume, of material with K-fabric" (Gile et al., 1966, p. 350). Nodules are often embedded in the K horizon and angular fragments of mudrock may also be caught up in the hardpan (Smith, 1990). The rate of induration of the K horizons is dependent on the amount of available carbonate in the overlying soil, the amount of infiltrating groundwater, and the speed of plugging of the profile (Reeves, 1970). Plugging of most of the pores in the horizon and complete separation of most of the grains by carbonate occur in the last part of this stage (Gile et al., 1966).

Machette (1985) divided stage IV of Gile et al. (1966) into three. Stage IV (Machette, 1985) pedogenetic calcretes occur in strongly developed soils (Retallack, 1990). In this stage, the plugged K horizon is impermeable and serves as a barrier to downward percolating waters (Retallack, 1990). The carbonate-rich waters flow over the layer, resulting in the formation of thin laminar layers less than 10 mm thick (Machette, 1985; Retallack, 1990). The horizon has a maximum thickness of 0.5 m to 1.0 m, and occurs as a cemented, platy to weakly tabular layer with thin indurated laminae sharply truncating the cemented zone (Machette, 1985). Stage V occurs as an indurated dense, strong platy to tabular layer between 1.0 m and 2.0 m thick and is characterised by thick laminae (>10 mm) and thin to thick pisolites (Machette, 1985). Vertical faces and fractures in the horizon are coated with laminated carbonate (Machette, 1985). Very strongly developed soils show Stage VI pedogenetic calcretes which occur as indurated and dense, thick (>2 m) strong tabular layers characterised by multiple generations of laminae, breccias, and pisolites (Machette, 1985). The crusts may have been broken by the penetration of large roots or by erosion (Retallack, 1990). The stage V and VI profiles may take over 100 000 years to form.

Goudie (1983) proposed the *per ascensum* and *per descensum* models to account for the formation of calcic horizons. In the *per ascensum* model, downward moving soil waters penetrate to a certain depth before being drawn back to the surface through capillary action (Goudie, 1983). Upward capillary draw of calcium-rich water from shallow groundwater tables may also occur (Blodgett, 1988). The capillary action results in the deposition of carbonate from the groundwaters due to evaporation (Goudie, 1983; Blodgett, 1988). Calcretes formed by the *per ascensum* model are rare however, as the distance of capillary rise has been calculated as generally less than 1 m (Hubert, 1978).

The *per descensum* model, preferred by most authors (Leeder, 1975; Hubert, 1978; Blodgett, 1988; Joeckel, 1991), involves the downward percolation of carbonate-rich rainwater. The decomposition of organic matter and the respiration of roots results in the generation of carbon dioxide, which, when combined with infiltrating rain or river water, produces carbonic acid. The carbonic acid dissolves carbonate from particles in the upper parts of the soil, resulting in carbonate-enrichment of the downward-percolating waters. A number of factors result in the precipitation of carbonate at depth within the profile. These include changes in permeability, an increase in pH, a decrease in the partial pressure of carbon dioxide, a decrease in temperature, and an increase in ion concentration due to evapotranspiration.

4.5.3 Source of Carbonate

Most authors agree that the major source of carbonate, needed for the development of calcic horizons and calcretes, is aeolian dust, which is generally rich in calcium carbonate (Reeves, 1970; Allen, 1974; Leeder, 1975; Hubert, 1978; Machette, 1985; Francis, 1986; McFadden, 1988; Smith, 1990; Gustavson, 1991). The volume of dust blown over dry floodplains can be substantial and large accumulations of aeolian material would be expected. This is not the case however, and Gile et al. (1966) suggest that dust deposited by one wind storm is blown on by the next. If wetting occurs between dust storms, carbonate in the dust would dissolve and move into the soil, precipitating as illuvial carbonate further down in the profile (Gile et al., 1966). Plants concentrate calcium in their roots and therefore, subsequent decay of plant material results in the concentration of calcium in soil water (Hubert, 1978). River water may contain calcium dissolved from the weathering of igneous and metamorphic rocks (Hubert, 1978). Other sources of calcium carbonate include rainwater and floodwaters containing dissolved Ca^{2+} and surface or near surface water from carbonate rocks (Leeder, 1975; Smith, 1990; Gustavson, 1991). Soil carbonate accumulation rates, and therefore, rates of calcrete development, vary over time in response to geological, geographic and climatic controls (Machette, 1985).

4.5.4 Controls on Calcrete Formation

Calcification of soils is controlled by a number of factors. Leeder (1975) observed that there is an inverse relationship between calcrete profile development and the rate of alluvial accretion. Soil profile development is a function of time and therefore the longer the period between depositional events, the more mature the soil and the better developed the profile.

Leeder (1975) recognised both intra- and extra-basinal factors that affect both local and regional alluvial accretion rates. Intrabasinal variations in accretion rates may be due to flooding, where high rates of accretion occur in the areas near the channel margin, and little to no accretion occurs in the more distal areas of the flood basin (Leeder, 1975). Immature profiles develop close to the channel due to the frequency of accretion. Intrabasinal variations due to channel diversion have also been recorded and include diversion by alluvial and non-alluvial processes (Leeder, 1975). The migration of a meandering stream across the floodplain is an example of channel diversion by alluvial processes where the new channel position results in increased sedimentation rates in some areas and sediment starvation in others, depending on the distance from the channel (Leeder, 1975). Tectonic upwarps or downwarps, or damming of river waters by lavas are examples of diversions caused by non-alluvial processes (Leeder, 1975). Down-faulting along active fault lines initially results in increased sedimentation rates (Leeder, 1975). If lavas dam river waters, the floodplain is starved of sediment and soil development is favoured until the active channel returns (Leeder, 1975).

Extrabasinal variations in accretion rates depend on regional/world-wide base-level changes and regional climatic changes (Leeder, 1975). A fall in sea-level would result in lowering of the base-level and related channel incision due to increased erosion. Resultant alluvial terraces become isolated from alluvial deposition and therefore calcretes could develop (Leeder, 1975). Climate and vegetation are important controls on the sediment yields in drainage basins (Leeder, 1975).

Climatic controls such as rainfall and wind are important to the formation of calcretes. According to Leeder (1975) the translocation of calcium carbonate and subsequent precipitation is determined by the amount of rainfall, rain through-flow amounts excluding sheet flow contribution, and soil moisture evaporation rate. On a local scale, the relationship between relief and climate, that is, temperature, precipitation, and run-off, is very important (Reeves, 1970). In arid areas, the low rainfall and associated lack of infiltrating waters results in the surficial accumulation of carbonate. In areas of high relief and/or high rainfall, the abundant infiltrating water will result in total leaching of calcium and other solubles from the soils (Reeves, 1970; Hubert, 1978). In semi-arid and some arid climates, the moderate to low rainfall results in the limited solution and related rapid deposition of carbonate (Ettensohn et al., 1988). The carbonate is not concentrated at the soil surface, nor is it leached from the profile (Ettensohn et al., 1988). Jenny and Leonard (1934) showed that the depth to carbonate accumulation is directly related to the amount of rainfall, however, in areas with a highly seasonal rainfall, the relationship between rainfall and carbonate accumulation breaks down (Arkley, 1963).

The rate, depth and amount of carbonate accumulation is strongly dependent on the carbonate supply, which is in turn dependent on the influx of dust into the depositional basin and the amount of carbonate present in the dust (Blodgett, 1988; McFadden, 1988). The nature of the parent material is also an important control on calcrete formation. Calcretes tend to form rapidly on relatively impermeable fine-bedded clays (Reeves, 1970). The profiles that develop lack carbonate formation but show the formation of laminated zones (Reeves, 1970). Calcretes developing in more permeable sands commonly show the formation of nodules (Reeves, 1970). Plugged horizons form at a much later stage due to the higher permeability (Reeves, 1970).

All types or stages of carbonate accumulation are not always present as the formation of calcretes depends on the complex interactions between the various factors outlined above. The formation of a calcrete profile cannot be attributed to any single cause. It is generally accepted that calcretes form in well-drained soils in semi-arid to arid climates with a moderate to low seasonal rainfall of between 100 mm and 500 mm (Reeves, 1970; Hubert, 1978; Retallack, 1983b; Machette, 1985; Francis, 1986; Blodgett, 1988; Ettensohn et al., 1988; Gustavson, 1991; Joeckel, 1991).

4.5.5 Kirkwood Formation Calcareous Glaebules and Hardpan Layers

Calcareous nodules of varying morphologies, septaria, crystallaria, hardpan lenses and hardpan layers are found in the mudrock facies of the study area. Nodular, hardpan and rare powder and laminar calcretes also occur.

The most common nodules are small (<5 mm diameter) dispersed white powdery nodules. These occur in many of the horizons and have clear to diffuse contacts. They are thought to represent stage I carbonate accumulation and possibly the beginning of stage II of

Gile et al. (1966) and Machette (1985).

Hard, discrete nodules are relatively abundant in the palaeosols of the lower mudrock sequence but occur less frequently in the other two sequences. They are not present in all of the palaeosols and vary in colour from cream-white to shades of pink, grey, maroon and dark brown. The darker maroon and brown colours are due to impregnation with iron oxide. The nodules are generally spherical although some more irregular ones are present. In places, clumps of three or more coalesced, spherical nodules occur. Horizontally oriented cylindrical nodules, bearing a strong resemblance to burrows, occur in the lower mudrock sequence. Retallack (1991) mentions the presence of log-shaped nodules and attributes their formation to carbonate-rich groundwaters. Their orientation in the horizontal plane may reflect the regional flow of groundwaters (Jacob, 1973). Cylindrical nodules formed by groundwaters generally have straight well-defined edges, are oval in cross-section, and are cemented by calcite. They commonly occur at the upper contact of the more sandy horizons although they may occur within the horizon (Jacob, 1973). It is possible that the cylindroidal nodules in the study area were formed by groundwaters, as they commonly occur in grey-brown sandstone horizons, are oval in cross section, and are cemented by calcite. However, their very sinuous form, and the presence of the proposed low water table in the study area does not really support this mode of formation. The origin of the cylindrical nodules is still uncertain but if they were indeed formed by groundwaters, their presence together with pedogenetic nodules in the same horizon, suggests formation in seasonally dry, shallow, river plain soils (Retallack, 1991).

Some of the more spherical nodules are widely dispersed and occur in association with thin green clay layers. It is possible that desiccation cracks allowed infiltration of carbonate-rich water, promoting the rapid formation of nodules in the immediate vicinity of the cracks. The desiccation cracks are commonly filled with clay and are representative of vertisols (Gustavson, 1991).

In thin section, the nodules show well-developed, undifferentiated crystic plasmic fabric, with the clastic grains floating in a micritic matrix. Some of the skeletal grains are bordered by carbonate crystals slightly coarser than the surrounding cement. The borders are thought to be the result of recrystallisation, possibly related to neomorphism, and are common features in many modern calcretes (Allen, 1974). Corroded skeletal grains are common in the carbonates of the area and some nodules show recrystallisation of micrite to microspar.

Nodules in the upper mudrock sequence are generally septarian (Figure 23) with radiating wedge-shaped cracks which die out towards the margins and other cracks which are crudely concentric with the margins. The nodules are composed of micrite while the cracks are filled with sparry calcite. The septarian nodules are generally dark maroon-grey due to the presence of iron oxides. According to Pettijohn (1975) and Smith (1990), case hardening of the exterior accompanied by chemical dessication of originally gel-like material results in colloidal contraction and the formation of the shrinkage crack pattern. The cracks are later filled with precipitated minerals, producing a network of veins. Septarian nodules are probably formed from lime-rich muds at a sediment-water interface (Smith, 1990). The nodules may have initially formed in stagnant ponds on floodplains but, on exposure to air, they dried out irreversibly with a resultant change in volume and the formation of syneresis cracks (Retallack, 1990).

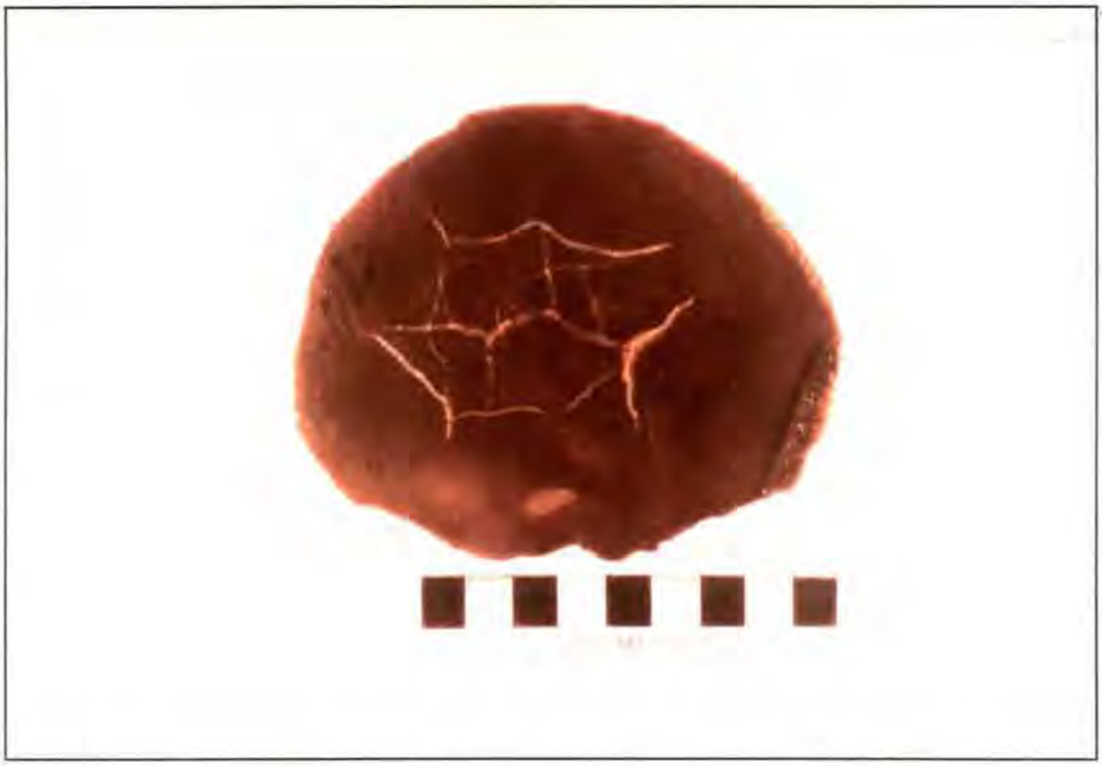


Figure 23. Handspecimen of a septarian nodule showing radiating cracks, which die out towards the nodules margin, and crude concentric cracks.

Crystallaria, which form in voids within a soil, are characterised by crystalline relatively pure minerals and are defined by Brewer (1964, p. 284) as "single crystals, or arrangements of crystals of relatively pure fractions of the plasma that do not enclose the s-matrix of the soil material but form cohesive masses; their morphology (especially shape and internal fabric) is consistent with their formation and present occurrence in original voids in the enclosing soil material". Two types of crystallaria, crystal sheets and crystal chambers, are observed in the mudrock sequences of the study area.

Figure 24. A thin carbonate crystal sheet (cs) from the lower mudrock sequence, Bk horizon, 55.13m from the top of the sequence, Appendices 2 and 3.

Rare crystal sheets of carbonate, formed in planar voids in the soil material, are less than 10 mm thick and may extend laterally in any direction for more than three metres (Figure 24).

The crystals of carbonate are oriented perpendicular to the planar void surface, but do not fill the entire void. The middle of the void is filled with a fine white powdery carbonate (powder calcrete). It is thought that the planar voids were formed due to alternate wetting and drying of the soil.

Crystal chambers are common, especially in the lower mudrock sequence. They are defined as "prolate to equant crystallaria formed in vughs, vesicles, and chambers; they usually show evidence of crystallisation from the walls inward by the preservation of a central void" (Brewer, 1964, p. 288). The crystal chambers observed in the study area are generally spherical and discrete, however, some occur as coalesced clumps. They vary in diameter from a few to a maximum of 100 mm. The crystal chambers can be classified as spherulites as they show the radial arrangement of crystals around a central point and, in thin section, under crossed nicols, they show dark crosses (Figure 25) resembling uniaxial interference figures. Both the above characteristics are typical of spherulites as defined by Pettijohn (1957) and Brewer (1964).

Spherulites show a radial structure whereas rosettes show radial symmetry and are thought to be incomplete spherulites (Pettijohn, 1957). Present in the lower mudrock sequence are rosettes with a morphology (Figure 26) closely resembling that of gypsum desert roses or sand crystals, which are essentially sand-filled calcite crystals (Macfayden, 1950). The rosettes show a symmetrical arrangement of tabular crystal clusters and in thin section, show skeletal grains floating in the carbonate cement with the inclusion of some host soil material. The rosettes do not show the formation of septarian cracks and are therefore not melikaria (weathered septarian nodules of Pettijohn, 1975). Rosettes generally form in warm, moderately saline, clay-rich sediments with concentrations of humic compounds (Cody and Cody, 1988). Sand crystals generally form at the sediment water interface in friable sands (Macfayden, 1950; Pettijohn, 1975). The rosettes in the study area are formed in siltstones and are believed to be calcite pseudomorphs after original gypsum desert roses. They are important indicators of a warm relatively arid climate with low to seasonal rainfall.

Proof that the nodules found in the mudrocks are formed *in situ* as a result of pedogenetic processes includes: the presence of nodules containing more weatherable minerals than the surrounding matrix; the occurrence of crystallaria, which form in pore spaces; and the inclusion of s-matrix in some of the more diffuse nodules. Proof that the nodules have not been inherited with the alluvium includes: the similarity in internal structure

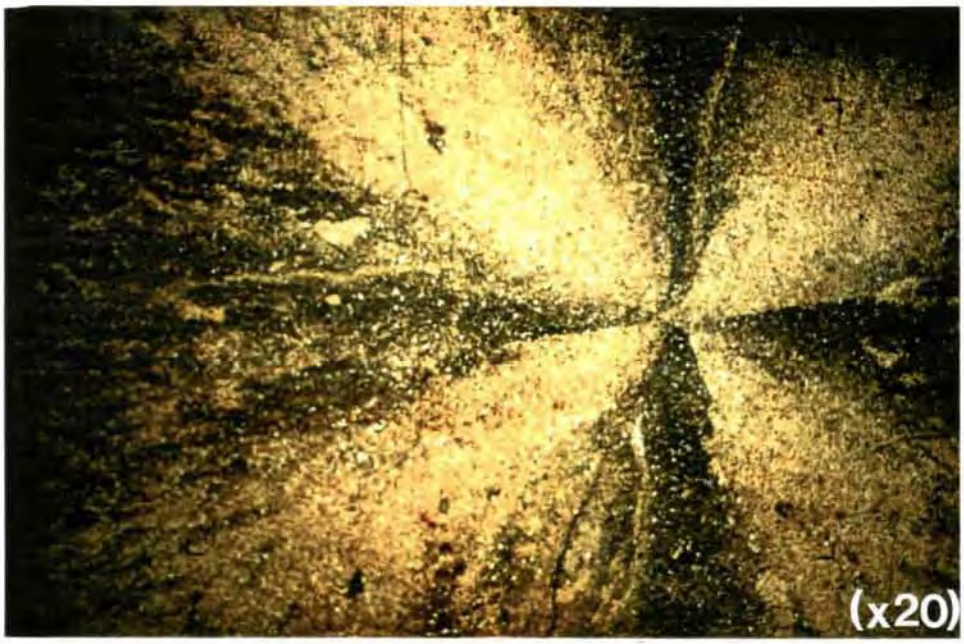


Figure 25. Thin section of a typical spherulite showing the radial arrangement of crystals around a central point and the characteristic dark cross, resembling a uniaxial interference figure.

Figure 26. Handspecimen of a rosette from the lower mudrock sequence, Bc horizon, 39.09m from the top of the sequence, Appendices 2 and 3.

(size and arrangement of internal skeleton grains) between the nodules and the surrounding soil matrix; the lack of carbonate nodule bearing soils and sediments in the source area; and the irregular external morphologies of some of the nodules, which would not occur if they had been transported for some distance. The nodules represent stage II and III carbonate accumulation of Gile et al. (1966) and Machette (1985). The formation of nodules is favoured in well-drained soils with a sufficient supply of carbonate, in warm to hot, semi-arid climates with seasonal rainfall.

Hardpan calcretes in the mudrock facies are generally less than 0.5 m thick. They occur as lenses or as laterally continuous layers with diffuse to gradual lower contacts and abrupt wavy upper contacts. The hardpan layers are generally more resistant to erosion and often stand out as positive weathering features. They are predominantly grey or cream-white, although some are darker pink to maroon and show impregnation by ferric oxides.

The hardpan layers are generally cemented calcic horizons comprising micrite and microspar. Some of the hardpans contain nodules (Figure 27) that have been incorporated during their formation and others include angular clasts of soil material. Because the formation of the hardpan is not displacive, the clasts and nodules were cemented into the horizons *in situ*. Rare hardpan horizons, formed by the cementing together of nodules, are also present. Root traces (crystal tubes) are preserved on the upper surfaces of some of the hardpan horizons (Figure 19), indicating that they were indurated at the time of soil formation. The presence of maroon-brown siltstone-filled root traces and burrows in some of the horizons indicates that cementation also occurred in the later stages of soil formation or by diagenetic processes after burial. In some cases, the hardpan horizons are not fully developed and occur as lenses concentrated at a particular level in the profile. In the areas where there is no hardpan development, rare nodules may be present.

Laminated calcrete is rare but occurs in profiles lacking definite hardpan development. The laminated calcrete comprises thin horizontal to subhorizontal, wavy laminations of cream and white carbonate. Clasts of maroon-brown siltstone and stringers of clay are incorporated into the laminated calcrete.

The hardpan horizons often occur between B and Cr horizons, that is, between the soil material and the parent alluvium. This is thought to indicate a genetic relationship arising from original differences in permeabilities between the developing soil profile and the parent material.

Figure 27. Handspecimen showing nodules incorporated into the base of a hardpan lense (Lower mudrock sequence).

Figure 28. Thin section of a spherical ferric concretion (20x magnification) (sample from the upper mudrock sequence, Btc horizon, 28.53m from the top of the sequence, Appendices 2 and 3).

In thin section, the hardpans and laminar calcretes show the development of crystic plasmic fabric, with the skeletal grains floating in a carbonate matrix. The grains are often corroded and in some cases, totally replaced. Recrystallisation, in the form of coarser borders around some grains, is also observed. The laminar calcretes and some of the hardpans show complex fabrics in thin section, including the presence of microscopic root traces, voids filled with sparry calcite, lamination due to differences in grain size of the micrite, and brecciation of original carbonate material.

The accumulation of carbonate in the mudrock sequences of the study area is an important indicator of the interrelationships between climate (including rainfall), calcium carbonate influx and concentration, nature of the parent material, rates of sedimentation and accretion, and distance of the soil profile from the fluvial channel. The Kirkwood Formation palaeosols that contain carbonate show stage II to III accumulation, with rare possible stage IV accumulation. The interrelationships between the profiles and the environment will be discussed later.

The mudrocks observed in the study area are generally deficient in carbonate, making an external source of carbonate more likely. Aeolian dust was probably the main source of calcium carbonate in the area, with minor contributions from Ca^{2+} dissolved in rainwater. Most of the calcretes in the area have formed above the water table and therefore groundwater calcium carbonate is of little importance. The calcretes generally occur in association with well-drained soils (vertisols, aridisols and alfisols) and are believed to indicate a warm to hot, semi-arid to arid palaeoclimate with a seasonal rainfall of between 100 mm and 500 mm. The water table was generally low as there is very little water table influence in the calcrete profiles.

4.5.6 Ferric concretions and nodules

Rare, spherical ferric concretions and spherical to irregular ferric nodules, often occurring in association with root traces, are present in the mudrock facies. The concretions display concretionary laminae (Figure 28) which are thought to be due to alternate wetting and drying of the soil. This may have occurred in response to a fluctuating water table (Sigleo and Reinhardt, 1988). Iron would have been transported in solution as ferrous hydroxides in the wet seasons and then precipitated as ferric oxides or hydroxides in the dry seasons (Sigleo and Reinhardt, 1988; Joeckel, 1991). Iron oxide nodules are red to orange with rare white haloes and are well-indurated, and spherical to irregular in shape. The nodules are also thought to indicate periodic wetting of the soils. The presence of thin root traces in some of the nodules implies that they were not lithified at the time of soil formation. In thin section the nodules show cementation by hematite, giving them a rich red colour.

The ferric nodules and concretions generally occur in horizons in which there is very little calcium carbonate accumulation. However, calcareous hardpan lenses and layers are often found in apparently the same profiles, but at a lower level in the palaeosol. The presence of both in the same profile seems contradictory as calcareous hardpans are generally formed in well-drained soils and ferric nodules and concretions in periodically waterlogged soils. It is possible that the formation of well-indurated hardpan layers and lenses preceded the formation of the ferric nodules. The hardpans may have acted as impermeable layers so that waters infiltrating the soils in periods of rainfall would dam up against them, resulting in temporary (seasonal) waterlogging of the soils above them and hence the formation of ferric nodules. An alternative interpretation is that the hardpan layers and the ferric nodules actually represent more than one superimposed soil profile but distinguishing them is difficult.

The ferric nodules and concretions indicate a climate with seasonal rainfall, as is indicated by the calcretes. A shallow water table may have existed at times to account for the formation of some of the concretions.

4.5.7 Lithorelicts, pedorelicts and papules

Some glaebules comprise aggregations of clay with sharp boundaries and, in some cases, it is possible to identify their origin. Lithorelicts are fragments of older material, usually claystone, in the parent material whereas pedorelicts are fragments of other soils in the parent material (Retallack, 1990). Both lithorelicts and pedorelicts are inherited pedological features (Brewer, 1964). Clay nodules are formed when pockets of minerals are weathered to clay. If the origin of the clay aggregations cannot be determined, the non-genetic term papule is used to describe the glaebule (Retallack, 1990).

Both lithorelicts and pedorelicts occur in the mudrock facies exposed in the study area. They generally occur as angular clasts of maroon siltstone caught up in the laminated calcrete horizons or as angular to subangular clasts, showing preferred horizontal orientation, in the sandier horizons. It is thought that the sandstones represent crevasse splay deposits and that the lithorelicts and pedorelicts observed represent clasts ripped up by scouring current action. The lithorelicts and pedorelicts appear to originate from older floodplain deposits and palaeosol horizons.

Papules of green clay are common in some of the palaeosol horizons, generally in association with clay-filled desiccation cracks common in the vertisol profiles. The papules have slightly diffuse contacts and in some cases, show associated clay stringers. Neither the significance of the papules, nor their genetic origin is known.

4.6 Desiccation Cracks

Desiccation cracks (mudcracks) and clastic dykes are common in sediments with more than 30% clay content (Birkeland, 1984; Gustavson, 1991; Driese and Foreman, 1992). Clay minerals generally swell on the absorbtion of moisture and shrink and/or crack on the loss of moisture from between their structural layers (Birkeland and Larson, 1989; Gustavson, 1991). When moist claystones and clay-rich siltstones are exposed to the atmosphere, they dry out and decrease in volume due to the loss of water from the clay minerals (Leeder, 1982; Hunt, 1972; Mack et al., 1993). This results in the formation of open, downward-tapering desiccation cracks, which vary in width and depth, depending on the depth of the desiccated layer (Pettijohn, 1975; Leeder, 1982; Birkeland, 1984). The cracks, which show a polygonal surface pattern, may be fairly wide during the dry season and may become filled with clay, silt or sand from aeolian or alluvial processes, or with material from overlying sand or siltstone horizons (Pettijohn, 1975; Birkeland, 1984; Gustavson, 1991; Driese and Foreman, 1992; Joeckel, 1994). Brecciated blocks of material from the side walls of the cracks may be incorporated in the dyke-fill material (Gray and Nickelson, 1989). Rejuvenation structures may result from repeated cycles of wetting and drying, with the cracks reappearing in approximately the same places (Joeckel, 1991).

Desiccation cracks are therefore classified as shrink-swell features which typically occur in clay-rich soils. Well-developed cracks reflect numerous episodes of shrinking and swelling due to wetting (flooding and/or rainfall) and drying (desiccation). They may reflect exposure of previously wet or waterlogged soils or subaerial drying of floodplain muds (Pettijohn, 1975). The degree of development depends on the clay content and mineralogy of the sediment and\or soil, the palaeoclimate, the duration of surface exposure, the frequency of flooding or rainfall, and the degree of desiccation (Gustavson, 1991).

Most authors (Vanstone, 1991; Gustavson, 1991; Joeckel, 1991, 1994; Driese and Foreman, 1992) agree that desiccation cracks and related structures, such as slickensides, are formed in a seasonal, semi-arid to dry subhumid climate with four to eight dry months, where the expansion and contraction of clays in response to wetting (rainfall/flooding) and drying is common.

The desiccation cracks\mudcracks in the study area have been preserved by clay-infilling. They are generally less than 25 mm in width and taper downwards. The cracks are called dykes due to their sheet-like nature and vertical orientation, and generally comprise green, green-grey and green-grey-blue clay. Thin clay veins often occur in association with the dykes and angular clasts of brecciated host material are common within the dyke material. The dykes vary in length, follow a slightly irregular path downwards, and cut through more than one horizon in places. Slickensided Bt horizons often form the host rocks and together with the presence of carbonate nodules, are typical of vertisols (see section 5.2.6). The dykes were formed in clayey siltstones in a semi-arid climate with a seasonal rainfall.

4.7 Slickensides

Slickensides are well known tectonic structures from faulted and deformed terrains where they occur as unidirectional grooves related to tectonic features. However, they also form in soils as clays expand and swell when they absorb water. The confined subsurface environment prevents uniform water absorbtion and clay expansion, with swelling pressures exceeding soil shear strength due to vertical and lateral movement (Gustavson, 1991). Small faults and fractures develop due to failure by shearing (Gustavson, 1991) and concave up, dish-shaped structures form from the intersection of sets and series of subparallel fracture planes (Brewer, 1964; Kraus and Aslan, 1993). With repeated wetting and drying, peds of soil are heaved past each other resulting in modification of the planes (Retallack, 1990) and alignment of clays in the soil and on the planes (Gray and Nickelsen, 1989; Kraus and Aslan, 1993). The resultant smeared, grooved and striated clay lines are termed slickensides or stress cutans (Retallack, 1990; Smith, 1990; Gustavson, 1991; Kraus and Aslan, 1993). In thin section, strongly oriented conjugate sets of clay stringers at 90° to each other (lattisepic fabric) are interpreted to be the microscopic expressions of slickensides (Retallack, 1990;

Kraus and Aslan, 1993). The formation of slickensides in soils can take between 5 and 200 years (Gustavson, 1991) and is aided by high clay content, homogeneity of material, calcium saturation, and uniform regular drying (Brewer, 1964).

Slickensides are also known to form when peds are crushed together during the burial of soils (Retallack, 1983b, 1988, 1990), and the only way to be sure that they are of true pedogenic origin, is to look for other pedological indicators such as peds, cutans, clastic dykes, root traces and burrows, calcrete horizons, and translocated clays (Gray and Nickelsen, 1989).

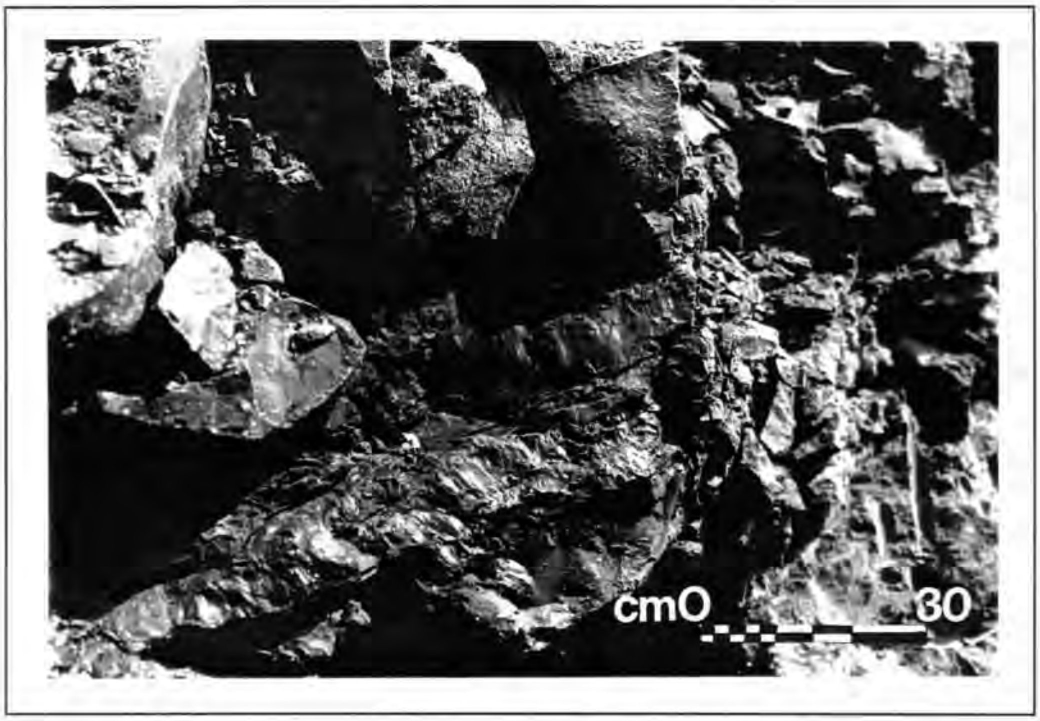


Figure 29. Large slickensides (stress argillans) are observed on ped surfaces (Lower mudrock sequence, Bt horizon, 51.05m from the top of the sequence, Appendices 2 and 3).

Abundant slickensided horizons occur in the mudrock sequences of the study area (Figure 29). The macroscopic slickensides show random orientation and are concentrated in definite, generally clay-rich maroon-brown siltstone or claystone horizons, and to a lesser extent, in some of the green-grey siltstone and/or claystone horizons. The slickensides observed in the study area generally occur as shiny, grooved clay lines, although some have only a dull sheen. They show random orientation and are restricted to specific horizons in apparently undeformed rocks, indicating that they are not of tectonic origin. That they are of pedogenic origin is indicated by their common association with horizons containing root traces and burrows, clastic dykes, calcrete horizons, and peds and cutans.

The Kirkwood Formation slickensides are interpreted to have formed by repeated shrinking and swelling of clays in response to numerous wet and dry cycles.

4.8 Soil Structure

Soil structure forms on alluvium as bedding structures and bedding planes are destroyed by pedogenetic processes (Retallack, 1990). Relict sedimentary structures may be preserved in some palaeosols and their presence reflects the degree of soil formation. Brewer (1964, p. 132) defines soil structure as "the physical constitution of a soil material as expressed by the size, shape, and arrangement of the soil particles and voids, including both the primary particles to form compound particles and the compound particles themselves; fabric is the element of structure that deals with arrangement". Soil structures are important in the interpretation of palaeosols as they reflect former drainage conditions and chemical behaviour (Retallack, 1988).

Soils generally appear hackly due to the presence of networks of irregular planes separating aggregates of soil, termed peds. Peds are formed by the break up of alluvium by root penetration, burrowing, alternate wetting and drying, and other pedogenetic processes (Retallack, 1988; 1990). A ped is defined as "an individual natural soil aggregate consisting of a cluster of primary particles, and separated from adjoining peds by surfaces of weakness which are recognisable as natural voids or by the occurrence of cutans" (Brewer, 1964, p. 138). Peds may be difficult to recognise if the palaeosols have undergone compaction and alteration after burial, and often they can only be recognised by the identification of cutans (Retallack, 1988; 1990). Peds are classified according to their size, angularity and shape (Table 4). Pedal soils, those in which peds are developed, may show further levels of development due to the occurrence of peds and interpedal features (Brewer, 1964). Primary peds are "the simplest peds occurring in the soil material; they cannot be divided into smaller peds, but they may be packed together to form compound peds of a higher level of organisation" (Brewer, 1964, p. 150). Secondary peds are aggregates of smaller primary peds and include the size, shape and arrangement of primary peds, their interpedal voids, and associated interpedal pedological features. Some soils may lack peds and are termed apedal.

Cutans are important pedological features in palaeosols as they can be used to distinguish peds in compacted and altered soils. Brewer (1964, p. 206) defined a cutan as a "modification of the texture, structure, or fabric at natural surfaces in soil materials due to concentration of particular soil constituents or *in situ* modification of the plasma; cutans can be composed of any of the component substances of the soil material". Cutans of varying composition occur and Brewer (1964) classified cutans according to the chief constituent present. Types of cutans include: argillans (clay skins); ferrans (iron stained surfaces); skeletans (veins of skeleton grains (clastic dykes)); sesquans (oxides of iron and aluminium); mangans (oxides and oxyhydrates of iron and manganese); soluans (soluble salts such as gypsum); calcans (calcite); silans (silica in the form of opal or chalcedony); and organans (organic matter) (Brewer, 1964; Retallack, 1990). Cutans can also be classified on the basis of their processes of origin (formation). Four major groups of cutans have been identified. (a) Illuviation cutans are formed by the washing down of cutanic material, in suspension or solution, into cracks and its subsequent deposition (Brewer, 1964, p.224; Retallack, 1990, p. 44). (b) Diffusion cutans form by the progressive alteration of a ped surface from the outside inwards, and therefore generally consist of altered ped material (Retallack, 1990, p. 44). The outermost boundary is sharp, whereas the inner boundary with the unaltered soil material is gradational (Retallack, 1990). (c) Stress cutans are formed *in situ* by the modification of soil material due to differential shear forces within the soil (Brewer, 1964; Retallack, 1990) and are commonly recognised by the presence of slickensides. (d) Complex cutans are formed by a combination of one or more of the above (Brewer, 1994). Other soil structures include glaebules (See section 4.5).

Peds are observed in the study area and show a considerable range in type. Some of the palaeosols are apparently apedal, with no evidence of cutan formation. Rare cutans present in apedal soils are irregular and do not define any ped types. If peds were present in the "apedal" soils at the time of formation, they have since been destroyed by subsequent burial and alteration. Argillans and peds are generally distinguishable in the B horizons of the mudrock facies where there is an illuvial accumulation of clay from leached A horizons.

Cutans are important in the recognition of peds and secondary peds in the mudrock sequences of the study area. Illuviation cutans are most common and are indicative of well-drained soils. The cutans are generally maroon-brown and red-brown due to the presence of sesquioxides, indicating the formation of the horizons above the water table in oxidised soils. Stress cutans are common in the more clayey Bt horizons and generally define angular to subangular blocky peds. They are formed by the shrinking and swelling of clays in response to seasonal wetting and drying, and therefore may be important reflections of frequency of rainfall. Mangans and sesquans are observed in some horizons, and rare calcans occur in carbonate rich horizons.

Jointing, which developed during burial of the palaeosols, is common throughout the mudrock facies and often masks the actual soil structures. Skeletans are often present between the joint planes and are thought to be related to post-burial processes and alteration (eogenesis). Clay dykes (skeletans) are present in some of the horizons and will be discussed later.

The identification of peds and cutans in the area is important in the final interpretation of the palaeoenvironment as the types present reflect conditions in the palaeosols at the time of formation, that is, wetting and drying cycles, water table levels, and movement of cutanic material within the soils (drainage). The types of peds and cutans preserved in the mudrock facies of the area reflect well-drained, oxidised soils, with generally low water tables, forming in possible semi-arid climates with seasonal rainfall.

4.9 Fossils

Fossil material is rare in the mudrock facies. In the lowest mudrock sequence, approximately 51.42 m from the top of the profile, numerous small bone fragments occur in a maroon-brown and grey sandstone horizon. They are generally concentrated in a 40-75mm thick band just above the lower contact, range in size from a few millimetres to 30mm and show no particular orientation. In the middle mudrock sequence, approximately 11.94 m from the top, 100 bone fragments of various sizes were found in the gully wash. Two slightly larger platy bones were found *in situ* and it is believed that the rest of the bone originated from the same horizon. The bone fragments were taken to the Albany Museum, Grahamstown (accession number AM4930). Some of the pieces were glued together to form relatively large pieces of platy bone up to 0.43 m in the longest dimension. They appear to be from the pelvic region of a stegosaurian dinosaur, possibly *Paranthodon africanus (Broom)* (de Klerk[1], *pers. comm)*. It is thought that this site is the same as or close to the site found by Atherstone and Bain in 1845, and later by Schwarz in 1913. The more platy

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[1] Billy de Klerk, Albany Museum, Grahamstown, South Africa.

bones show better preservation than the rounded bones. Rare organic plant fragments were also found.

Recently, bone fragments, including two small crocodile jaws, a fish spine, and numerous theropod and sauropod teeth (AM 4936 A, B, C), were found in related Kirkwood Formation mudrock sequences exposed in the Shamwari Game Reserve, approximately 15km to the west of the study area (Ross et al., 1995). The Shamwari mudrocks are stratigraphically higher than those exposed in the study area. Palaeosols, similar to those observed in the study area, have been recognised in the Shamwari mudrocks and include entisols, inceptisols, alfisols, ultisols, vertisols and aridisols (Machin, 1994).

Figure 32. In situ bone fragments (accession number AM4930) from the middle mudrock sequence, Bkc horizon, 11.94m from the top of the sequence, Appendices 2 and 3).

CHAPTER 5
PALAEOSOL CLASSIFICATION

5.1 Introduction

Palaeosols can be interpreted and classified by comparing features observed in them with similar features in modern soils (Retallack, 1990). At present, there is still no universally accepted soil classification scheme but many of the classification schemes in current use have some features in common (Birkeland, 1984). Although South Africa has its own soil classification, it was not used for the classification of the Kirkwood palaeosols as it is not universally known, nor is it easily applied to older soils.

There are three schemes commonly used in the classification of modern soils and palaeosols (Retallack, 1990). They are: 1) The Handbook of Australian soils, prepared by the Commonwealth Scientific and Industrial Organisation (CSIRO) of Australia (Stace et. al., 1968), which is based on stable mid-continental soils of the mid-latitudes; 2) The Soil Map of the Food and Agricultural Organisation (FAO 1971-1981), prepared by the United Nations Economic and Scientific Organisation (UNESCO), which is based on soils of tropical regions; and 3) The US Soil Taxonomy, prepared by the Soil Conservation Service (Soil Survey Staff, 1975) of the United States Department of Agriculture (USDA), which is based on soils of temperate climates in tectonically active, volcanic and glaciated terrains (Retallack, 1990). Each of these classifications seems to have limited use.

The FAO classification is a hierarchial system requiring a series of decisions and is a "hybrid of traditional classifications like that of the Australian handbook and of more recent classifications such as that of the US Soil Taxonomy" (Retallack, 1990, p. 97). It is not commonly used outside of the agricultural industry, although a few scientists have used it for the classification of palaeosols. The Handbook of Australian soils is more useful as each name represents an independent soil, with each soil type based on actual field examples (Retallack, 1990). Although widely recognised and used for palaeosol interpretation, the classification does not include soils found in alpine, tectonically active or arctic environments. Another drawback of the system is that when new soil-types, differing from those in the classification, are found, they are "added to the existing list rather than interpolated between existing categories, as in other classification schemes" (Retallack, 1990, p. 92).

The USDA Soil Taxonomy is by far the most commonly used in the classification of palaeosols, possibly because most of the work done on palaeosols is based in the United States. The soil taxonomy has a hierarchial structure with 10 orders subdivided into 47 suborders which are further subdivided into groups, then subgroups, then families, and finally into soil series.

The classification of soils at the highest level is very general with only 10 orders (Figure 31, Table 10), which are based on horizons or horizon combinations found within the soil profiles (Birkeland, 1984). At the lowest levels of classification, there are many series because of the restrictions emplaced by the limiting diagnostic properties (Birkeland, 1984). The classification is easily applied to Quaternary soils and even to older palaeosols which have not undergone diagenesis or alteration due to burial. However, complications occur when one has cumulative soil profiles, polygenetic profiles, top-truncation of the soil profiles, and diagenetic and burial alteration (Mack et. al., 1993). An important criticism of the classification is the excessive use of terminology which does not aid in the understanding or communication of the subject as few understand it (Hunt, 1972). Another criticism is that in order to classify the soil, particularly at the suborder level and below, it is necessary to know the soil properties and the soil moisture and temperature regimes (Mack et. al., 1993). These can rarely be determined in palaeosols and therefore the detailed classification of palaeosols is difficult to do without making gross assumptions. Mack et. al. (1993) have proposed a simpler classification scheme in which there are only 9 orders. It is easily applied to palaeosols which have been subjected to diagenetic and burial alteration but has not been formally accepted as a classification scheme.

The Kirkwood Formation palaeosols found in the study area have been classified at order level, the highest classification level (Figure 31, Table 10), of the USDA Soil Taxonomy (Soil Survey Staff, 1975), however, reference is made to Mack et al.'s (1993) classification where possible. It is not possible to classify the palaeosols at lower levels in the Soil Taxonomy (Soil Survey Staff, 1975) without making assumptions and using terminology understood only by soil scientists.

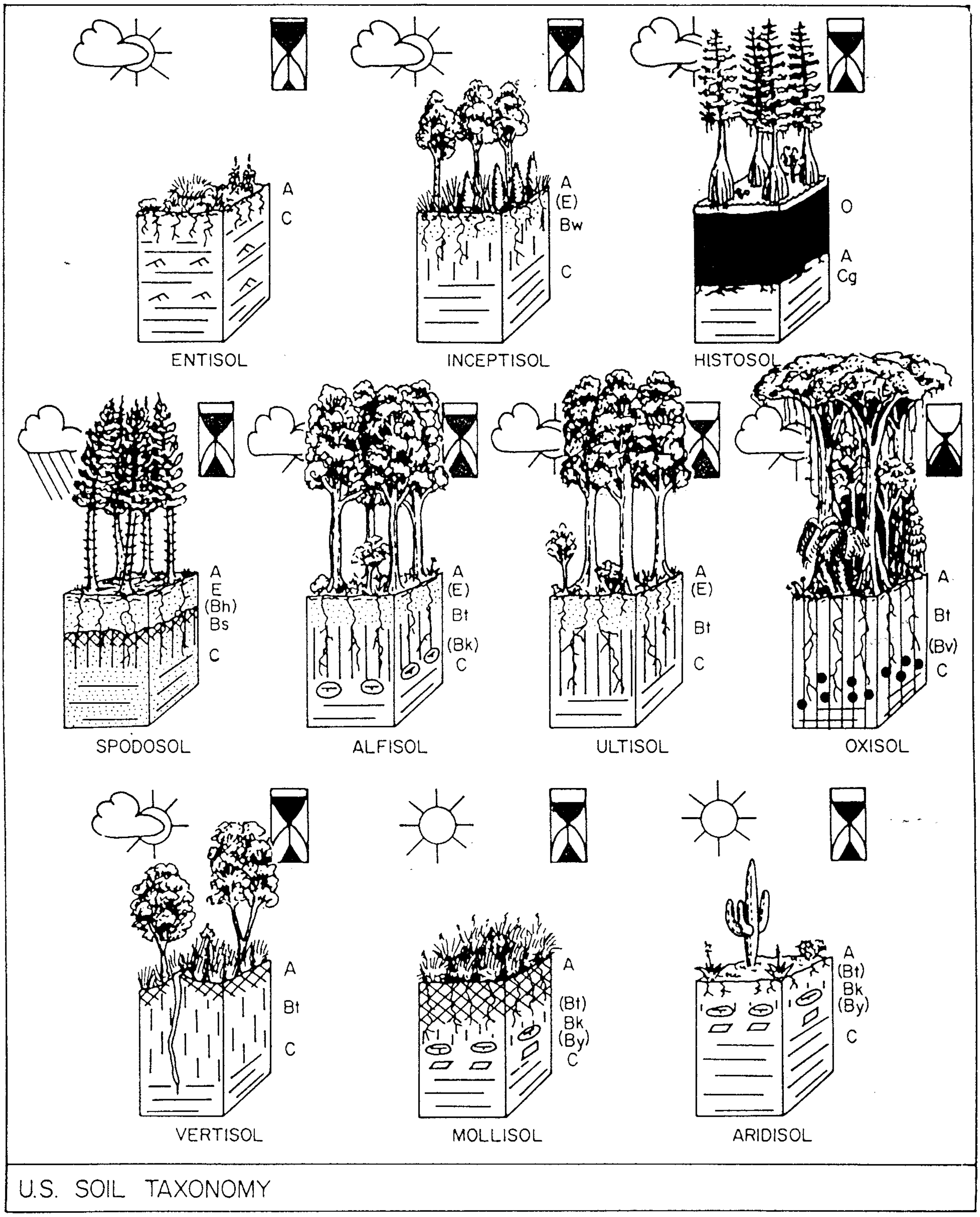

Figure 31. Cartoons of climate, vegetation and profile from the various orders of soils defined by the US soil taxonomy (based on data from Soil Survey Staff, 1975). (From Retallack, 1990, p. 102).

Table 10. New U.S. Soil Classification scheme (modified from Birkeland and Larson, 1989, p. 303).

Order	Generalised properties
Entisol	Minimal development, an A horizon may be present
Inceptisol	Weak development, with an A horizon, a B horizon that lacks clay enrichment, with or without a Bk horizon
Mollisol	Thick, dark A horizon, high in organic matter, a B horizon that may or may not be clay enriched, with or without a Bk horizon
Alfisol	Relatively thin A horizon overlying a clay-enriched B horizon, with an E horizon separating the A and B layers in places
Spodosol	Highly organic surface horizon above an E horizon that in turn, rests on an iron-enriched B horizon
Ultisol	A horizon over highly weathered B horizon
Oxisol	A horizon over an extremely weathered B horizon
Aridisol	Thin A horizon above a relatively thin B horizon, some are clay enriched, with a Bk or K horizon at depth
Histosol	Peaty soil
Vertisol	Very high content of clays; shrinks and swells with seasonal moisture variation

5.2 Palaeosols of the Kirkwood Formation

Only six of the ten soil orders of the USDA Soil Taxonomy have been identified in the palaeosols of the study area. These include entisols, inceptisols, ultisols, alfisols, vertisols and aridisols (Figure 31). Figure 32 is a key to all symbols used in the logs of the type sections (also applicable to logs of mudrock sections in Appendix 3).

Some pedogenetic features commonly occur in most or all of the palaeosol profiles. These include the types of burrows present, the source areas for the sediments, and the origin of carbonate found in the sediments.

Most of the burrows (pedotubules) found in the mudrocks exposed in the study area are vertically to subvertically oriented and are interpreted as being the burrows of small invertebrates, possibly arthropods. It is unlikely that the isotubules (burrows) were formed by vertebrates as most are too small, having average diameters less than 10mm.

As far as the source of alluvium is concerned, thin section compositional, roundness

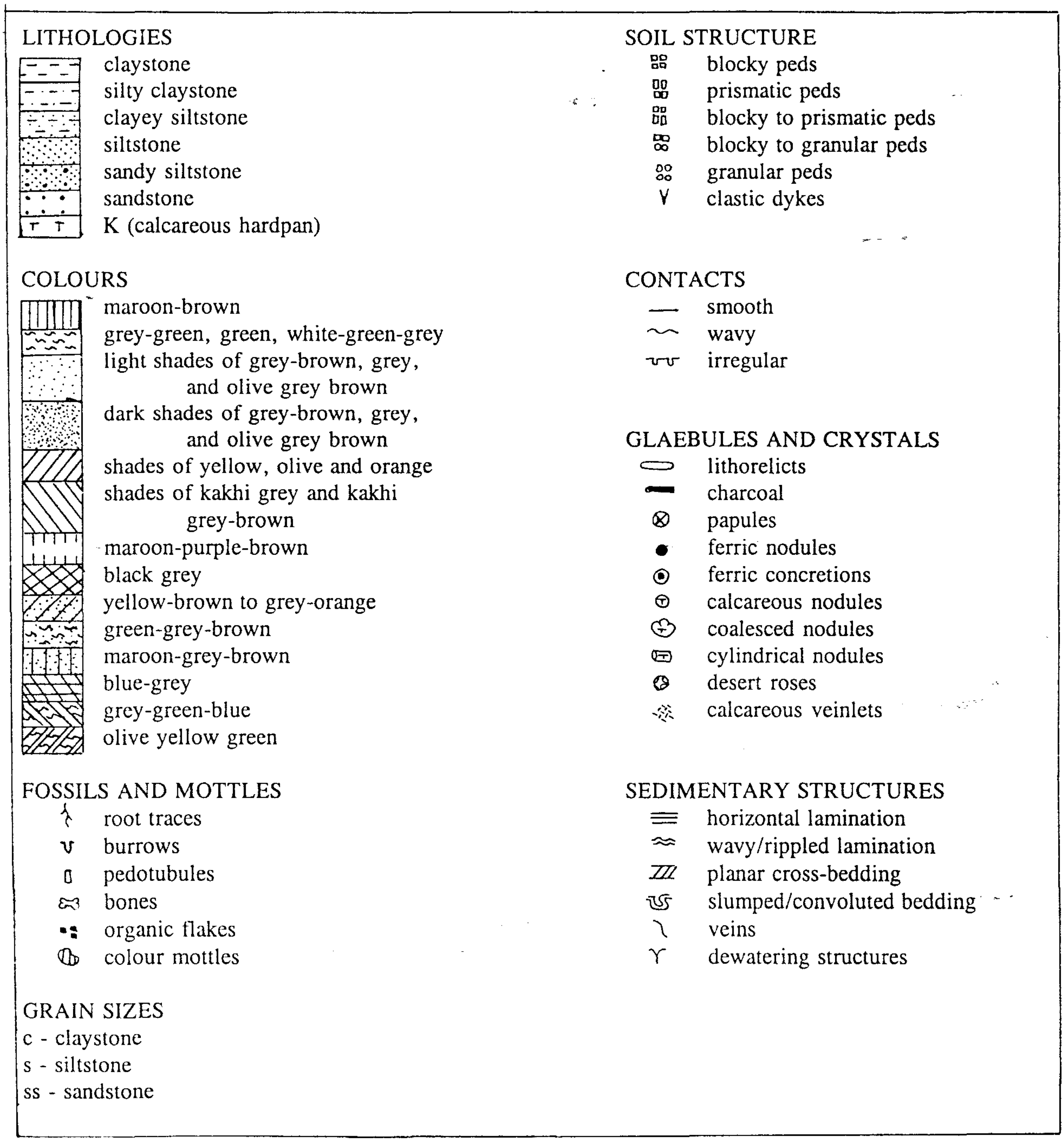

Figure 32. Key to the following palaeosol type sections

and sphericity studies indicate a distal source for the detrital grains. However, the presence of possible lithorelicts and pedorelicts in the laminated horizons indicates that some of the alluvium was eroded from older soils and sediments within the depositional basin.

The presence of calcic and petrocalcic horizons, particularly in the lower mudrock sequence, indicates that there was a fairly substantial supply of carbonate to the sediments. As there are no carbonate-rich source rocks, the carbonate in the inceptisols is thought to originate from external sources such as solid carbonate in aerosolic dust, silt and sand and from Ca^{2+} dissolved in rainwater.

5.2.1 Entisols

Definition. Entisols are very immature palaeosols showing little evidence of soil horizonation (Hunt, 1972; Birkeland, 1974, 1984; Wright, 1986; Retallack, 1990). The A horizon is poorly developed with little alteration of the parent material and the presence of root traces and burrows may be the only diagnostic pedogenetic features (Birkeland, 1974; Birkeland and Larson, 1989; Retallack, 1990). There may also be evidence of initial clay accumulation, as well as carbonate-enrichment at depth. Some of the root traces are preserved by calcareous white powder, some by clay infilling and some as crystal tubes (Retallack, 1990; Hanneman et al., 1994).

Entisols are similar to inceptisols but rarely show the development of B horizons, with no clay accumulation observed. The lack of a B horizon was used to distinguish between entisols and inceptisols in the study area.

Diagnosis. Relatively thick, weakly developed palaeosol with slightly bleached A horizon and C horizons showing the preservation of relict sedimentary structures. Some pedogenetic features such as burrows, root traces and dispersed white powdery carbonate nodules are present.

Type example. The type entisol (Figure 33) is from the middle mudrock sequence exposed in the study area with the top of the palaeosol 31.38 m from the top of the sequence (Appendices 1 and 2).

Note: *In this description and in ensuing descriptions, the first number of each paragraph is the depth from the top of the palaeosol to the top of the described horizon, and the letters are its interpretation as a soil horizon. Unless otherwise stated, the grain size of the mottles and pedotubules is the same as that of the soil matrix, and the nodules, concretions and hardpan lenses are very strongly calcareous. Horizons marked with * have been combined with the horizon immediately below them on the logs (Appendices 1 and 2) as they are too thin to represent separately.*

+0.09 m; cover (Cr horizon of overlying palaeosol); fine-grained sandstone; dark maroon-brown, light maroon-pink and grey-pink in different layers, weathering light maroon; very weakly calcareous; few to common distinct, medium maroon-red clay-filled root traces lined with green argillans, are randomly oriented; relict laminations are planar, parallel and laterally continuous; clear wavy contact to

0 m; A; very fine-grained sandstone; grey-green, weathering grey; calcareous in patches; few to common distinct, medium red-brown clay-filled root traces lined with green argillans and showing thin white haloes (<3mm thick), are randomly oriented and branch outwards; common distinct, fine to medium, white calcareous para-isotubules (after roots) lined with green argillans and showing diffuse white haloes, are randomly oriented and branch downwards; dispersed white powdery carbonate nodules occur; smooth gradual contact to

-0.17 m; Cr; very fine-grained sandstone; dark and light maroon in different layers, weathering maroon-grey; non-calcareous; few to common distinct, medium very dark maroon-brown clay-filled root traces with rust orange brown haloes (<4mm thick), are vertically oriented; many distinct, fine to medium, green clay-filled root traces are vertically oriented and branch outwards, forming dense networks; faint relict laminations are parallel, continuous and discontinuous or lens-like, and rippled to irregular; discontinuous blue black mangans occur on some ped surfaces; discontinuous maroon-brown illuviation argillans outline irregular areas; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-0.46 m; Cr; very fine-grained sandstone; dark grey-green and dark maroon-brown in different layers, weathering light grey-green; non-calcareous; common distinct, medium green clay-filled root traces are vertically to subvertically oriented and branch downwards; parallel, continuous coarsening-upward relict laminations are generally planar or rippled but are irregular where disturbed by root traces; blue-black mangans occur on some ped surfaces; blocky peds show red-brown illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; gradual to abrupt irregular intertongued contact to

-0.83 m; Cr; very fine-grained sandstone; light maroon-pink, dark maroon, and grey in different layers, weathering grey-pink; non-calcareous; common distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; relict laminations are parallel and both planar and rippled; black mangans occur on some ped surfaces; towards the upper contact, angular blocky peds show red-brown illuviation argillans; clear abrupt contact to

-1.75m; underlying palaeosol (Bt horizon of underlying palaeosol); clayey siltstone; dark maroon, weathering light maroon-pink; non-calcareous; few distinct, fine to medium, green clay-filled root traces are vertically oriented; blue-black mangans occur on some ped surfaces; subangular blocky peds show dark maroon illuviation and stress argillans; dispersed white powdery carbonate nodules occur.

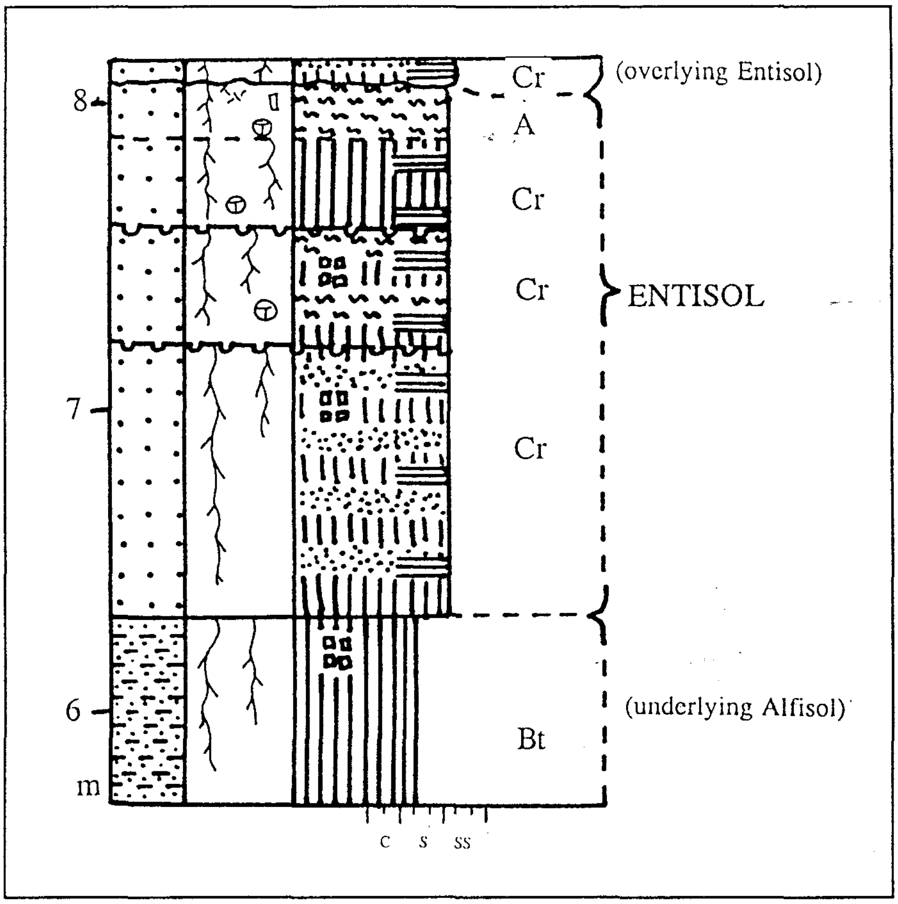

Figure 33. Schematic diagram of the type Entisol (below 8.06m) from the middle mudrock sequence.

The palaeosol is very weakly developed with little evidence of pedogenesis. Soil structures, such as angular blocky to blocky peds, are poorly developed. Thin beds and laminations are well-preserved and show little alteration due to pedogenetic processes. Very little organic matter is present and although root traces, sometimes showing the development of diffuse bleached haloes (drab haloes), cut through both the A and Cr horizons, the grain-size changes within the profile and the preservation of relict sedimentary structures indicate a relatively short period of formation. The presence of an entisol does however, indicate an hiatus of a few years between depositional events.

Further examples. Entisols occur in all three mudrock sequences (Appendices 1 and 2). Some display features not observed in the type example. These include: flakes of black organic material; mottles of varying colour and grain size; tubules of varying grain-size and orientation; calcans, cutans and argillans; and hardpan lenses and calcareous nodules. Many of the features listed above hint at more mature soil profiles. However, the presence of clear laminations and beds suggests that there has been very little soil formation. It is possible that the entisols have inherited features from older, more mature palaeosols on which they have been superimposed.

As a river channel migrated across its floodplain, the soil profiles developing in the more distal regions became more proximal and more prone to frequent flooding and higher rates of sedimentation. In some cases the A, and possibly part of the B horizon, of the more mature profiles may have been eroded and then redeposited by floodwaters.

Because of the closer proximity to the stream channel, periodic flooding resulted in the soils receiving small increments of sediment (parent material), including eroded soil material, while pedogenesis was occurring. The periodic addition of material resulted in cumulative soil profiles developing. These cumulative soils are characterised by both sedimentary and pedogenetic features, as observed in many of the entisols preserved in the study area. Relict features from the more mature profiles may also be preserved within the more immature entisol profile.

Parent material. Some of the entisols found in the study area developed on fine-grained sandy alluvium in close proximity to a stream. Others developed on more distal, finer-grained sediments (siltstones). The latter show slightly better horizonation and the effects of pedogenesis are more apparent, though still vague. It is possible that flood waters frequently reached the more distal parts of the floodplain resulting in the deposition of thin increments of fine-grained sediment. The period between flood events was too short to allow more mature profiles to develop.

Palaeotopography. The entisols generally formed in close proximity to the stream channels and probably formed on crevasse splays and dry floodplains flanking the streams. Some of the root traces are surrounded by drab haloes, indicating waterlogging. The drab haloes may confirm proximity of the developing profile to the stream. It is possible that the soils formed in interstream waterlogged depressions, some distance from the stream.

Fossil Flora and Fauna. The entisols characteristically show fine to medium root traces but lack larger examples. The root structures are thought to represent pioneer vegetation, including shrubs and maybe even small trees.

No bones were found in the entisols preserved in the study area. This may be because the soils were exposed to frequent flooding and erosion, forming over a relatively short period of time. Any bone present would have been removed by flood waters. It is also possible that the waters were slightly acidic, making bone preservation unlikely.

The infilled isotubules present probably represent burrows of small invertebrates, possibly arthropods. It is unlikely that the isotubules (burrows) were formed by vertebrates as most are small, with average diameters less than 10mm.

Classification. In the U.S.D.A. classification (Soil Survey Staff, 1975) these palaeosols would be classified as entisols or alluvial soils. Modern soils of this kind are found in close proximity to lakes and rivers. They commonly occur on the first terrace above the stream (if present) or on the levee banks and crevasse splay deposits. Because they represent such a short period of formation, they cannot be used to define a particular vegetation type, nor can they be used as a climatic indicator. They are useful when attempting to determine rates of deposition and frequency of flooding. Thick deposits of laminated sediments showing slight pedogenesis may indicate frequent/periodic flooding over an extended period of time. Between periods of flooding, the entisol profiles form and record at least a few years of pedogenesis. This results in the formation of cumulative soils.

Mack et al. (1993) preferred to use the term PROTOSOL, defined to cover the characteristics of both entisols and inceptisols, as it is often difficult to distinguish between the two in modern and fossil soils. PROTOSOLS are characterised by very weak soil horizon development.

5.2.2 Inceptisols

Definition. Inceptisols, which are slightly better developed than entisols, are young immature soils showing some horizon development (Hunt, 1972; Birkeland, 1984; Wright, 1986; Retallack, 1990). They are commonly found in alkaline sandy and silty soils, between entisols, which develop close to a stream channel, and the more mature soil profiles developing at some distance from the channel. Root traces and burrows are commonly observed, and organic material is present in some of the horizons.

The pedogenetic horizonation of the soil is mainly due to alteration of the parent material, however, there may also be evidence of leaching, limited mineral alteration, and deposition and accumulation in the subsurface horizons (Hunt, 1972; Birkeland, 1984; Wright, 1986; Retallack, 1990). Inceptisols are generally characterised by a "light-coloured surface horizon (ochric epipedon) over a moderately weathered subsurface horizon (cambic horizon)" (Retallack, 1990, p. 108). Yellow, grey or brown inceptisols, which generally develop in alluvium, show good bone preservation and are often calcareous, with a calcic horizon developed close to the surface (Retallack, 1990). Clay accumulation may occur in the B horizon but is insufficient to warrant classifying the horizon as an argillic (Bt) horizon (Retallack, 1990). Unlike the case in entisols, relict sedimentary features, such as laminations and beds, show varying degrees of preservation and may be difficult to determine in inceptisols (Retallack, 1990).

Diagnosis. Relatively thin, moderately developed maroon- to grey-brown palaeosol which lacks an A horizon. The B horizon shows slight clay-enrichment towards the top contact and relict sedimentary structures and a calcic horizon towards the basal contact. The C and R horizons show well-preserved sedimentary structures. Pedogenetic features such as root traces and pedotubules (burrows) are concentrated towards the top of the profile; colour mottles occur in the BC and C horizons; and cutans (argillans and skeletans) are present throughout the profile.

Type example. The type inceptisol (Figure 34) is from the lower mudrock sequence exposed in the study area with the top of the inceptisol 12.61m below the top of the sequence (Appendices 1 and 2).

+0.18 m; cover (Cr horizon of overlying palaeosol); siltstone; dark maroon-brown and dark grey maroon-brown in different layers, weathering maroon; non-calcareous; relict laminations are continuous, parallel and planar; apedal, but discontinuous red-brown shiny illuviation argillans outline irregular areas; abrupt wavy contact to

-0 m; Bw; clayey siltstone; dark maroon, weathering maroon; non-calcareous; common distinct, medium grey-green clay-filled root traces are vertically oriented; blocky peds show poorly developed calci-argillans; abrupt irregular contact to

-0.29 m; B*; very fine-grained sandstone; grey-brown, weathering cream-brown; very weakly calcareous; many distinct, medium to coarse, dark maroon-brown meta-isotubules (after burrows?) are vertically to subvertically oriented; abrupt irregular contact to

-0.36 m; Br; clayey siltstone; maroon-brown and dark grey-brown in different layers, weathering maroon; very weakly calcareous to calcareous in patches; common distinct, fine to medium, very dark maroon-brown meta-isotubules vary in orientation; few distinct, fine to medium, sandy brown-grey fine-grained sandstone metagranotubules (after burrows) are vertically to subvertically oriented; planar relict laminations are faint and are disrupted by the pedotubules; abrupt, very irregular contact to

-0.41 m; Bk; medium-grained sandstone; dark brown-grey to olive-grey, weathering white-grey; very weakly calcareous to calcareous; few distinct, medium dark maroon meta-isotubules, concentrated towards the upper contact, are vertically to subvertically oriented; red-brown very fine-grained sandstone skeletans occur between some joint planes; abrupt very irregular contact to

-0.54 m; BC*; clayey siltstone; dark maroon-brown, weathering cream grey-brown; very weakly calcareous; massive; abrupt irregular contact to

-0.58 m; BC; fine-grained sandstone; light grey-brown with green tint, weathering cream brown-grey; calcareous; few to common, faint to distinct, maroon-brown mottles vary in shape; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-0.64 m; Cr; siltstone and very fine-grained sandstone; dark maroon-brown, and light and dark grey-brown in different layers, weathering maroon; non-calcareous; few to common distinct, fine to medium, dark maroon-brown siltstone mottles (lithorelicts?) are lens-shaped, concentrated towards the upper contact, and vertically to subvertically oriented; relict laminations are planar, parallel, and continuous; brown sandy siltstone skeletans occur between some joint planes; abrupt wavy contact to

-0.70 m; R; siltstone and very fine-grained sandstone in different layers; dark maroon-brown and dark grey-brown in different layers, weathering cream grey-brown; non-calcareous; relict laminations and beds are generally planar, continuous, and parallel, with some more discontinuous dark maroon-brown laminae; abrupt wavy contact to

-0.85 m; underlying palaeosol (B horizon of underlying palaeosol); sandy siltstone; dark maroon-brown, weathering maroon; non-calcareous; common faint, medium dark grey-brown mottles vary in shape; few green clay papules are irregular in shape; few distinct, fine to medium, green-grey clay-filled root traces, concentrated towards the upper contact, are vertically oriented and branch downwards; maroon clayey siltstone skeletans occur between some joint planes; abrupt irregular contact

The palaeosol shows a moderate degree of development with horizonation easily discernable. The generally maroon-brown to grey-brown soil shows evidence of oxidation while the slight clay enrichment in the B horizon, together with the development of calci-argillans, is evidence of lessivage and/or eluviation. Soil structures such as irregular to blocky peds are not well defined. No organic material is present but root traces and pedotubules (after burrows) are common, especially towards the top of the profile. A thin calcic horizon occurs in the transitional zone between the B and C horizons. The layer is not well indurated and the calcium carbonate generally occurs as cement in irregular patches. Relict laminations and beds are well preserved towards the base of the profile, showing little

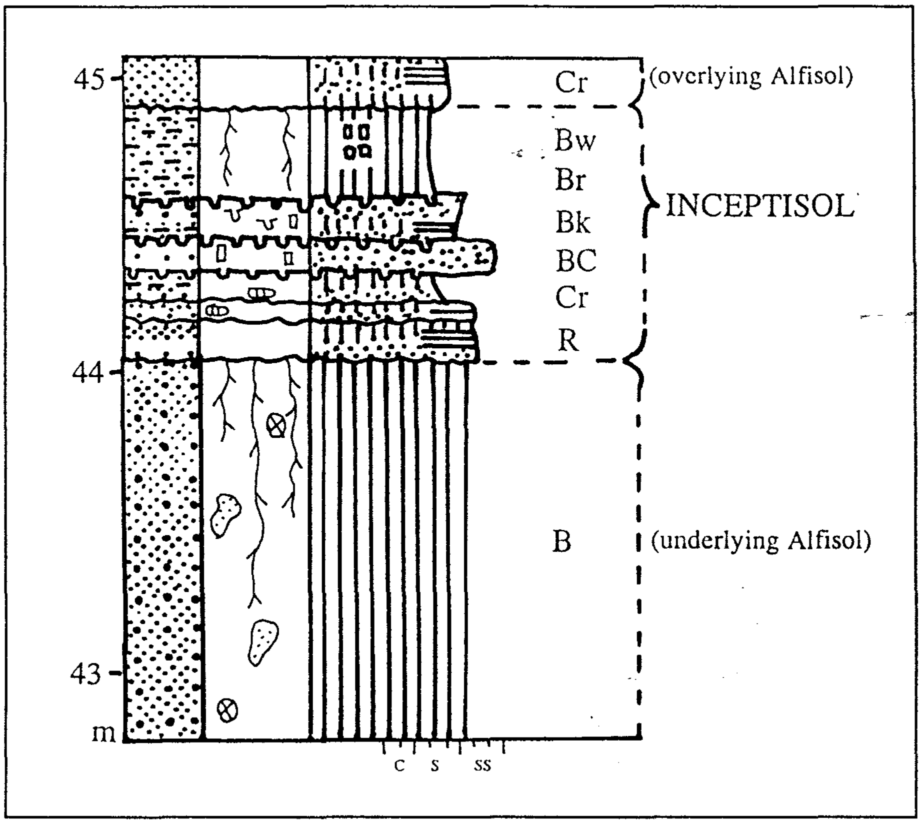

Figure 34. Schematic diagram of the type Inceptisol (below 44.9m) from the lower mudrock sequence.

alteration due to pedogenesis. Some relict laminations, which occur midway through the profile, show evidence of pedoturbation but are still easily discernable.

Although relict laminations and beds are observed, the presence of common root traces and pedotubules (burrows) together with evidence of clay enrichment, cutans and horizonation, suggests that the inceptisol was exposed to pedogenesis for a relatively significant period of time, possibly a few hundreds to tens of thousands of years.

Further examples. Inceptisols occur in all three mudrock sequences (Appendices 1 and 2), although they are most common in the lower mudrock sequence and rare in the upper mudrock sequence. Some display features not observed in the type example. These include: flakes of black organic material; small wood and charcoal chips of varying size; bone fragments; lithorelicts; mottles of varying colour and grain size; tubules of varying grain size and orientation, including rare crystal tubes of carbonate on the upper surfaces of hardpan layers and rare white calcareous para-isotubules; calcans, mangans, sesquans, and stress and illuviation argillans defining peds varying in shape from platy and prismatic through angular and subangular blocky to granular and rounded; clay papules; calcareous and ferric nodules; and hardpan lenses and layers. Some of the features listed above do occur in the type example, but differ in grain size, colour, contrast, abundance, orientation with respect to the top of the profile, and size. Relict laminations also show differences, with convolute and rippled laminations present. In the lower mudrock sequence some of the laminations show intense deformation (eg. Cr horizon 49.36 m below top; Brc horizon 49.68 m below top).

Many of the inceptisols have calcic and petrocalcic horizons which generally occur in the more sandy, permeable layers. In some horizons the calcium carbonate occurs in patches and in others it is concentrated in the more sandy laminae. Calcans and calci-argillans also occur, forming "boxworks" in places. The more calcareous inceptisols are generally found in the lower mudrock sequence.

Parent material. The inceptisols found in the study area developed on alluvium with a range in grain size from silty-claystone through siltstone and very fine-grained sandstone to medium-grained sandstone, however most developed on interbedded and interlaminated siltstones and very fine- to fine-grained sandstones. The inceptisols developed on alluvium some distance from the stream, but close enough to experience frequent flooding and moderate sediment accretion rates. The detrital grains indicate a distal source for the alluvium, however, the presence of possible lithorelicts and pedorelicts in the laminated horizons indicates that some of the alluvium was eroded from older soils and sediments.

The presence of calcic and petrocalcic horizons, particularly in the lower mudrock sequence, indicates that there was a relatively high supply of carbonate to the sediments. As there are no carbonate-rich source rocks, the carbonate in the inceptisols is thought to originate from external sources such as solid carbonate in aerosolic dust, silt and sand and from Ca^{2+} dissolved in rainwater.

Palaeotopography. The inceptisols commonly formed on alluvium close enough to the stream channel(s) to be influenced by frequent flooding and moderate rates of sediment accretion, but far enough from the stream channel(s) to allow moderately mature profiles to develop, i.e., further from the stream channel(s) than entisols. They probably formed on the more distal parts of crevasse splays and on the dry floodplains flanking the streams.

Some of the root traces are surrounded by drab haloes, indicating waterlogging. It is possible in these cases that the soils formed in interstream depressions, some distance from the stream. The drab haloes may also be an indication of impeded drainage, possibly due to clayey subsurface horizons and the low relief of the floodplain. The presence of calcic and petrocalcic horizons in the inceptisols indicates that the soils were generally permeable with good drainage, and together with the lack of prominent gley features, they indicate that if waterlogging did occur, it was only for very short periods of time.

Fossil flora and fauna. The inceptisols generally show fine to medium root traces. Rare larger (coarse) root traces are preserved as crystal tubes on the upper surfaces of some hardpan layers and as clay-filled tapering pedotubules. The root structures are common in most the inceptisols and are generally concentrated towards the tops of the profiles. They are thought to represent pioneer to moderately established vegetation, including shrubs, ferns, cycads and small trees (Bamford, 1986).

Approximately 100 bone fragments (accession number AM4930) of various sizes were found in gully wash and are believed to come from the same horizon as two slightly larger platy bones (accession number AM4930) found in situ in an inceptisol in the middle mudrock sequence (11.94m from the top of the sequence in the contact zone with an overlying alfisol). The bone appears to be from the pelvic region of a stegosaurian dinosaur, possibly *Paranthodon africanus* (Broom) (Dr W. J. de Klerk[1], *pers. comm*). The bone is not very well-preserved and is highly fragmented, however, the taphonomy suggests that the bone has undergone very little transportation and that the fragmentation is due to exposure to weathering on the original palaeosurface.

The infilled granotubules and isotubules, with an average diameter of less than 15mm, probably represent invertebrate burrows. The burrows are generally featureless and have tentatively been placed in the ichnogenus *Skolithos*.

Classification. In the U.S.D.A. classification (Soil Survey Staff, 1975) these palaeosols would be classified as inceptisols. Modern soils of this kind are found relatively close to streams, between the immature entisols on the point bars, crevasse splays, and stream banks, and the more mature profiles developing on the floodplain further from the channel, in areas with low sediment accretion rates and infrequent flooding. They commonly occur on the more distal areas of crevasse splays and on the dry floodplains adjacent to the stream channel. Inceptisols may form in a variety of climatic regimes and may support a wide range of vegetation types.

The calcic horizons present in the inceptisols of the study area correspond to stages I and II of Gile et al. (1966) while the petrocalcic horizons (hardpan lenses and layers) correspond to early stage III of Gile et al. (1966). These probably represent at least 4000 to 9000 years of formation. The depth to carbonate accumulation is related to the amount of rainfall; however, in areas where there is a highly seasonal rainfall, this relationship breaks down. The presence of the calcic and petrocalcic horizons can give an estimate of the conditions of formation of the inceptisols. They are similar to modern soils which form on alluvium (generally well-drained) in warm to hot semi-arid climates with a seasonal rainfall of between 100 mm and 500 mm.

In the classification of Mack et al. (1993) some of the inceptisols would be classified as PROTOSOLS, while others would be classified as CALCISOLS because of the presence of prominent calcic horizons.

5.2.3 Ultisols

Definition. Ultisols are strongly developed, mature soils showing a deeply-weathered acidic profile (Hunt, 1972; Birkeland, 1974; 1984; Retallack, 1990; Huggett, 1991; Hanneman et al., 1994). Because of the long time of formation (tens to hundreds of thousands of years), they form on a variety of parent materials and generally show low base saturation (Wright, 1986; Retallack, 1990).

Base saturation is "calculated as the percentage of total cations that are basic" (Retallack, 1990, p. 82). The base saturation percentage is "the sum of exchangeable Ca, Mg, Na, and K expressed as a percentage of cation exchange capacity measured at a specific pH" (Soil Classification Working Group, 1991). The cation exchange capacity is "the total negative charge on the surface" (of the soil colloid) while exchangeable cations are those cations "that are attracted to the negatively charged surfaces" (Birkeland, 1974, p. 21). Base status is a qualitative expression of base saturation.

In an alluvial system, ultisols develop some distance from the stream channel, where flooding is infrequent and sediment accretion rates are low (Retallack, 1990).

Ultisols, showing thick, well-differentiated profiles, are characterised by an A horizon (may be absent), a highly weathered, clay-enriched Bt (argillic) horizon, and a C horizon (Hunt, 1972; Birkeland, 1974; 1984; Wright, 1986; Birkeland and Larson, 1989; Retallack, 1990; Huggett, 1991). A well-leached E horizon may be present in some profiles.

Ultisols and alfisols (to be discussed later) have similar overall profiles, including the argillic (Bt) horizon, however, unlike alfisols, ultisols are acidic soils with a low base saturation (Retallack, 1990). They have more deeply weathered profiles with a general lack of preserved weatherable minerals, and there is no calcareous material in the profile (Hunt, 1972; Retallack, 1990). The latter was one of the main characteristics used to differentiate between ultisols and alfisols in the study area.

Ultisols commonly form in low to mid latitudes, in areas with warm humid climates and a definite wet season (Wright, 1986; Retallack, 1990).

Diagnosis. Thick, very strongly developed palaeosol which lacks an A horizon. The B horizon shows strong clay-enrichment which decreases downwards, while the C horizon shows poorly preserved relict laminations. Pedogenetic features such as root traces and pedotubules are common and are concentrated towards the top of the profile, however, some of the root traces may penetrate down through the profile to the C horizon. Illuviation argillans occur throughout the profile whereas stress argillans occur towards the top of the profile.

Type example. The type ultisol (Figure 35) is from the lower mudrock sequence exposed in the study area with the top of the palaeosol 7.79 m from the top of the sequence (Appendices 1 and 2).

+0.71 m; cover (Crck horizon of overlying palaeosol); coarse-grained sandstone; dark grey-green and dark maroon-grey in different layers, weathering white cream-grey; very weakly calcareous; dark maroon rounded lithorelicts are concentrated in crude layers; relict laminations are faint, crudely defined, planar and parallel; numerous vertical, dark grey-green clay sheets/dykes (skeletans?), <4mm in width, cut through the horizon; well-indurated, white crystalline, randomly oriented nodules and vertically oriented dykes, weathering cream, are irregular in shape; wavy abrupt contact to

0 m; B; clayey siltstone; dark maroon-brown grading into purple-maroon upwards, weathering dark maroon-pink; non-calcareous; common distinct, medium meta-isotubules are randomly oriented and less than 0.05m long; many distinct, fine to medium, green clay-filled root traces with pale green diffuse haloes, are randomly oriented and form a dense network; black mangans occur on some ped surfaces; yellow medium-grained sandstone and red-brown sandy siltstone skeletans occur between some joint planes; angular blocky peds show maroon-purple shiny illuviation and stress argillans; irregular abrupt contact to

-0.78 m; Bt; clayey siltstone; green-grey, weathering cream pink-grey; non-calcareous; common to many distinct, coarse dark maroon-brown mottles vary in shape; few faint, fine dark green shiny clay-filled root traces are randomly oriented; sandy red-brown skeletans occur between some joint planes; subangular blocky peds show few red-maroon illuviation argillans; clear irregular to broken contact penetrating down to

-1.01 m; Bt; clayey siltstone; dark maroon-brown, weathering pink with orange tint; non-calcareous; common distinct, medium green-grey clayey siltstone meta-isotubules (after burrows? and/or roots?) are vertically oriented and are concentrated towards the upper contact; blocky peds show thick red-brown illuviation argillans which increase in abundance downwards; clear irregular contact to

-1.17 m; Bt*; silty claystone; green-grey, weathering light pink-maroon; non-calcareous; common distinct, medium maroon-brown silty claystone meta-isotubules (after burrows? and\or roots?) are vertically oriented; abrupt irregular to broken contact to

-1.20 m; Bt*; silty claystone; purple maroon-brown, weathering light pink-maroon; non-calcareous; common distinct, medium green-grey mottles vary in shape; maroon very fine-grained sandstone skeletans occur between some joint planes; blocky peds show red-brown illuviation argillans; abrupt and wavy contact to

-1.52 m; Bt; silty claystone; pale olive-green, weathering light pink-maroon; non-calcareous; irregular in thickness along strike; abrupt irregular contact to

-1.54m; Bw; siltstone; dark maroon-brown, weathering dark maroon-pink; non-calcareous; many distinct, coarse grey-green mottles vary in shape; common distinct, medium green clay-filled root traces are vertically oriented; black mangans occur on some ped surfaces; red-brown sandy siltstone skeletans occur between some joint planes; blocky peds show rare green-black illuviation argillans; abrupt wavy contact to

-1.83 m; Cr*; siltstone; grey-green, grey-brown and light grey maroon-brown in different layers, weathering light grey with patches of maroon; non-calcareous; common distinct, medium to coarse, dark maroon-brown clayey siltstone mottles (after bioturbation?), vary in shape; common distinct, medium dark maroon clay-filled root traces are vertically oriented; faint relict laminations are crudely defined and discontinuous; black mangans and rust orange sesquans occur on some ped surfaces; secondary peds show red and green skeletans and illuviation argillans; platy peds show discontinuous planar maroon red-brown illuviation argillans (after relict laminations); abrupt wavy contact (lined with thin layer of rust orange clayey siltstone) to

-2.18 m; C; clayey siltstone; bright green, weathering white grey-green; non-calcareous; irregular in thickness along strike; black mangans present on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; subangular blocky peds show poorly developed maroon red-brown illuviation skeletans; abrupt wavy contact to

-2.21 m; underlying palaeosol (ACr horizon of underlying palaeosol); clayey siltstone and sandy siltstone in different layers; dark maroon-brown and sandy grey-brown in different layers, weathering pink grey with green tint; non-calcareous; few flakes of black organic material vary in size and are randomly oriented; common distinct, medium maroon-brown clayey siltstone mottles vary in shape; few to common distinct, medium green clayey siltstone mottles vary in shape; common distinct, coarse light grey sandy siltstone mottles vary in shape; all mottles increase in abundance upwards; green clay papules are irregular in shape; few distinct, fine to medium, green clay-filled root traces are vertically oriented; faint, discontinuous and irregular, thin relict beds occur; very fine to medium, angular peds show well developed maroon red-brown and green shiny illuviation argillans; abrupt wavy contact

The palaeosol is well developed with strong evidence of pedogenesis. The presence of illuviation argillans and well-developed argillic (Bt) horizons provides good evidence for lessivage. Soil structures such as angular- and subangular-blocky to blocky peds are well developed and are generally bounded by illuviation argillans. Relict sedimentary structures, such as faint laminations, are rare and occur near the base of the profile. Planar argillans also occur towards the base of the profile and it is possible they reflect relict sedimentary laminations and bedding. No organic material is present, although root traces and pedotubules are common, with the latter occurring throughout the profile. This is predominantly maroon-brown indicating oxidising conditions at the time of formation but the presence of interbedded green-grey horizons, together with colour mottling and the development of drab-haloed root traces, suggests that the soil was waterlogged periodically during its development.

The general lack of relict structures, the well-developed argillic (Bt) horizon, and the presence of pedogenetic features such as root traces and pedotubules (after burrows) suggests that the soil had a relatively long period of formation, possibly tens to hundreds of thousands of years.

Further examples. Although ultisols occur in all three mudrock sequences (Appendices 1 and 2) in the study area, they are rare and develop on parent material ranging in grain size from silty claystone through clayey siltstone, siltstone and sandy siltstone to very fine- and fine-grained sandstone. Some display features not observed in the type section. These include: flakes of black organic material, with and/or without rust orange haloes (occur in situ or as illuvial concentrations); mottles of varying grain size and shape; tubules of varying grain size and orientation; mangans, sesquans, and illuviation and stress argillans of varying colour defining peds which vary in shape from blocky through angular- and subangular-blocky to granular and rounded; iron-rich nodules and concretions; and very rare thin layers of iron-rich material. Some of the features listed above do occur in the type example but differ in grain size, colour, contrast, abundance, orientation with respect to the top of the profile, and size. Some of the profiles are less mature than the type example and display preserved relict structures such as planar and ripple cross-laminations, and convolute and disturbed (by pedoturbation and/or bioturbation) laminations.

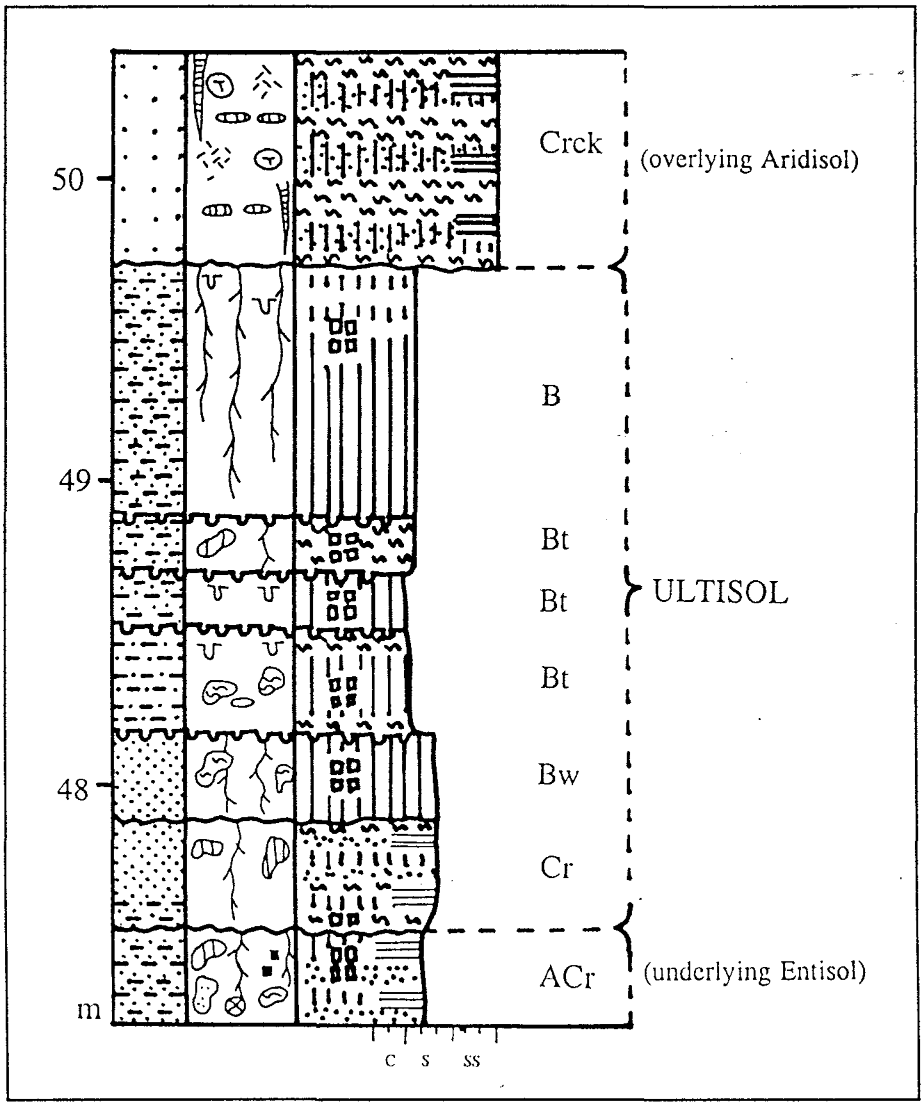

Figure 35. Schematic diagram of the type Ultisol (below 49.72m) from the lower mudrock sequence.

Although ultisols are defined as not having calcareous material present, rare powdery calcium carbonate nodules occur in some of the horizons. The carbonate was probably introduced to the profile in the later stages of formation through the leaching of wind-blown carbonate-rich sediment (dust). The change from a temperate climate, with a relatively high seasonal rainfall, to a more arid climate and a change in base status could result in carbonate accumulation in the soils. Under normal conditions the carbonate would be leached out of the characteristically acidic soils.

Parent material. The ultisols found in the study area developed on alluvium with a wide range in grain size. The presence of minor amounts of carbonate in the profiles suggests that there was an influx of carbonate-rich sediment (aerosolic dust), probably in the later stages of the profile development as it would otherwise not have been preserved in the typically acidic, well-leached ultisols.

Palaeotopography. The ultisols commonly developed on dry floodplain alluvium some distance from the stream channel(s). They developed on those parts of the floodplain beyond the influence of frequent flooding where the rates of sediment accretion were minimal to absent.

The presence of green and green-grey horizons within the profiles, together with mottling and drab-haloed root traces, suggests possible waterlogging of the sediments at some time (maybe seasonally) during pedogenesis. The most likely cause of the reducing conditions is impeded drainage in the sediments. It is possible that the more clayey horizons may have acted as relatively impermeable barriers to downward percolating waters, impeding drainage and resulting in waterlogging of the sediments directly above them, creating localised reducing conditions. Likewise, some of the more clayey horizons, being less porous, may have retained water, resulting in localised reducing conditions within an otherwise well-drained, oxidised profile. Alternatively, if the profiles developed in topographic lows on the floodplain, they may have been waterlogged for long periods during the wet season, due to the formation of small ponds in the lower lying areas (See section 4.4).

Fossil flora and fauna. The ultisols generally show fine to medium root traces with rare larger (coarse) root traces preserved as sediment-filled tapering pedotubules. The root structures are common in all the ultisol profiles and, although they penetrate all horizons of the profiles, they are generally more prolific towards the top. They are thought to represent moderately to well established vegetation, including shrubs, ferns, cycads and relatively small trees (probably some kind of conifer) (Bamford, 1986).

The infilled isotubules and granotubules probably represent small invertebrate burrows. The pedotubules are generally small (average diameter less than 15 mm), vertically to subvertically oriented, and featureless and have therefore tentatively been placed in the ichnogenus *Skolithos*. It is important to note that some of the pedotubules may represent preserved root casts. Bioturbation in some of the horizons provides further proof of faunal burrowing activity.

Classification. In the U.S.D.A. classification (Soil Survey Staff, 1975) these palaeosols are similar to ultisols or alfisols. However, the profiles generally lack carbonate (may be present in very minor percentages), are well differentiated with strong clay enrichment in the Bt horizons (argillic), and lack many weatherable minerals (thin section). They are therefore classified as ultisols.

Modern soils of this kind form over 8000 to 10000 years, show well-developed mature profiles and are found on a variety of parent materials. In this case, they are found on the more distal parts of the floodplain in areas of infrequent flooding, where the rates of sediment accretion are minimal to absent. The ultisols represent soils that generally occur in climates ranging from warm humid to subhumid, to Mediterranean, to temperate and seasonally dry (Wright, 1986; Retallack, 1983b; 1990). They support a variety of vegetation types ranging from forests to open shrubby woodlands.

Mack et al. (1993) prefer to use the term ARGILLISOL, defined as a palaeosol "whose most prominent feature is an argillic horizon" (Mack et al., 1993, p. 132). They use ARGILLISOL to cover both alfisols and ultisols and criticise the dependence of the U.S.D.A. classification on the base status of the soils, arguing that it is not a reliable parameter on which to base a classification as it is affected and altered by diagenesis. They do acknowledge that base status can be calculated, but argue that the results are too "imprecise and equivocal" (Mack et al., 1993, p. 133) to be used to classify palaeosols at the order level. Classification of the argillic palaeosols in the study area as ARGILLISOLS would probably have been more correct as the base status is not known. However, the presence of thick, well-differentiated profiles lacking carbonate, suggests that they are ultisols as most of the other palaeosols present show evidence of at least stage II to III carbonate accumulation using the classification of Gile et al. (1966).

5.2.4 Alfisols

Definition. Alfisols are well-developed mature soils showing a deeply-weathered, basic to slightly-acidic profile (Retallack, 1990; Huggett, 1991). They have a relatively long time of formation (thousands to tens of thousands of years) and form on sediments and rocks of intermediate to basaltic composition. Alfisols generally show a high base saturation (greater than 35%) (Birkeland, 1974; 1984; Wright, 1986; Retallack, 1990; Soil Classification Working Group, 1991). According to Retallack (1990, p. 111), high base saturation can be "assumed for palaeosols when they contain nodules of carbonate in a horizon (Bk) deep within the profile". If there are no carbonate nodules present, then the alfisols can be distinguished from base-poor soils (ultisols) by the presence of smectitic clays (base-rich) and abundant weatherable minerals (e.g. feldspar). In an alluvial system, the alfisols develop on alluvium some distance from the stream channel, where flooding is infrequent and sediment accretion rates are low (Retallack, 1990).

The alfisols showing thick well-differentiated profiles are characterised by an A, (E), B, C soil horizon sequence (Birkeland, 1974; Retallack, 1990). The A horizon is generally light coloured and thin (may be absent), and may contain preserved organic matter. The E horizon, if present, generally separates the A and B horizons. The B horizon, which may show strong red colouration due to the presence of sesquioxides, shows appreciable clay-enrichment and is classified as an argillic (Bt) horizon (Hunt, 1972; Birkeland, 1974; 1984; Wright, 1986; Retallack, 1988, 1990; Birkeland and Larson, 1989; Huggett, 1991; Soil Classification Working Group, 1991). It has moderate to high base saturation, indicated by the presence of carbonate nodules (the reaction to dilute (10%) hydrochloric acid proving calcareous (Table 2.2)), and the abundance of weatherable minerals (Retallack, 1988, 1990). The C horizon may have relict sedimentary structures preserved.

As mentioned in the previous section, alfisols and ultisols have similar profiles, however, alfisols have high base saturation (greater than 35%), contain weatherable minerals, and commonly show carbonate accumulation at depth, whereas ultisols have low base saturation (less than 35%) and lack preserved weatherable minerals and carbonate (Hunt, 1972; Retallack, 1990). It is important to note that calcareous material is not necessarily present in alfisols, and that carbonate accumulation is a function of carbonate supply, climate (rainfall and wind), and time (see section 4.5.4).

Modern alfisols commonly form in a variety of topographic settings with a range in vegetation from wooded grassland to open forest, and a range in climate from sub-humid to semi-arid (Retallack, 1990; Huggett, 1991). Alfisols may form in areas with extremely varied temperatures and seasonal rainfall (the latter is not always the case) (Retallack, 1990).

Diagnosis. Thick strongly-developed palaeosol which lacks an A horizon. The B horizon is complex and shows strong clay enrichment (argillic (Bt) horizon) at varying levels.

Illuvial accumulation of organic matter occurs towards the base of the B horizon, while the C horizon shows preservation of relict sedimentary structures. Pedogenetic features such as root traces, calcareous para-isotubules, and mottles are common in the B horizon, with the last also occurring in the C horizon.Illuviation argillans occur throughout the profile while stress argillans are concentrated in the B horizon. Dispersed white powdery carbonate nodules and filamentous carbonate are present towards the base of the B horizon.

Type example. The type alfisol (Figure 36) is from the middle mudrock sequence exposed in the study area with the top of the palaeosol 33.13 m from the top of the sequence (Appendices 1 and 2).

+0.92 m; cover (Cr horizon of overlying palaeosol); very fine-grained sandstone; light maroon-pink, dark maroon, and grey in different layers, weathering grey-pink; non-calcareous; common distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; relict laminations are parallel and both planar and rippled; black mangans occur on some ped surfaces; towards the upper contact, angular blocky peds show red-brown illuviation argillans; clear abrupt contact to

0 m; Bt; clayey siltstone; dark maroon, weathering light maroon-pink; non-calcareous; few distinct, fine to medium, green clay-filled root traces are vertically oriented; blue-black mangans occur on some ped surfaces; subangular blocky peds show dark maroon illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-0.62 m; Bt; siltstone; dark maroon-brown, weathering light pink maroon; non-calcareous; common faint, fine light maroon mottles vary in shape; common distinct, fine to medium, green clay-filled root traces are vertically oriented and branch downwards; blue-black lustrous mangans occur on some ped surfaces; platy to blocky peds show maroon-brown shiny illuviation and stress argillans which increase in abundance upwards; clear smooth contact to

-1.74 m; Bw; clayey siltstone; dark maroon-brown, weathering light maroon; non-calcareous; few to common distinct, fine green clay-filled root traces are vertically oriented and branch downwards; smooth gradual contact to

-2.40 m; B; siltstone; dark maroon-brown, weathering light grey; non-calcareous; common distinct, fine maroon red-brown clay-filled root traces lined with green argillans are vertically oriented; many distinct, fine to medium, rust orange and yellow clay-filled root traces with cream and pale green haloes (<2mm thick), are randomly oriented, branching outwards to form a dense network; smooth gradual contact to

-2.76 m; Bh; siltstone; dark maroon-brown, weathering maroon; non-calcareous;

flakes of black organic material are present; common distinct, fine to medium, green clay-filled root traces, with pale green to white diffuse haloes, are vertically to subvertically oriented and branch downwards; blue-black mangans occur on some ped surfaces; subangular blocky to granular peds show orange-brown illuviation and stress argillans; clear wavy contact to

-3.89 m; Bt; clayey siltstone; dark maroon-brown, weathering maroon; non-calcareous; common distinct, fine to medium, white calcareous para-isotubules (after roots), with pale green diffuse haloes, are vertically oriented and branch downwards; common distinct, fine to medium, green clay-filled root traces are vertically oriented and branch downwards; blocky peds show orange illuviation argillans; dispersed white powdery carbonate nodules and filamentous carbonate occur; wavy clear contact to

-3.97 m; Bt; clayey siltstone; dark maroon-brown, weathering light maroon; non-calcareous; many distinct, medium to coarse, green clay-filled root traces are randomly oriented and branch outwards, forming a dense network; black mangans occur on some ped surfaces; granular peds show maroon-brown illuviation argillans; clear broken bioturbated contact to

-4.25 m; Cr; fine-grained sandstone; grey-green and maroon-brown in different layers, weathering grey with slight brown tint; non-calcareous; common faint, medium light maroon mottles vary in shape; few distinct, fine to medium, dark maroon-brown very fine-grained sandstone mottles vary in shape; faint relict laminations are layer parallel and continuous; apedal, but sparse discontinuous maroon-brown illuviation argillans outline irregular areas; abrupt wavy contact to

-4.97 m; underlying palaeosol (Bw horizon of underlying palaeosol); silty claystone; green, weathering grey-maroon; non-calcareous; common distinct, coarse maroon mottles vary in shape; rust yellow sesquans occur on some ped surfaces; subangular blocky peds show red maroon-brown illuviation argillans; clear gradational bioturbated contact to

The palaeosol is well developed with strong evidence of pedogenesis. The presence of well-developed argillic (Bt) horizons and illuviation argillans indicates lessivage. Soil structures such as peds, ranging in shape from platy, through subangular blocky and blocky, to granular, are well developed and are generally defined by illuviation and stress argillans. Relict sedimentary structures such as faint planar, continuous laminations occur towards the base of the profile. Organic material occurs in the B horizon, and is believed to have been concentrated by illuvial processes. Root traces and colour mottles are common. The profile is predominantly maroon-brown indicating oxidised, well-drained soils.

The general lack of preserved sedimentary structures, the well-developed argillic (Bt)

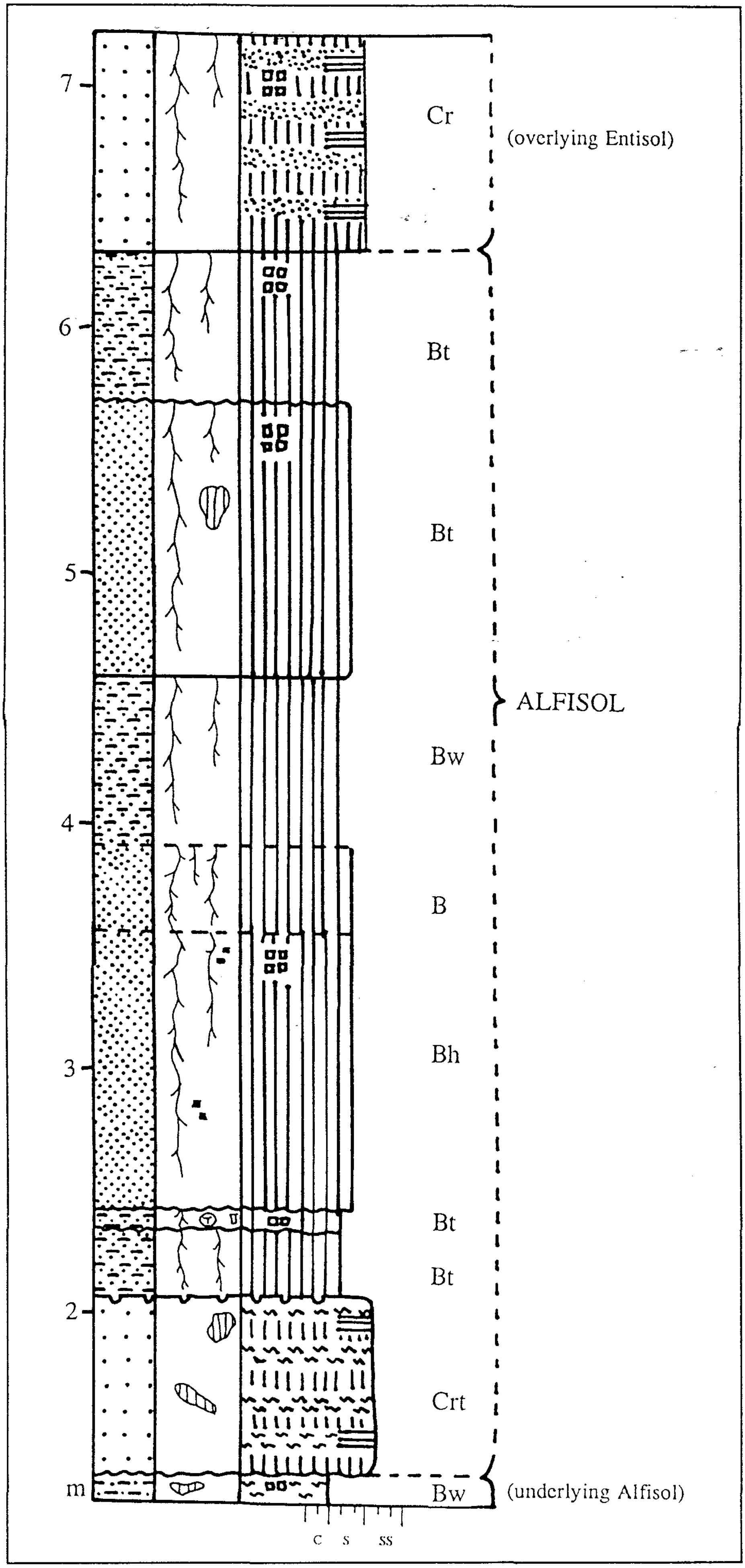

Figure 36. Schematic diagram of the type Alfisol (below 6.31m) from the middle mudrock sequence.

horizons, and the presence of pedogenetic features such as root traces and colour mottles suggest that the soil formed over a relatively long period, possibly a few thousand years.

Further examples. Alfisols are common in all three mudrock sequences (Appendices 1 and 2) in the study area. They developed on parent material (alluvium) ranging in grain size from silty claystone, through clayey siltstone, siltstone and sandy siltstone, to very fine- to medium-grained sandstone. Some of the alfisols display features not observed in the type profile. These include: flakes of black and brown organic material (occurs in situ in A horizon or as illuvial concentration in B/C horizons); clay papules of varying colour and shape; small unidentifiable bone fragments; lithorelicts; mottles of varying colour, grain size and shape; tubules of varying type, grain size and orientation, including crystal tubes; root traces of varying colour, abundance and orientation, including calcareous rhizocretions; calcans, mangans, sesquans, skeletans, calci-argillans, ferri-sesquans, and diffusion, illuviation and stress argillans of varying colour defining peds which vary in shape from platy and prismatic, through blocky, angular- and subangular-blocky, to granular and rounded; iron-rich nodules and concretions, sometimes surrounded by pale diffuse haloes; calcareous nodules and hardpan layers and lenses; calcareous desert rose pseudomorphs; and calcareous crystal sheets and spherulites. Some of the features listed above do occur in the type example but differ in grain size, colour, contrast, abundance, orientation with respect to the top of the profile and size. Relict laminations (planar and parallel, discontinuous and/or continuous) may occur in the basal sections of some profiles.

Unlike the type example, many of the alfisol profiles have calcic and petrocalcic horizons which generally indicate stage II to III morphology (Gile et al., 1966). In some of the more sandy horizons the calcium carbonate occurs in patches or throughout the horizon. The calcareous nodules and hardpan layers are commonly associated with the more silty horizons (and profiles) although they may occur in the sandier horizons. Calcareous alfisol profiles occur in all three mudrock sequences.

Parent material. Most of the alfisols found in the mudrocks of the study area developed on silty to sandy alluvium at some distance from the stream channel. The sediment source is distal, with carbonate introduced from aerosolic dust.

Palaeotopography. The alfisols commonly formed on dry floodplain alluvium (interchannel areas) some distance from the stream channel(s). They developed on those parts of the floodplain beyond the influence of frequent flooding where the rates of sediment accretion were minimal.

Some of the root traces are surrounded by drab haloes. They are thought to be due to chelation reactions in the rhizosphere, together with later enhancement of the haloes by the process of diagenetic reddening (see section 4.1). It is unlikely that they were formed due to gleization (waterlogging), as the surrounding soils are generally maroon-brown, indicating oxidising conditions at the time of pedogenesis. Some green and green-grey horizons are observed, suggesting possible waterlogging of the sediments at some time during pedogenesis or removal of ferrous iron from the sediments by interstitial waters. However, there is no conclusive evidence to support either hypothesis.

The presence of calcic and petrocalcic horizons, together with iron-rich concretions and nodules, indicates that the soils were generally permeable with good drainage and a high base saturation.

Fossil flora and fauna. The alfisols generally show fine to medium clay-filled root traces and calcareous para-isotubules (after roots), often with associated drab haloes. Larger root traces are less common and include crystal tubes (rhizocretions) with diameters up to 30 mm. The root structures are common in all the alfisol profiles and, although they penetrate down through all horizons of the profiles, they are generally more common towards the top of the profile. They are thought to represent moderately to well established vegetation, including shrubs, ferns, cycads, and trees (perhaps some type of conifer) (Bamford, 1986).

Small, unidentifiable bone fragments were found in an alfisol in the lower mudrock sequence (51.42 m from the top of the sequence in a fine-grained sandstone (Cir) horizon). The extreme fragmentation of the bone may reflect a long period of exposure to weathering before burial.

The infilled granotubules and isotubules probably represent invertebrate burrows. They have an average diameter of less than 15mm and are generally featureless and vertically to subvertically oriented. The burrows have tentatively been placed in the ichnogenus *Skolithos*.

Classification. In the U.S.D.A. classification (Soil Survey Staff, 1975) these palaeosols are similar to alfisols or ultisols. However, the presence of abundant carbonate (nodules, hardpan, effervescent reaction with dilute (10%) HCl) and weatherable minerals (thin section), together with the dominantly maroon-brown colouration of the horizons, suggests that the soils have high base saturation and they are therefore classified as alfisols.

Modern soils of this kind show well-developed mature profiles and are found on sediments and rocks of intermediate to basaltic composition (Retallack, 1990). In this study, they are found on the more distal parts of the floodplain in areas of infrequent flooding and low sediment accretion rates, with a generally high supply of carbonate from external sources. The alfisols represent soils generally occurring in climates ranging from humid to subhumid, to temperate and subtropical, to semi-arid (Retallack, 1983b, 1990; Huggett, 1991). The climate is generally seasonal, with an average rainfall of between 100 mm and 500 mm and a definite dry season (necessary to allow calcium carbonate to accumulate within the profile). Alfisols generally support a variety of vegetation ranging from wooded grassland (modern) and shrubland to open forests (Retallack, 1990).

The calcic and petrocalcic horizons present in the alfisols of the study area correspond to stage II and III of Gile et al. (1966), and together with the generally thick, well-developed profiles, indicate a similarity to modern alfisols

In the classification of Mack et al. (1993), the profiles with a prominent argillic horizon would be classified as ARGILLISOLS while those with prominent calcic horizons would be classified as CALCISOLS. If both argillic and calcic horizons are present, the palaeosols could be classified as CALCIC ARGILLISOLS or ARGILLIC CALCISOLS depending on which horizon was more prominent.

5.2.5 Aridisols

Definition. Aridisols are moderately developed, mature, saline or alkaline soils (Hunt, 1972; Retallack, 1990; Huggett, 1991). They have a variable time of formation, from a few thousand to tens of thousands of years, and form on a variety of parent materials, including unconsolidated alluvium, loess and till (Retallack, 1990). In an alluvial system, the aridisols form in low lying areas some distance from the stream channel, where flooding is infrequent and rates of sediment accretion are low (Retallack, 1990).

The aridisols are characterised by an A, (Bt), (Bk), (By), C soil horizon sequence. The A horizon is generally thin and light coloured (grey to brown), with very little organic matter (Birkeland, 1974, 1984; Retallack, 1988, 1990; Birkeland and Larson, 1989; Huggett, 1991). The B horizon (sometimes absent) may show clay-enrichment (argillic (Bt) horizon)

(Wright, 1986; Birkeland and Larson, 1989; Retallack, 1990). The low rainfall, typical of aridisol regions, is insufficient to leach soluble salts from the soils, resulting in the possible formation of "shallow calcareous (calcic, petrocalcic, Bk), gypsiferous (gypsic, petrogypsic, By) or salty (salic or Bz) horizons" (Retallack, 1990, p. 110). The C horizon may show accumulation of calcium carbonate and relict sedimentary structures are often observed. The carbonate generally occurs as nodules, concretions, and/or hardpan layers, reflecting the carbonate accumulation stages II, III and possibly IV of Gile et al. (1966).

Modern aridisols commonly occur in areas with semi-arid to arid climates, characterised by high temperatures, low rainfall and at least 6 dry months per year (Hunt, 1972; Birkeland, 1974; 1984; Wright, 1986; Retallack, 1990; Soil Classification Working Group, 1991).

Diagnosis. Thin, weakly to moderately developed, grey-brown to maroon-brown palaeosol with very thin A horizon, and no B horizon. The C horizon shows carbonate-enrichment (calcic and petrocalcic horizons) and preserved relict sedimentary structures. Pedogenetic features such as pedotubules (roots and burrows) are concentrated towards the top of the profile, but do occur further down.

Type Example. The type aridisol (Figure 37) is from the lower mudrock sequence with the top of the palaeosol 31.26 m from the top of the sequence (Appendices 1 and 2).

+0.10 m; cover (Cr horizon of overlying palaeosol); siltstone; dark grey-brown, dark maroon-brown, and very dark maroon-brown in different layers, weathering maroon; non-calcareous; few distinct, coarse grey-brown fine-grained sandstone metagranotubules (after burrows?) are vertically to subvertically oriented; common faint, medium to coarse, dark maroon-brown siltstone para-isotubules (after burrows) are vertically oriented; irregular, rippled relict laminations are both continuous and discontinuous and lens-like; red-brown clayey siltstone skeletans occur between some joint planes; abrupt, wavy to irregular contact to

0 m; AC; fine-grained sandstone; grey-brown with green tint, weathering grey-brown; non-calcareous to very weakly calcareous; common distinct, medium to coarse, maroon-brown clayey siltstone meta-isotubules (after roots and burrows) are vertically to subvertically oriented; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-0.11 m; Cr; siltstone; very dark and dark maroon-brown, and dark grey-brown in different layers, weathering maroon; very weakly calcareous; few to common distinct, medium to coarse, grey-brown fine-grained sandstone metagranotubules (after burrows) are vertically oriented; common distinct, fine to medium, dark maroon-brown clay-filled root traces are vertically oriented and concentrated towards the upper contact; relict laminations are planar, parallel, and continuous at the base but become indistinct, discontinuous and thicker upwards due to destruction by granotubules; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-0.43 m; Ckm at the top to Cr at the base; fine-grained sandstone; light grey-brown, green-brown, and dark maroon-brown in different layers, weathering light olive-brown; non-calcareous; few to common distinct, coarse dark maroon-brown clayey siltstone meta-isotubules (after burrows) are randomly oriented; relict laminations are vaguely planar to irregular and continuous; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; blocky peds show pale green-grey illuviation argillans; well-indurated grey-white, faintly laminated, coarse-grained crystalline hardpan lenses, weathering brown-white, occur in the upper 60mm of the horizon and have numerous horizontally oriented white very strongly calcareous crystal tubes (after burrows? and/or roots?) running across the upper contact surfaces; abrupt smooth contact to

-0.58 m; Crkc; siltstone and silty claystone in different layers; light and dark grey-brown and maroon-brown, and red-brown and very dark maroon-brown in different layers, weathering light maroon; non-calcareous; parallel, rippled and planar relict laminations are continuous; black mangans occur on some ped surfaces; red-brown silty claystone skeletans occur between some joint planes; blocky peds show green shiny illuviation argillans which are well-defined towards the upper contact; well-indurated, brown-white crystalline nodules, weathering dark brown-white, occur towards the upper contact and are irregular to triangular in shape; thin white calcareous filaments are associated with the nodules and cut vertically down through the horizon (after roots?); abrupt smooth contact to

-1.36 m; Cr; siltstone; dark maroon-brown and maroon-brown in different layers, weathering dark maroon; non-calcareous; faint relict laminations are planar, parallel and continuous; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-1.45 m; underlying palaeosol (Bc horizon of underlying palaeosol); clayey siltstone; dark grey-green, weathering grey-pink; non-calcareous; common to many distinct, medium maroon-purple mottles vary in shape; few to common faint, medium to coarse, dark maroon-brown clay-filled root traces are randomly oriented and branch outwards; red-brown clayey siltstone skeletans occur between some joint planes; dark rust orange, iron-rich concretions, with thin pale green-white haloes, are spherical and occur throughout the horizon.

The palaeosol is weakly to moderately developed, with evidence of pedogenesis. Soil structures such as blocky peds are rare and occur towards the base of the profile. Relict sedimentary structures such as planar laminations and ripple cross-laminations are common in the lower parts of the profile and are generally well-preserved. No organic material is present, although root traces and pedotubules (after roots and burrows) are common, becoming more abundant towards the top of the profile.

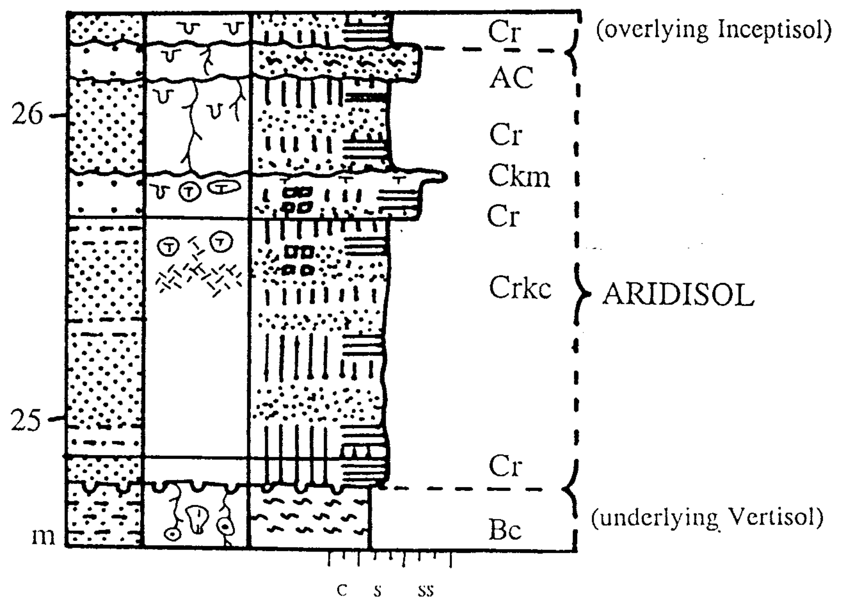

Figure 37. Schematic diagram of the type Aridisol (below 26.25m) from the lower mudrock sequence.

Thin (approximately 60 mm thick), well-indurated, petrocalcic (hardpan) lenses, which are laterally persistent along strike, are faintly laminated and have gradational lower contacts and abrupt upper contacts. The upper contact surface is criss-crossed by horizontal calcareous crystal tubes (after burrows? and/or roots?). A relatively thick calcic horizon occurs below the petrocalcic horizon. Thin filaments and stringers of carbonate are commonly associated with irregular to triangular calcareous nodules.

Although relict beds and laminations are observed, the presence of common root traces and pedotubules, together with petrocalcic and calcic horizons representing stage II and III carbonate accumulation (Gile et al., 1966), suggests that the aridisol represents at least 4000 years of soil formation.

Further examples. Aridisols only occur in the lower and upper mudrock sequences (rare) in the study area (Appendices 1 and 2). They developed on parent material (alluvium) ranging in grain size from silty claystone, through clayey siltstone, siltstone and sandy siltstone, to very fine- to coarse-grained sandstone. Some display features not observed in the type example. These include: rare flakes of black organic material; clay papules; lithorelicts; mottles of varying colour, grain size and shape; tubules of varying type, grain size and orientation, including calcareous para-isotubules and crystal tubes (after roots? and/or burrows?); root traces of varying colour, abundance and orientation; mangans, sesquans, skeletans and illuviation and stress argillans of varying colour defining peds which vary in shape from platy and prismatic, through blocky, angular- and subangular-blocky to granular; calcareous nodules, hardpan lenses and layers; and calcareous dykes/sheets and veins. Some of the features listed above do occur in the type example but differ in grain size, colour, contrast, abundance, orientation with respect to the top of the profile, and size. Some of the aridisol profiles are more mature than the type example and show evidence of clay accumulation; in rare cases clay enrichment is enough to classify the horizon as an argillic Bt horizon. Relict laminations and beds are common in most profiles.

Carbonate enrichment, in calcic and petrocalcic horizons, is common in all profiles, although there is a great variation in the mode of occurrence. The nodules vary in shape from irregular and blocky to rounded, while the hardpan layers may be laminated, may comprise coalesced nodules, or may occur as well indurated lenses seated in a more powdery carbonate (host material?). Carbonate accumulation in the aridisols is typically stage II and/or III of Gile et al. (1966), and commonly occurs in the more sandy horizons in the profiles.

Parent material. The aridisols found in the mudrocks of the study area are developed on well-drained alluvium with a range in grain size, however, most developed on siltstone and fine- to medium-grained sandstone. Fine increments of wind-blown sediment may also have been added to the profiles during pedogenesis. The aridisols developed on dry floodplain alluvium at some distance from the stream channel, beyond the influence of frequent flooding and high sediment accretion rates. The common preservation of relict sedimentary structures in the aridisol profiles is probably due to the lack of sufficient seasonal rainfall (leaching) and pedoturbation rather than due to a frequent influx of sediment.

The abundant calcic and petrocalcic horizons indicate a constant, relatively high source of carbonate to the floodplain sediments.

Palaeotopography. Aridisols are commonly found on dry floodplain alluvium (interchannel areas) some distance from the stream channel(s). They developed on those parts of the floodplain where sediment accretion rates were minimal and flooding infrequent. The presence of calcic and petrocalcic horizons indicates the soils were generally permeable with good drainage and a relatively high base saturation.

Fossil flora and fauna. The aridisols show fine to medium clay-filled root traces and calcareous para-isotubules (after roots), the latter showing rare association with drab haloes. The root structures are relatively common and are generally concentrated towards the top of the aridisol profiles. Slightly larger crystal tubes (after burrows? and/or roots?) were observed on the top surfaces of hardpan layers and lenses. The finer root traces are thought to represent shrub vegetation while the crystal tubes may be evidence for small bushes or trees.

The generally featureless, vertically to subvertically oriented granotubules and isotubules (representing small invertebrate burrows) have an average diameter of less than 8 mm and have tentatively been placed in the ichnogenus *Skolithos*. Cylindrical nodules were observed in one of the aridisol profiles, but as mentioned previously (section 4.2), they cannot be classified as burrows due to a lack of evidence.

Classification. In the U.S.D.A. classification (Soil Survey Staff, 1975) these palaeosols would be classified as aridisols. Modern soils of this kind are commonly found on unconsolidated alluvium, loess, and till in low lying areas as soils developing on steep slopes in arid areas tend to be entisols (Retallack, 1990). In this study they are found on dry, permeable alluvium on the more distal parts of the floodplain, with a high influx of carbonate (throughout pedogensis) from an external source. Aridisols commonly occur in areas with semi-arid to arid climates, characterised by relatively high temperatures, low rainfall and at least 6 dry months per year. Modern aridisols support generally sparse vegetation which includes prickly shrubs and cacti (Retallack, 1990).

The calcic and petrocalcic horizons present in the aridisols of the study area correspond to the carbonate accumulation stages II and III of Gile et al. (1966), representing at least 4000 to 8000 years of formation.

Mack et al. (1993) prefer to classify the aridisols as CALCISOLS. They criticise the classification of palaeosols as aridisols as knowledge of factors, such as "soil temperature, annual precipitation, and temporal distribution of soil moisture" (Mack et al., 1993, p. 134), necessary for the classification of modern aridisols, are not preserved in palaeosols.

5.2.6 Vertisols

Definition. Vertisols are well-developed mature soils showing a deeply weathered, relatively homogenous profile (Retallack, 1990). They are commonly found in neutral to alkaline soils with a high base status and form on a variety of parent materials, including alluvium, marls and limestones, volcaniclastic sandstones, and rocks of intermediate to basaltic composition (Mermut and Dasog, 1986; Retallack, 1990). Vertisols may form over hundreds to several thousands of years. Their degree of formation is dependent on a number of factors, including: clay content and mineralogy; climate; the amount of time that the surface is exposed; the frequency of flooding or rainfall events to which the sediments are subjected; the degree of desiccation; and the rate of subsequent burial by later sedimentation (modified from Gustavson, 1991, p. 459).

Vertisols are "clay rich soils predominantly composed of swelling clays (smectite)" (Wright, 1986, p. 296). They are characterised by thick uniform clayey profiles, either showing an A, Bt, C soil horizon sequence, or lacking soil horizon development due to argillipedoturbation, a result of seasonal shrinkage and swelling of clays in response to flooding or rainfall (wetting) and desiccation (drying) (Hunt, 1972; Wright, 1986; Birkeland and Larson, 1989; Retallack, 1990; Gustavson, 1991; Huggett, 1991). Because of the shrinking and swelling of clays, one or more of the following soil structures or features are observed: hummock and swale structure (mukkara); mulch and nutty zones; wedge-shaped and angular blocky soil aggregates (peds); desiccation cracks; clastic dykes; slickensides on intersecting fracture surfaces; calcium carbonate nodules, filaments and films (stage I to III of Gile et al. (1966)); and manganese oxides or hydroxides on the fracture surfaces (Birkeland, 1984; Retallack, 1988; 1990; Gustavson, 1991; Soil Classification Working Group, 1991; Mack et al., 1993).

Modern vertisols are found in humid to semi-arid, tropical to temperate climates with a pronounced dry season and a rainfall varying from 180 to 1520 mm/year (Wright, 1986; Retallack, 1990; Gustavson, 1991). The environment must be wet enough to cause the clays to swell and dry enough to cause them to crack (Hunt, 1972).

Diagnosis. Thick strongly-developed palaeosol which lacks an A horizon. The thick, well-developed B horizon shows strong clay enrichment (argillic (Bt) horizon), while the C horizon shows poorly-preserved relict laminations. Pedogenetic features such as mottles, root traces, including calcareous para-isotubules (after roots), and pedotubules (burrows) are common and are concentrated towards the top of the profile. Desiccation cracks (preserved by vertically-oriented clay sheets) and stress argillans (slickensides), both important in the classification of vertisols, are well preserved in the B horizon.

Type Example. The type vertisol (Figure 38) is from the upper mudrock sequence exposed in the study area with the top of the vertisol 2.71 m below the top of the mudrock sequence (Appendices 1 and 2).

+0.23 m; cover (Cr horizon of overlying palaeosol); siltstone; dark maroon brown, light maroon brown, and light grey maroon in different layers, weathering pink maroon; non-calcareous; common distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; relict laminations are very thin (<2mm), planar and parallel; black mangans occur on some secondary ped surfaces; sandy-brown siltstone diffusion cutans define very coarse secondary subangular blocky peds; medium subangular blocky peds show poorly defined (<1cm long) green illuviation argillans; dispersed white powdery carbonate nodules occur and are generally associated with diffusion cutans; abrupt irregular contact to

0 m; Bt; silty claystone; purple-maroon, weathering light purple; non-calcareous; many distinct, fine to medium, green clay-filled root traces with pale green diffuse haloes (<1mm thick), are randomly oriented and form a dense network; few distinct, fine thin white calcareous para-isotubules (after roots), with pale green diffuse haloes (<1mm thick), are randomly oriented and branch outwards; vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <2mm in width, cut through the horizon; light grey brown clayey-siltstone skeletans occur between some of the joint planes; medium to coarse angular blocky peds show common shiny purple illuviation and stress argillans and very poorly developed, minor red-maroon argillans; dispersed white powdery carbonate is common; abrupt wavy to irregular contact to

-0.99 m; Bt; siltstone; red maroon-brown, weathering dark maroon brown with tint of orange; non-calcareous; few faint to distinct, medium dark olive orange-brown glaebules are oval in shape (maximum diameter 7mm); green-grey friable, irregularly-shaped papules are present; common distinct, medium green clay-filled root traces are vertically to subvertically oriented and branch slightly; very thin green argillans occur as horizontally-oriented sheets which lens out laterally; medium to coarse angular blocky peds show common maroon-brown shiny, well-defined illuviation and stress argillans; dispersed white powdery filaments (up to 5mm long) of carbonate are present; abrupt irregular contact to

-2.46 m; BCr; sandy siltstone; dark maroon-brown, maroon-brown and light grey-green in different layers, weathering light grey green with patches of maroon weathering; non-calcareous; common distinct, medium to coarse, blue green-grey siltstone mottles (after bioturbation?) vary in shape; very few distinct, fine green-grey clay-filled root traces are randomly oriented and branch slightly; relict laminations are crudely defined and are interrupted by bioturbation and mottling; thick platy peds show dark maroon brown illuviation argillans; dispersed white powdery carbonate nodules occur; abrupt broken contact to

-2.55 m; Cr; siltstone; maroon-brown and shades of grey-green, with blue tint in different layers, weathering light grey-green with patches of maroon weathering; non-calcareous; few distinct, medium to coarse, red maroon-brown mottles vary in shape; few distinct, coarse red maroon-brown clayey siltstone meta-isotubules (after burrows) are randomly oriented; thin planar, parallel and poorly defined relict laminations are dominated by faint laminations of different shades of green-grey, with thin discontinuous lenses of maroon-brown; light red-brown siltstone skeletans occur between some of the joint planes; dispersed white powdery carbonate is common; abrupt broken contact to

-2.65 m; underlying palaeosol (A horizon of underlying palaeosol); siltstone; blue grey-green, weathering as patches of white grey-green and light pink; non-calcareous; abundant distinct, medium to coarse, maroon mottles are randomly oriented (after bioturbation); light red-brown clayey siltstone skeletans occur between some of the joint planes; dispersed white powdery carbonate nodules occur.

The palaeosol is well developed with strong evidence of pedogenesis. The presence of illuviation argillans and well- developed argillic (Bt) horizon(s) provides good evidence for lessivage. Desiccation cracks, filled with clay (dykes and/or sheets), and stress argillans (slickensides) are good indicators for shrinkage and swelling of expandable clays in the profile. Soil structures such as platy and angular blocky peds are well developed and are generally bounded by illuviation and stress argillans. The platy peds are found towards the base of the profile together with poorly-preserved relict sedimentary structures, including faint planar laminations. It is possible that the horizontally-oriented planar argillans bounding the platy peds formed along planes of weakness (lamination planes), therefore reflecting the original sedimentary structures. No organic material is present, although root traces and pedotubules, including calcareous para-isotubules, are common. The profile is predominantly maroon-brown indicating oxidising conditions at the time of formation but the presence of colour mottling suggests that the soils may have been periodically waterlogged during pedogenesis.

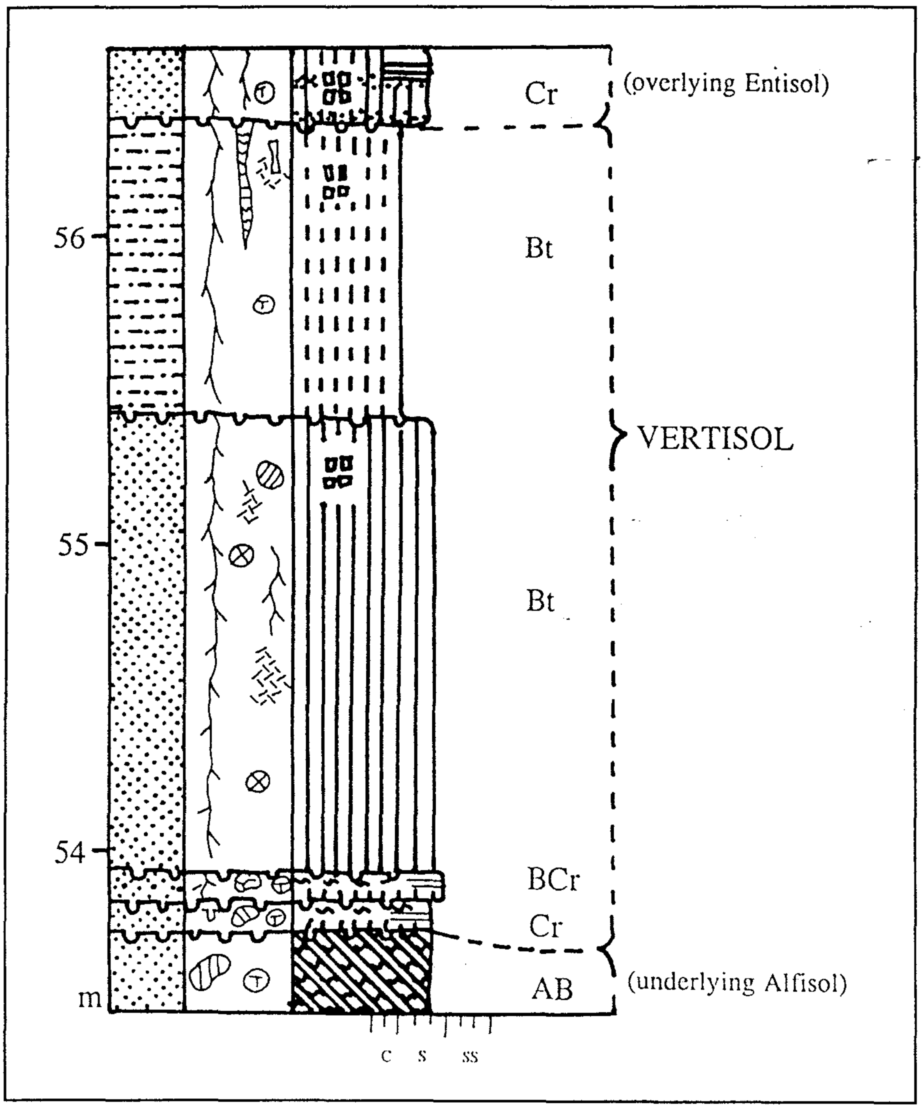

Figure 38. Schematic diagram of the type Vertisol (below 56.4m) from the Upper mudrock sequence.

The time that vertisol profiles take to develop is often dependent, amongst other factors, on the type of parent material. However, the general lack of sedimentary structures, the presence of well-developed thick argillic (Bt) horizons and pedogenetic features such as slickensides, desiccation cracks, root traces and pedotubules suggests that the soil had a relatively long time of formation, possibly several hundred to a few thousand years.

Further examples. Vertisols only occur in the lower and upper mudrock sequences in the study area (Appendices 1 and 2). They developed on parent material (alluvium) ranging in grain size from claystone and silty claystone, through clayey siltstone, siltstone and sandy siltstone, to very fine- to medium-grained sandstone. Most vertisols developed on alluvium of silty grain size. Some display features not observed in the type example. These include: clay papules; glaebules of unknown origin; lithorelicts; mottles of varying colour, grain size and shape; vein mottles of varying colour associated with clay dykes; tubules of varying type, grain size, and orientation, including calcareous para-isotubules and crystal tubes (after roots? and/or burrows?); root traces of varying colour, abundance and orientation; mangans, sesquans, skeletans, sesqui-argillans, cutans, and diffusion, illuviation and stress argillans of varying colour defining peds which vary in shape from platy and prismatic, through blocky, angular- and subangular-blocky, to granular; clay dykes and/or sheets (after desiccation cracks); sandy clastic dykes; iron-rich nodules and concretions, sometimes surrounded by pale diffuse haloes; calcareous nodules, hardpan lenses and layers, and dykes and/or sheets. Some of the features listed above do occur in the type example but differ in grain size, colour, contrast, abundance, orientation with respect to the top of the profile, and size. Relict laminations (planar and parallel, rippled, continuous and/or discontinuous) occur towards the base of most vertisol profiles and are often deformed in the vicinity of the desiccation cracks (clay dykes and/or sheets) and/or disturbed by bioturbation and pedoturbation.

Unlike the type example, many of the vertisol profiles have calcic and petrocalcic horizons which generally indicate stage II to III morphology of Gile et al. (1966). The nodules are often more concentrated in the area immediately surrounding the clay dykes and/or sheets. It is thought that surface water infiltrated the soils and/or sediments along predominantly vertical desiccation cracks rather than along a broad front (Gustavson, 1991). As evaporation occurred, solutes such as calcium carbonate were concentrated in and near the desiccation cracks (Gustavson, 1991). This resulted in the common association of the nodules with the desiccation cracks. The presence of petrocalcic and some associated calcic horizons indicates that carbonate also accumulated over a broad front with time (*per descensum* model - section 4.5.2).

Iron-rich nodules and concretions are also present in some of the vertisol profiles. If they occur together with carbonate nodules, lenses and hardpan layers in a profile, they generally occur at a higher level within the profile. The iron-rich concretions (and nodules) indicate seasonal wetting and drying of the soil profile (see section 4.5.6).

Parent material. The vertisols found in the mudrocks of the study area are developed on generally well-drained silty alluvium with a high percentage of swelling clays (probably smectite). For desiccation cracks to develop, repeated episodes of flooding and/or precipitation and desiccation are necessary, therefore the vertisols probably formed some distance form the stream channel, beyond the influence of erosive floodwaters and high sediment accretion rates, but close enough to the channel to receive thin increments of fine-grained sediment during flooding.

Relict sedimentary structures occur towards the base of many of the vertisol profiles with the more poorly-preserved structures occurring in the thicker, more mature profiles. Lithorelicts of parent material, which had broken off and fallen into the desiccation cracks, are also observed. Fine increments of wind-blown sediment may also have been added to the profiles during pedogenesis.

The abundant calcic and petrocalcic horizons indicate a constant, relatively high source of carbonate to the floodplain.

Palaeotopography. Vertisols are commonly found in clay-rich alluvium some distance from the stream channel(s). They probably developed in topographic lows on the floodplain which formed shallow ponds during the wet season. Exposure of the soils, due to subaerial drying or desiccation in the dry season, would result in the formation of cracks. Repeated episodes of flooding and/or precipitation and desiccation would result in the formation of desiccation cracks, typical of vertisol profiles. The presence of calcic and petrocalcic horizons indicates that the soils were generally permeable with good drainage and a relatively high base saturation, while the presence of colour mottles, drab root haloes, green-grey horizons and iron-rich concretions (and nodules) indicates that the soils were waterlogged or water saturated at some time (periodically) during pedogenesis.

Fossil flora and fauna. The vertisols show fine to medium clay-filled root traces and calcareous para-isotubules (after roots), both often showing associated drab haloes. The root structures are generally common and concentrated towards the top of the vertisol profiles. They are thought to represent moderately established vegetation including shrubs, ferns and cycads (Bamford, 1986).

The infilled isotubules and granotubules representing small invertebrate burrows, are tentatively placed in the ichnogenus *Skolithos*. Bioturbation in some of the horizons provides further proof of faunal burrowing activity. It is important to note that some of the pedotubules may represent preserved root casts.

Classification. In the U.S.D.A. classification (Soil Survey Staff, 1975) these palaeosols would be classified as vertisols. They commonly show the development and preservation of angular blocky soil aggregates (peds), desiccation cracks, clastic dykes, slickensides, and calcium carbonate nodules, filaments and films, all typical characteristics of vertisols.

Modern soils of this kind are commonly found on a variety of parent materials including alluvium, marls and limestones, volcaniclastic sandstones, and rocks of intermediate to basaltic composition (Mermut and Dasog, 1986; Retallack, 1990). In this study they are commonly found at some distance from the stream channel, on seasonally dry, clay-rich alluvium with a relatively high influx of carbonate (throughout pedogenesis) from an external source. Modern vertisols commonly occur in a variety of climates ranging from humid to arid, subtropical to temperate, all with definite wet and dry seasons. They generally support vegetation ranging from grassland and wooded grassland to open woodland (Retallack, 1990).

The calcic and petrocalcic horizons present in the vertisols of the study area correspond to carbonate accumulation stages II and III of Gile et al. (1966), representing several hundreds to thousands of years of formation.

Mack et al. (1993) retain the use of the term VERTISOL, defining VERTISOLS as palaeosols whose "most prominent feature is evidence of homogenisation of the profile by pedoturbation" (Mack et al., 1993, p. 132).

5.3 Summary

Six soil orders of the USDA Soil Taxonomy have been identified in the palaeosols of the study area. These include entisols, inceptisols, ultisols, alfisols, aridisols and vertisols.

The entisols occur in all three mudrock sequences. They are commonly developed on fine-grained sandy alluvium in close proximity to the stream channel, either on levee banks or crevasse splay deposits, and may show evidence of waterlogging. The entisols indicate soils formed over a relatively short period of time and cannot be used to define a particular vegetation type, nor to interpret climatic conditions at the time of pedogenesis.

The inceptisols occur in all three mudrock sequences in the study area, although they are most common in the lower mudrock sequence and rare in the upper mudrock sequence.

They commonly developed on silty and sandy alluvium some distance from the stream channel, but close enough to experience frequent flooding and moderate sediment accretion rates (either on the distal parts of crevasse splay deposits or on the dry floodplains flanking the stream channel). The inceptisols in the study area generally formed over 4000 to 9000 years, in warm to hot semi-arid climates with a seasonal rainfall of between 100 mm and 500 mm, and supported pioneer to moderately established vegetation.

The ultisols occur in all three mudrock sequences in the study area, but are rare. They commonly formed on floodplain alluvium, with a wide range in grain size, some distance from the stream channel. Evidence of seasonal waterlogging is common. The ultisols in the study area formed over at least 8000 to 10000 years, in warm humid to subhumid, temperate and seasonally dry climates, and generally supported moderately to well established vegetation.

The alfisols are common in all three mudrock sequences exposed in the study area. They commonly formed on silty to sandy alluvium some distance from the stream channel beyond the influence of frequent flooding and high sediment accretion rates. Evidence of waterlogging is present in some alfisols, however common petrocalcic and calcic horizons indicate generally well-drained soils. The alfisols generally formed over a few thousand to tens of thousands of years, in temperate to semi-arid climates with a definite dry season, and generally supported moderately to well-established vegetation.

The aridisols occur in the lower and upper (rare) mudrock sequences exposed in the study area. They commonly developed on silty and sandy, well-drained alluvium at some distance from the stream channel. Petrocalcic and calcic horizons are common. The aridisols formed over 4000 to 8000 years, in seasonal arid to semi-arid climates with and average rainfall of 300 to 400 mm's per year, and supported sparse, moderately to well-established vegetation.

The vertisols occur in the lower and upper mudrock sequences exposed in the study area. They commonly developed on well-drained silty alluvium with a high percentage of swelling clays (smectite). Shrink and swell pedogenetic structures such as desiccation cracks and slickensides are common, as well as calcic and petrocalcic horizons. The vertisols formed over several hundreds to thousands of years, in temperate to semi-arid climates with definite wet and dry seasons, and supported moderately established vegetation.

CHAPTER 6
PALAEOENVIRONMENTAL AND PALAEOCLIMATIOLOGICAL INTERPRETATION

During the Jurassic, all the continents were still assembled as a single continent, Pangaea, which stretched from the northern to southern polar regions (Francis and Frakes, 1993). In what is now southern Africa, towards the end of the late Jurassic, a series of fault-controlled depositional basins, confined to the Cape Fold Belt, formed as a result of subsidence along east-west trending faults caused by regional tensional stresses as Gondwana began to split apart (Hill, 1972; Dingle, 1978; McLachlan and McMillan, 1976; SACS, 1980; Francis and Frakes, 1993). The formation of these basins marked the beginning of Kirkwood sedimentation (Shone, 1978). According to Shone (1978), there is no major break in the deposition of the Kirkwood Formation, indicating that the deposition and burial of the sediment was controlled by moderately even rates of subsidence. This, together with repetition of similar lithological units (vertically and laterally), uniform sandstone composition, and uniform palaeocurrent direction, suggests that sedimentation occurred under essentially uniform tectonic conditions (Shone, 1978). Most authors (Winter, 1973; Lock et al., 1975; McLachlan and McMillan, 1976; Shone, 1976; 1978; Truswell, 1977; Dingle, 1978; Tankard et al., 1982; Dingle et al., 1983) agree that the Kirkwood sediments were deposited in a continental fluviatile (meandering river) environment.

The interrelationships between the conglomerate, sandstone, and mudrock facies, the numerous palaeopedological features observed in the three mudrock sections studied, and the palaeosol horizons and profiles identified provide invaluable information on the palaeoenvironmental and palaeoclimatic conditions that existed in the study area, approximately 140-120 million years ago.

6.1 Depositional palaeoenvironment

A number of fining-upwards sequences occur in the study area and typically comprise a conglomerate facies fining upwards into a sandstone facies which, in turn, fines upwards into a mudrock facies. They are interpreted as having been deposited in a meandering river system as channel deposits, channel-margin deposits and overbank deposits (see chapter 3.2). The source area for the sediments is both distal and/or extrabasinal (Witteberg Group and possibly Dwyka Formation rocks), and intrabasinal or proximal (Suurberg Group volcanics, basin floor rocks, and eroded older Kirkwood sediments). It is thought that fluvial system was fairly large, depositing thick sequences of mudrocks on the floodplains and concurrently, transporting fairly coarse bedload, including pebbles, logs and fairly large bone material in the channels as channel lag (Abson, 1993).

The proportion of conglomerate facies decreases upwards through the sequence. This may indicate: 1) a decrease in flood intensity with time; 2) a retreating source area as erosion cuts back into the hinterland, resulting in a gradual change from a proximal to more distal environment of deposition with respect to the source; and 3) a change in climate in the source area from a fairly wet climate with high, frequent rainfall, to a drier, more arid climate. The decrease in conglomerate facies is probably predominantly a result of a retreating source area, with a decrease in flood intensity playing a minor role.

Large logs of wood and smaller wood chips and charcoal chips are commonly found in both the sandstone and mudrock facies. It is thought that fairly thick vegetation, including large conifers and cycads, and smaller ferns grew close to the river channel (possibly occurring only on the levees and very proximal crevasse splays), thinning rapidly away from the channel towards the flood basin (Bamford, 1986). Numerous dead trees and branches probably littered the "forest" floor. Evidence of boring can be seen in many of the fossilised logs found in the study area. The presence of abundant charcoal chips (fusain) and charred wood chips and logs suggests that fires were fairly common in the late Jurassic/early Cretaceous. These "wildfires" were probably started by lightning strikes and appear to have been fairly common in the geological past (Scott and Jones, 1991). Wildfires may influence rates of erosion and subsequent deposition as they remove the soil-binding vegetation, making it more susceptible to erosion (Scott and Jones, 1991). Dinosaur bones have been found in the Kirkwood sediments. The dinosaurs probably lived close to the river banks, feeding off the more prolific vegetation. In the study area, sauropod (herbivore), stegosaur and hypsilophodont bones were found.

The sandstone facies was probably deposited by point bars in the meander channel. The point bar deposits are often underlain by channel lag deposits and overlain by levee, crevasse splay, channel-fill and even overbank deposits. During the rainy season, floodwaters would overtop the channel banks, flowing out onto the flood basin and depositing fine-grained sediments. In the channel area, debris including wood and bone, was swept up and washed downstream, being deposited downstream as channel lag deposits (Abson, 1993).

The floodplain was probably sparsely vegetated, with small plants and scrub occurring. Some fossil bone has been found in the overbank mudrock sequences. It is very poorly preserved and probably lay exposed on the flood basin surface for some time before being buried by a subsequent flood event. Between flood events, the flood basin was exposed to pedogenesis and several palaeosols have been identified.

6.2 Palaeosol palaeoenvironment

6.2.1 Introduction

The alluvial flood plain, including channel-margin and flood basin deposits, is the lowest lying part of the fluvial system and is generally flat and featureless. The potential for soil formation on the floodplain depends on the length of time between flood events, and on the amount of sediment deposited (Smith, 1990). Other factors also contributing to the formation of and types of soils that develop include climate, topographic relief, vegetation, organisms, drainage conditions, nature of the parent material, time of formation, and the position of the section on the floodplain relative to the position of the channel (Kraus, 1987).

Floodplain sediments are not uniform and the associated palaeosols are generally heterogeneous due to differences in accretion rates, topography and vegetation types (Smith, 1990). The maturity of the profiles developing on the flood plains depends on the frequency of flooding and sedimentation; immature profiles develop in areas where the floodplain is inundated with frequent flood events, too frequent to allow any significant pedogenesis; and mature profiles develop in areas where the inundation of sediment bearing floodwaters is low, allowing the new material to be incorporated into the soil horizon without affecting the solum (Smith, 1990). Generally, palaeosols develop in aggrading alluvial systems where the sediment accumulation rates decrease away from the channel (Kraus and Aslan, 1993). Alluvium deposited by overbank floods generally thins away from the channel and overbank areas farther from the channel may be less frequently flooded than those close to the channel (Kraus and Aslan, 1993). There is generally an inverse relationship between sediment accumulation rates and soil maturity (Leeder, 1975; Kraus and Aslan, 1993).

Kraus and Bown (1986; 1988) and Smith (1990) concluded that variations in the pedogenic maturity of palaeosols can be attributed to their proximity to the ancient channel margin. The least mature soil profiles develop closest to the channel margin and the most mature soil profiles develop on the distal parts of the floodplain, beyond the influence of frequent sedimentation (Bown and Kraus, 1986; Smith, 1990; Kraus and Aslan, 1993).

The differential rates of pedogenesis versus those of flood basin accretion through deposition of sediments during flooding, result in a variety of palaeosol types. Palaeosols commonly develop on the flood basin and channel-margin deposits in areas where there is little topographic variation and a low slope. According to Smith (1990), alluvial palaeosols can be used as indicators of geomorphology, floodplain accretion rates, migration behaviour of the channels, and time-equivalent floodplain sedimentation. The floodplain accretion rates are influenced by: i) intrabasinal variations, either due to flooding, or due to channel diversion by alluvial processes (avulsion or lateral channel migration); and ii) extrabasinal variations due to changes in the regional climate and variations in sediment yield related to the climate and the type of vegetation (changing amounts of precipitation cause variations in flood frequency and sediment concentration) (Leeder, 1975). It is important to note that over significant geological time periods, external climatic and tectonic factors are important controls on the rates of sediment accumulation (Kraus, 1987). The effect of tectonics may be recorded by the maturity of the palaeosols; maturity generally decreases during tectonic activity and increases in periods of quiescence (Kraus, 1987).

Palaeosols are recognised by comparing the features observed (such as form, composition and associated structures) within the palaeosols with those observed in modern soil profiles (Bown and Kraus, 1981). According to Kraus and Aslan (1993), the episodic nature of flood basin deposition and the heterogeneous nature of the flood basin sediments makes the recognition of palaeosols representing discrete pedogenic episodes difficult. With the influx of sediment into the flood basin, existing soil profiles may be buried and pedogenesis halted, or the sediment may be incorporated into the existing profile, resulting in vertical profile accretion and cumulative pedogenesis (Kraus and Aslan, 1993).

Simple palaeosol profiles developed when the rate of sedimentation was fairly rapid (close proximity to the channel) and thus each of the palaeosols represents an individual depositional episode followed by a period of pedogenesis (Kraus and Aslan, 1993). Pedogenesis was halted with the next depositional event (Kraus and Aslan, 1993). A cumulative palaeosol profile developed initially as a simple palaeosol. However, in cumulative palaeosol profile development, the initial stage of rapid sedimentation was followed by a longer period of slow and episodic sedimentation (Kraus and Aslan, 1993).

Sedimentation and pedogenesis could occur concurrently as the influxes of sediment were slow enough and sporadic enough not to result in complete burial of the developing profile (Kraus and Aslan, 1993). The cumulative profiles are generally well-developed, with abundant root traces and burrows. They commonly represent palaeosols formed on true overbank deposits, at some distance from the channel.

Kraus (1987) identified a number of different types of palaeosol sequences. Simple sequences (3 to 7 metres thick) comprise one or more soil profiles, bounded above and below by crevasse splay deposits, the latter showing little to no evidence of pedogenesis (Kraus, 1987). Compound sequences (tens of metres thick) are multistorey sequences comprising several simple sequences, bounded above and below by channel sandstones. The pedogenic maturity of the multistorey palaeosols commonly increases and then decreases, reflecting a response to periodic channel avulsion (Kraus, 1987). Variations in sediment accumulation rate and type of parent material, controlled by local depositional and erosional conditions, generally control the formation of simple and compound sequences (Kraus, 1987). A third type of sequence, the palaeosol megasequence, is defined by Kraus (1987, p. 608) as comprising "at least several compound pedofacies sequences" and is characterised "by a distinct upward change in the maximum or overall maturity of its constituent compound pedofacies sequences".

Multistorey palaeosol sequences are observed in the study area. Numerous simple sequences, with each sequence bound at the upper and lower contacts by crevasse splay and/or levee deposits, are sandwiched together between thick sandstone channel deposits, forming compound sequences. The formation of the simple and compound sequences was largely controlled by the frequency of flooding and the rates of sediment accumulation, the nature of the parent material (alluvium), and the distance from the channel.

6.2.2 Palaeosol profiles and sedimentary facies

In the study area, palaeosols are present in the lower, middle and upper mudrock sequences. The palaeosols include entisols, inceptisols, ultisols, alfisols, aridisols and vertisols in different stages of pedogenic maturity. The mudrock sequences are all underlain by fining-upward, coarser-grained, channel-related sandstone deposits, which are often capped by finer-grained levee and proximal crevasse splay deposits showing little to no evidence of pedogenesis. The lower and middle mudrock sequences show an erosional contact with the overlying channel-related deposits, which mark the base of the next fining upward cycle (Appendix 1). The upper mudrock sequence is overlain, with angular unconformity, by the horizontal beds of the Tertiary Alexandria Formation. The three mudrock sequences can be classified as three individual compound palaeosol sequences.

As previously mentioned, the Kirkwood Formation rocks represent sediments deposited by a meandering river system and its associated flood basin. The flood basin environment, including the channel-margin and overbank areas, as in similar modern meandering river systems, was probably fairly dynamic. The palaeosols are thought to have developed on a large, fairly featureless alluvial plain, and were preserved through almost continuous floodplain aggradation (vertical accretion). Periods of non-deposition, weathering and pedogenesis were interrupted episodically by flood events. The parent material (alluvium) on which the palaeosols developed was fairly heterogeneous, comprising fine-grained sandstones and siltstones (proximal and distal crevasse splay and/or levee deposits) interbedded with flood basin siltstones and claystones.

Some of the more immature entisols and inceptisols are characterised by simple profiles, reflecting formation in close proximity to the meandering channel (Figure 39). The more mature palaeosols in the study area (alfisols, ultisols, vertisols and possibly aridisols) show cumulative profiles where small increments of sediment were added periodically by low energy floodwaters. These cumulative profiles generally show well-developed pedogenic features and probably represent palaeosols formed on overbank deposits, some distance from the channel (Figure 39).

Three depositional facies have been identified within the channel-margin and overbank areas, depending on distance from the channel and frequency of flooding. These facies include the channel-margin comprising levee and proximal crevasse splay deposits, the proximal flood basin deposits comprising distal crevasse splay deposits interbedded with flood basin deposits, and the distal flood basin deposits comprising flood basin siltstones and claystones (Figure 39). The boundaries between the three facies are not always clear cut, especially between the proximal and distal flood basin facies.

Six palaeosol orders, including entisols, inceptisols, ultisols, alfisols, aridisols and vertisols have been identified from the three mudrock sequences. The entisols and inceptisols commonly occur within the channel-margin facies (Figure 39). The remaining four orders may occur in both the proximal and distal flood basin facies depending on their maturity, the

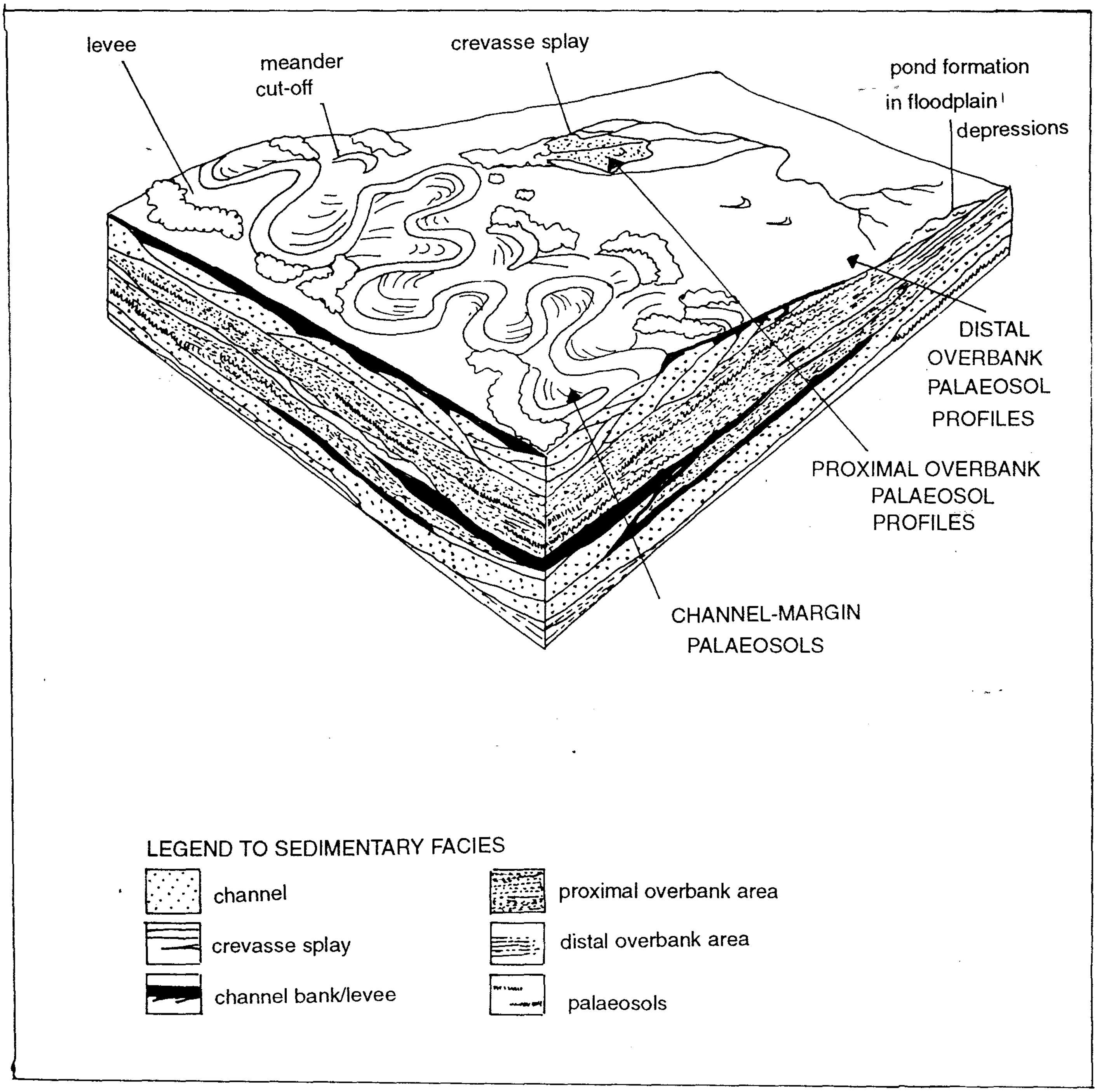

Figure 39. Summary diagram of showing the distribution of the channel-margin, proximal flood basin, and distal flood basin palaeosol profiles.

nature of the parent material, and the frequency of flooding (proximity to the channel) (Figure 39).

A. Channel-margin palaeosols

The channel-margin palaeosols identified in the study area include entisol and inceptisol profiles, which are typically poorly developed and immature, with little evidence of pedogenesis. Horizonation is poorly developed with little alteration of the parent material. The channel-margin palaeosols formed on levee and proximal crevasse splay sediments and were deposited in close proximity to the channel.

The entisols show very little to no soil horizonation. Poorly developed A and C horizons are present in some of the more mature entisol profiles, but no B horizon is present. The entisols commonly consist of yellow-orange and olive sandstones, and alternating, interlaminated and interbedded grey, grey-brown and maroon-brown sandstones, siltstones and rare claystones. Relict laminations are common and are generally unaltered by pedogenesis. Evidence that there has been some pedogenesis includes the presence of root traces, burrows and mottles. Flakes of black organic material and rare calcareous nodules also occur in some entisols, while initial clay accumulation is evident in a few of the entisol profiles. The root traces are generally fine to medium and vertically oriented. Some pedotubules (after roots? and/or burrows?) are also present. The calcareous nodules are generally small and rounded.

The inceptisols are similar to the entisols but commonly show the development of a faint B horizon. They commonly consist of yellow-orange and olive, grey, grey-green and grey-brown sandstones, maroon-brown siltstones and alternating, interlaminated and interbedded grey, grey-brown and maroon sandstones, siltstones and rare claystones. Relict laminations are common in the C horizons but faint relict laminations are also present in some inceptisol B horizons and even A horizons. Evidence for pedogenesis includes faint horizonation, the presence of root traces, burrows, mottles and rare, generally poorly-developed soil structures such as peds and even cutans. Flakes of black organic material and calcareous nodules also occur in some inceptisols, with initial clay accumulation evident in most profiles. Patches of calcareous cemented material (not nodules) occur in some of the B and/or Cr horizons. The root traces are generally fine to medium and vertically oriented. Some pedotubules (after roots? and/or burrows?) are also present. The calcareous nodules vary in shape, size and abundance, and occur in laterally continuous horizons. Poorly-preserved fragments of bone were found in a calcareous inceptisol in the middle mudrock sequence (Bkc horizon, 11.94m from the top of the sequence).

Both palaeosol orders are characterised by poorly-developed profiles consisting of predominantly yellow-orange, olive, grey, grey-brown and grey-green sandstones and interlaminated grey-brown and maroon-brown siltstones and sandstones. Root traces and burrows are interpreted as indicating a portion of the A horizon. This may pass down into the C horizon in entisols and the B and/or C horizon in the inceptisols. The calcareous nodules are commonly found in the B and/or C horizons and are generally more developed and larger in the inceptisols. Mottling commonly occurs in all horizons. The colour banding present in both palaeosol orders is thought to reflect the original beds and laminations. The sedimentary sequences resemble those found in modern levee and proximal crevasse splay deposits found in close proximity to the channel (channel-margin deposits). The levee deposits are not as well preserved as the crevasse splay deposits. In most cases, the laminations preserved are parallel and planar, although some do show soft sediment deformation.

Following a flood event, burrowing invertebrates and plants colonised the deposits. With time, carbonate-rich rain waters percolated downwards, precipitating in the lower horizons and eventually becoming concentrated into glaebules (nodules). It is possible that the nodules were precipitated from groundwaters, however, there is little evidence to support a high water table and/or prolonged waterlogging of the sediments. Pedogenesis was halted by the next major flood event, resulting in preserved simple palaeosols and reflecting frequent flooding and relatively high rates of sedimentation. In modern meandering river systems, this occurs in areas which are in close proximity to the channel (levees and/or proximal crevasse splays). In some cases, small increments of sediment may have been added to the palaeosols without interrupting the pedogenesis resulting in cumulative palaeosols. The periodicity of major flooding would still have to be frequent enough to prevent the formation of more mature palaeosol profiles. Smith (1990) observed similar palaeosols in the Late Permian Adelaide Subgroup strata northwest of Beaufort West. He classified the palaeosols as levee/channel-bank palaeosols (Smith, 1990).

Thus the entisols and inceptisols found in the mudrock sequences of the study area probably formed in close proximity to the channel, on levee and proximal crevasse splay deposits.

B. Proximal overbank palaeosols

The proximal overbank palaeosols identified in the study area include ultisols, alfisols, vertisols, and aridisols and very rare more mature inceptisols. The palaeosols commonly form on the more distal crevasse splay deposits which are commonly interbedded with flood basin sediments, between the more proximal channel-margin facies and the distal overbank facies. The proximal overbank deposits generally make up the bulk of the interchannel deposits, accumulating on the fairly level areas at some distance from the channel (Smith, 1990).

The ultisols show well-differentiated, mature profiles and consist of parent material ranging from sandstone, through siltstone to claystone. Colours are more variable than in the channel-margin palaeosols and vary from green and green-grey to maroon-brown, the latter being more common. Faint relict horizontal and rippled laminations often occur in the basal horizons of the palaeosols. Root traces and pedotubules (after burrows?) are common, and are concentrated towards the top of the profiles. The ultisols are distinguished from the alfisols by their lack of carbonate accumulation. The maroon-brown colouration of the horizons suggests oxidising conditions, however, the presence of common grey green horizons, together with colour mottling and drab-haloed root traces, suggests periodic waterlogging of the soils during their development. The ultisols have well-developed soil structures (peds), illuviation argillans and argillic (Bt) horizons, some horizons showing the development of iron-rich nodules and concretions.

The alfisols show generally mature, well-differentiated profiles showing strong clay enrichment in the argillic (Bt) horizons. They consist of parent material with a range in grain size from sandstone through siltstone to claystone. Colours range from grey and grey-green to maroon-brown and maroon purple. Shades of the latter two are predominant, indicating well aerated, oxidised soils. Relict planar and rippled laminations occur towards the bases of the alfisol profiles, although faint laminations may be visible further up in the sequence (emphasized by the original sedimentary texture) indicating slow sediment accumulation during pedogenesis (cumulative palaeosols). Root traces and pedotubules (after burrows?) are common, and are concentrated towards the top of the profiles. Soil structures such as peds and cutans are well developed and colour mottling is common. Most alfisols identified in the mudrock sequences contain abundant calcareous nodules of varying shape, size and abundance. Calcareous spherulites, crystal sheets and rare calcareous desert rose pseudomorphs have been found in some alfisol profiles. Hardpan layers and lenses are also common, especially in the lower mudrock sequence. The calcic and petrocalcic horizons generally indicate stage II to III morphology (Gile et al., 1966).

The aridisols generally show moderate development and are formed on grey, grey-brown, yellow-brown, and maroon-brown parent material ranging in grain size from sandstone through siltstone to mudstone. Relict sedimentary structures, including planar laminations and ripple cross-laminations, are well preserved towards the bases of the aridisol profiles and soil structures are rare. Root traces and pedotubules (after burrows) are common, becoming more abundant towards the top of the profiles. Calcareous nodules and hardpan layers and lenses are common and are concentrated in well-developed calcic and petrocalcic horizons. Calcareous crystal tubes (after roots and/or burrows) are common, and calcareous dykes, sheets and veins occur in some of the profiles. The carbonate accumulation in the aridisols is stage II to III of Gile et al. (1966) and commonly occurs in the sandier horizons.

The vertisols show well-differentiated, mature soil profiles with extensive clay enrichment in the argillic (Bt) horizons. They are very similar to the alfisols in most characteristics such grain size, colour and soil structure. Root traces and pedotubules are common, as are calcareous nodules and hardpan layers and lenses. The calcic and petrocalcic horizons generally indicate stage II to III morphology (Gile et al., 1966). A distinguishing feature in the vertisols is the presence of well-developed stress argillans (slickensides) and numerous clay-filled desiccation cracks (form clay dykes and/or sheets) which often penetrate deep within the profile. The vertisol profiles are predominantly maroon-brown indicating oxidising conditions at the time of formation, however, the presence of colour mottling suggests some waterlogging. The presence of iron-rich concretions and nodules, together with well-developed stress argillans suggests seasonal wetting and drying of the soil profile. In most profiles, there is a concentration of calcareous nodules in the vicinity of the clay sheets and/or dykes. Calcareous septarian nodules occur and are most common in the upper mudrock sequence vertisols. Relict sedimentary structures, including planar and ripple laminations, are common towards the base of the profiles.

All four palaeosol orders are characterised by moderately to well-developed profiles with well-defined horizonation. They commonly form on parent material with a wide range in grain size. Colour banding is common, with predominant maroon-brown horizons indicating well-drained, oxidised soils. The palaeosols developed on the relatively level areas of the flood basin, on the distal parts of crevasse plays deposits and adjacent flood basin deposits. Where preserved, relict planar laminations and/or ripple cross-laminations are predominant. These structures are typical of distal crevasse splay and flood basin deposits, indicating formation of the palaeosols at some distance from the channel.

In the aridisol profiles, the horizontation is not very well developed and there is little evidence of clay illuviation. It is thought that the aridisols developed further from the channel than the other three palaeosol orders. The ultisols are distinguished by the lack of carbonate and the presence of well-developed argillic horizons. They probably formed in depressions on the flood basin. Ponding of water during the wet season or poor drainage due to the abundant clay, accounts for the presence of drab haloes around the root traces, green-grey colouration of some of the horizons, and the colour mottling common in most of the profiles. The alfisols and vertisols formed on the well-drained parent material and form the bulk of palaeosols found in the proximal overbank facies. The translocation of clay and carbonate probably took place simultaneously, with the calcic and petrocalcic horizons indicating stage II to III morphology (Gile et al., 1966).

Because of the distance from the channel, flooding is reduced in periodicity and intensity, and weathering and pedogenic processes are active for long periods of time (up to tens of thousands of years). It is likely that between major flood events, small increments of sediment were added to the profiles, either from smaller, low intensity flood events, or from aeolian dust (main source of $CaCO_3$). This resulted in the formation of cumulative palaeosols as the amount of sediment deposited during the small floods was not enough to halt pedogenesis by complete burial of the soil profiles.

Following a major flood event, plants and burrowing invertebrates colonised the sediments and pedogenic processes began. With time, carbonate and clay were leached from the upper horizons and precipitated in the lower horizons. During flooding, the profiles in the lower lying depressions on the flood basin became waterlogged, drying out during the dry season. Episodic, low energy floods may have occurred but they were generally too small to halt pedogenesis.

The maturity of the proximal overbank palaeosols generally indicates that they developed on well-aerated, oxidised sediments in areas where the frequency of flooding and the rates of sediment accumulation were low. In modern river systems, this occurs in areas at some distance from the channel (on distal crevasse splay and associated flood basin sediment).

Thus, it is likely that a large proportion of the ultisols, alfisols, aridisols and alfisols identified in the study area formed away from channel influences on distal crevasse splay deposits and adjacent flood basin deposits.

C. Distal overbank palaeosols

The distal overbank palaeosols observed in the mudrock sequences are rare. They include the less mature vertisols and aridisols and possibly relatively immature alfisols and ultisols. These palaeosols consist of grey-brown, green-grey and maroon-brown interbedded siltstones and claystones with minor sandstones. Relict laminations are generally well preserved. The profiles are similar to those occurring in the proximal overbank palaeosols but are more immature, with less evidence of clay illuviation. Desiccation cracks and calcic and petrocalcic horizons are common. Aeolian dust is an important source of sand and carbonate in this facies.

The relative immaturity of the palaeosols is not due to frequent flooding and sedimentation, but due to a lack of water which is necessary in the translocation of clay. Because the parent materials are deposited in the axial depression of the flood basin, it is possible that the ground water table was high during the wet season. This caused waterlogging of the lower soil horizons for part of the year resulting in drab-haloed root traces, colour mottling and drab coloured horizons. It is thought that the carbonates may have been precipitated during the dry season, in response to evaporation and the lowering of the water table.

Distal overbank palaeosols observed in the study area are rare and formed at great distance from the channel, beyond the influence of all but the most catastrophic flood events. In this facies, the maturity of the palaeosols is not a reflection of distance from the channel and frequency of sedimentation.

6.2.3 Pedofacies sequences

The three types of depositional facies and their associated palaeosols are interpreted as having formed on aggrading channel-margin and overbank deposits. The three mudrock sequences comprise successions of stacked palaeosols (both simple and cumulative palaeosols).

Bown and Kraus (1987, p. 599) define pedofacies as "laterally contiguous bodies of sedimentary rock that differ in their contained lateral contiguous palaeosols as a result of their distance (during formation) from areas of relatively high sedimentation". This definition is applicable to the palaeosols found in the study area as different pedofacies can be determined from the differences in the types and maturities of the palaeosols as one moves away from the channel.

In the study area, the vertical fining-upward sequences are the result of deposition in an aggrading meandering river system. The basal sediments comprise channel lag and point bar deposits which fine upwards into levee and possibly very proximal crevasse splay deposits (Appendix 1, section A). Section A is capped by siltstones showing no evidence of pedogenesis. The basal sediments (section A) were deposited by a meandering river channel (channel deposits) (Figure 40a(i)). The channel may have migrated laterally with time, but appears to have been confined in some way to a relatively narrow meander belt. According to Walker and Cant (1984), abandoned meander loops ultimately become plugged with siltstone and claystones, and with time, the plugs become more abundant. The plugged meander loops are fairly resistant to erosion and thus the meandering rivers can become confined to a relatively narrow meander belt (Walker and Cant, 1984). With continued deposition the channel becomes elevated above the flood basin until, during flooding, a catastrophic break in the levees results in channel avulsion.

In the study area, the thickness of the channel deposits in section A (Appendix 1) suggests that the meandering river was confined to a meander belt. With time, the channel may have become elevated above the flood basin, eventually resulting in avulsion to a new path on a lower part of the flood basin. The thickness of the siltstones capping the sandstones is approximately 10 metres. The siltstones were probably deposited by crevasse splays close to the new meander channel, with the frequency of sedimentation preventing pedogenesis (Figure 40a(ii)).

With time the channel migrated back to its initial position on the floodplain (higher

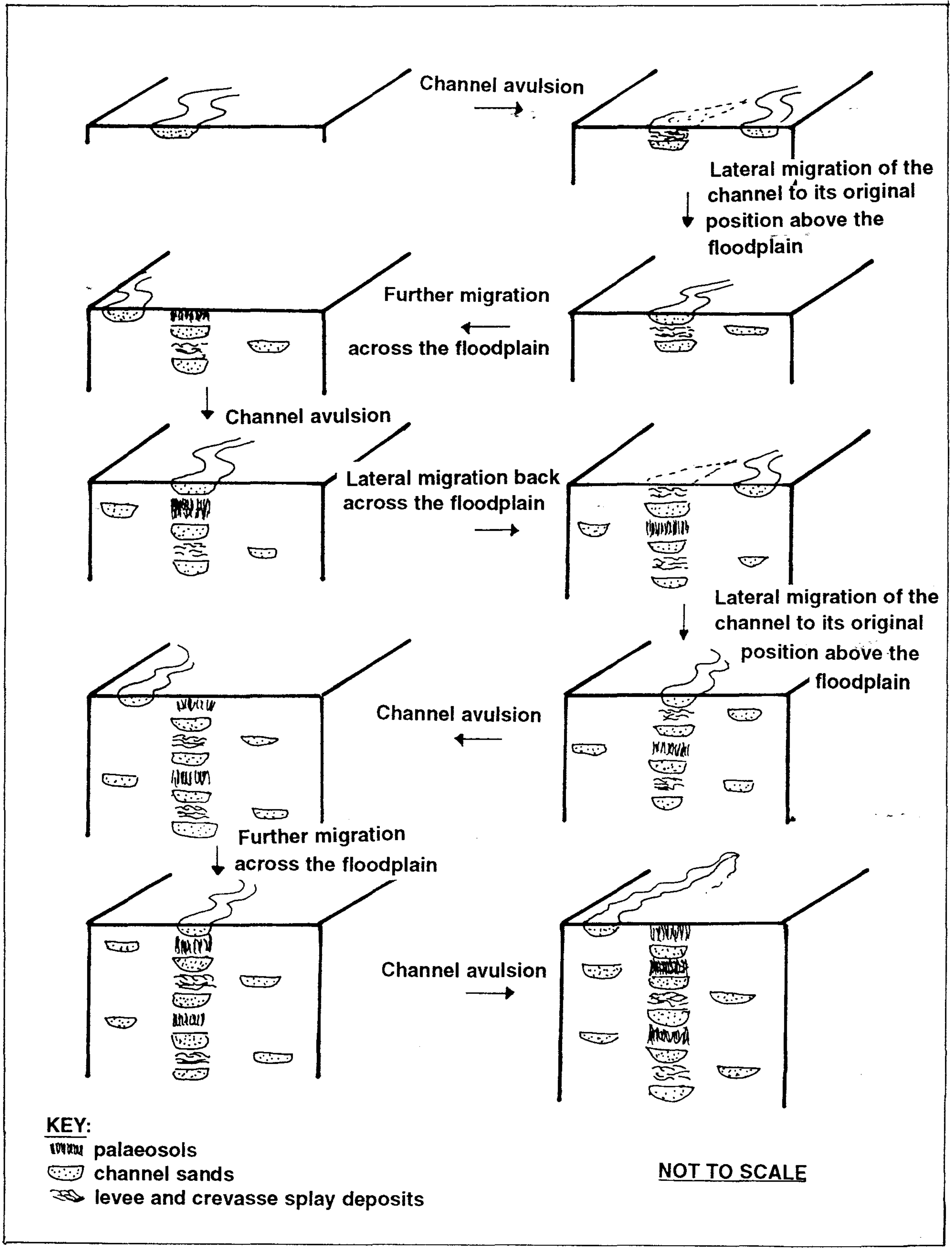

Figure 40. Schematic diagrams showing the possible sequence of events which resulted in the formation of the sedimentary and palaeosol sequences observed in the Kirkwood Formation sediments exposed in the study area.

in sequence due to aggradation and vertical accretion) (Figure 40b). The conglomerates and sandstones at the base of section B (Appendix 1) were subsequently deposited by the meandering channel. The channel deposits are not nearly as thick the basal sandstones, suggesting that the channel continued to migrate across the flood basin without being restricted by abandoned clay-plugged meander loops. Crevasse splay and flood basin sediments were deposited over the channel deposits with time and pedogenesis occurred during periods of non-deposition.

A detailed sedimentological and pedological log of the interchannel lower mudrock sequence, overlying the channel sandstones in section B (Appendices 1 and 3.1), shows sequences of pedofacies that are linked to distance from the meandering channel. Crude depositional cyclicity is evident. Simplified, the cycle generally begins with channel-margin deposits (levee and proximal crevasse splay deposits) and associated palaeosols (entisols and inceptisols). Root traces and burrows are common, but there is little evidence of horizonation. Calcareous nodules may be present in some of the inceptisols but they are not abundant.

The channel-margin deposits give way upwards to proximal overbank deposits with associated ultisols, alfisols, vertisols and aridisols. Clay enriched horizons are common and the profiles are generally mature and well differentiated. Calcareous nodules and hardpan layers are evident in most of the palaeosols, with the exception of the ultisols. The calcareous palaeosols formed on well-drained oxidised soils, possibly on slight topographic highs while the ultisols probably formed in depressions on the flood basin surface. The proximal overbank deposits formed on distal crevasse splay and adjacent flood basin sediments (Figure 39, 40c).

In some cases, the proximal overbank deposits and palaeosols grade upwards into distal overbank deposits, formed on "true" flood basin sediments away from the channel influence. The palaeosols include fairly immature alfisols, ultisols, aridisols and vertisols. It may be difficult to distinguish between these profiles and inceptisols, however, the levels of carbonate accumulation in some indicate that more mature profiles formed over approximately 10 000 years. These then give way upwards to proximal overbank deposits and palaeosols and/or channel-margin deposits and palaeosols.

An exception to the cycle occurs in the first palaeosols directly above the basal channel sandstones in section B (Appendices 1 and 3.1). These are relatively mature alfisols, formed on interbedded distal crevasse splay and flood basin deposits. This may indicate that the channel moved away from its original position on the floodplain by avulsion and not by gradual stream migration.

The simplified cycles are similar to the simple pedofacies sequences described by Kraus (1970). The change from channel-bank to proximal overbank palaeosols and vice versa reflects the movement of the meandering channel across the flood basin. As the channel moved towards the area represented by the log, so incursions of crevasse splays onto the flood basin became more frequent and deposition rates increased. Between depositional events, there was only enough time for poorly-developed palaeosols to form. As the channel moved way from the area logged, so the frequency of flooding and deposition decreased and more mature profiles developed. Wind blown aeolian dust was also deposited and incorporated into the sediments, providing an important source of Ca^{2+}, necessary in the formation of calcic and petrocalcic horizons.

The lower mudrock sequence comprises several stacked simple pedofacies sequences, representing a compound multistorey sequence as defined by Kraus (1987). The sequence is underlain and capped by channel deposits.

The lower mudrock sequence abruptly gives way to the basal conglomerates and sandstones in section C (Appendix 1). The contact between the mudrocks and the overlying conglomerates is erosional and abrupt, recording the arrival of the channel and its erosion of the flood basin sediments (Figure 40d(i)). The conglomerates and sandstones in section C (Appendix 1) represent channel deposits; channel lag deposits overlain by point bar deposits. Between section C and section D (Appendix 1) there is a scree gap of approximately 30 metres. The nature of the sediments beneath the scree is unknown. In the study area, this section is marked by an eroded valley, and it is likely that the sediments beneath are mudrocks although there is no surface outcrop or evidence to support this.

Section D comprises sandstones and siltstones representing channel and channel-margin deposits (point bar, very proximal crevasse splay and levee deposits) (Figure 42d(ii)). There is no evidence of pedogenesis. The fining upwards may indicate the lateral migration of the channel giving way, vertically, to the aggrading channel-margin deposits.

The conglomerates (channel lag deposits) and sandstones (channel deposits - point bars and levee deposits) at the base of section E have a sharp erosional contact with the top of section D (Appendix 1). This indicates the return of the channel and erosion of the near-channel deposits (Figure 42d(iii)). The channel deposits comprising the basal part of section E (Appendix 1) are relatively thick, hinting at the formation of a confined meandering channel within a meander belt. Eventually, avulsion occurred and a new channel formed on a lower part of the flood basin (Figure 40e).

A detailed sedimentological and pedological log of the interchannel middle mudrock sequence, overlying the channel sandstones in section E (Appendices 1 and 3.2), shows sequences of pedofacies again linked to distance from the meandering channel. The middle mudrock sequence is not as thick as the upper and lower mudrock sequences. Again crude depositional cyclicity, similar to that in the lower mudrock sequence, is evident.

The palaeosols are similar to those found in the pedofacies of the lower mudrock sequence, however, the abundant calcic and petrocalcic horizons present in the lower mudrock sequence are absent in this sequence. Calcareous nodules do occur in some of the palaeosols but hardpan layers and lenses are absent. The lack of carbonate may reflect a change in the climate or a reduction in the amount of Ca^{2+} infiltrating the soil, due to a reduction in the amount of aeolian dust being incorporated into the sediments. Towards the middle of the section there is a thick sequence of stacked inceptisols developed on crevasse splay sands. This suggests that the channel was in close proximity to the area, represented by the section, for a considerable amount of time. However, other palaeosols such as the proximal overbank palaeosols, indicate that the channel did migrate away from the area. If there was an increase in the annual rainfall, together with an increase in frequency of flooding and a decrease in the amount of dust entering the meandering river system, any carbonate entering the system may have been leached from the soils.

The middle mudrock sequence is characterised by palaeosols formed on near-channel and proximal overbank deposits, with a number of simple pedofacies sequences stacked to form a multistorey compound pedofacies sequence. The changes in the maturity of the palaeosols upwards through the sequence reflect the movement of the channel away from and towards the area represented by the logs.

The middle mudrock sequence (Section E, Appendix 1; Appendix 3.2) coarsens upwards into the channel sandstones at the base of section F (Appendix 1). This reflects a relatively gradual return of the channel (Figure 40f). The sandstones at the base of section F (Appendix 1) were deposited as levee, channel lag and point bar sediments. The sequence is relatively thick, possibly reflecting confinement of the meandering river to a meander belt.

Again avulsion resulted in the formation of a new channel on a low part of the flood basin (Figure 40g).

A detailed sedimentological and pedological log of the interchannel upper mudrock sequence, overlying the channel sandstones in section F (Appendices 1 and 3.3), shows sequences of pedofacies that are linked to distance from the meandering channel. Crude depositional cyclicity is evident, as in the other two sequences. The simple pedofacies sequences, bounded above and below by channel-margin crevasse splay deposits, are thicker than those in the other two mudrock sequences and comprise several palaeosols.

The palaeosols (alfisols), directly above the channel sandstones (Appendix 3.3) are well developed, supporting the theory that the channel abruptly moved to another part of the flood basin, resulting in sediments that were initially proximal, becoming distal. Generally the simple pedofacies sequences reflect the movement of the meandering channel towards and away from the area represent by the logged section.

In the palaeosols of the upper mudrock sequence, there is a general lack of calcareous nodules and hardpan layers and lenses, however, they are more common than in the middle mudrock sequences. Septarian nodules dominate the types of calcareous nodules present, indicating waterlogging of the horizon in which they formed, followed by desiccation. The septarian nodules may have formed in palaeosols representative of the distal overbank palaeosol facies, that is, they formed in soils developing on true flood basin sediments.

Relatively thick crevasse splay (channel-margin palaeosols) deposits occur within the mudrock sequence (Appendices 1 and 3.3), indicating formation of the palaeosols) in close proximity to the channel for a relatively long period of time. The top of the upper mudrock sequence is not visible in the study area. The upper mudrock series has an abrupt erosional contact with the overlying Tertiary Alexandria Formation limestones (Figure 40h).

Thus the fining-upwards sequences exposed in the study area represent a dynamic, vertically accreting meandering river system. Palaeosols present in the interchannel areas can be used to determine distance from the channel and give an idea of the rates of sedimentation and the migration of the channel across the flood basin. Unfortunately, the interpretation is limited by the lack of laterally extensive outcrop, with exposures in the area generally less than 20 m wide. The lateral continuity of the channel, channel-margin and overbank (and associated palaeosol) deposits is unknown.

6.2.4 Interpretation of common pedogenic features

There are several indicators of pedogenesis within the mudrock sequences. These include root traces, burrows and/or pedotubules, mottles, colour banding, glaebules, desiccation cracks, slickensides and soil structures (see chapter 4, p.43). These are important to the understanding of the drainage conditions, the vegetation and climate, and to a lesser extent, the topography, at the time of palaeosol formation.

Root traces observed in the study area occur in most palaeosol orders, although the abundance varies depending on distance from the channel and maturity of the palaeosol. The root traces are generally fine to medium in size, indicating small plants, including scrub, fern-like vegetation and possibly a few scattered trees. There is very little evidence (only one horizon with large taproots is observed) for forests of trees on the flood basin. However, the presence of large fossil logs in the coarser-grained channel-related deposits suggests that large trees were present. It is thought that the trees, including conifers and cycads, formed a canopy of riparian forest on the banks of the channel. These forests thinned rapidly away from the channel, giving way to sparse scrub- and fern-like vegetation in the more distal areas of the flood basin. Drab root haloes are present in some of the horizons and are interpreted, in some cases, as indicative of waterlogging. In other palaeosols, the drab haloed root traces occur in association with calcretes, which form in dry, well-aerated soils. Here, they are thought to be due to a combination of factors including chelation of iron and manganese in the rhizosphere, post burial and subsidence groundwater gley, and enhancement through diagenetic reddening (see section 4.2).

In this study, root traces were used to define the tops of palaeosols. The traces are significant as they indicate periods of non-deposition on the floodplain, while their size suggests relatively small plants. The depth of penetration of the root traces in the palaeosols is variable, however, they commonly penetrate through most horizons within any one profile. The root traces and burrows and/or pedotubules indicate well-aerated oxidised soils and a generally low water table (see sections 4.2 and 4.3).

Colour mottles are also common and are thought to represent hydromorphic processes, reflecting fluctuations in the water table, impeded drainage, or episodic or seasonal soil saturation. As the water table is interpreted as being fairly low, it is probable that the mottles formed due to surface water gley in lower lying areas on the flood basin (ponds or abandoned channels). The soils forming in these areas would have been subjected to episodic or seasonal soil saturation, either in response to periodic overbank flooding, or in response to seasonal fluctuations of the ground water table, especially in the low lying areas adjacent to the channel (see section 4.4).

Colour banding is common with maroon-brown, grey-green and grey-brown horizons predominating. The maroon-brown horizons are most common and indicate that pedogenesis took place under oxidising conditions. The green-grey horizons reflect waterlogging due to a seasonally high water table and/or ponding in depressions on the flood basin after flooding or during the wet season. Grey-brown horizons are common in palaeosols close to the channel margin. Generally the colour of the horizons was dependant on the oxidation or reduction of iron in the sediments at the time of pedogenesis (see section 4.5).

Calcareous glaebules and hardpan layers and lenses are very common to dominant in the lower mudrock sequence, fairly rare in the middle mudrock sequence, and few to common in the upper mudrock sequence. The numerous calcrete profiles (stage II to III accumulation of Gile et al., (1966)) in the lower mudrock sequence indicate that the palaeosols formed in well-drained sediments some distance from the channel, beyond the influence of frequent flooding, that is, in the proximal overbank facies. This agrees with the pedofacies interpretation in section 6.2.3. The formation of the calcretes (petrocalcic and calcic horizons) suggests that there was a high influx of Ca^{2+}-rich aeolian dust into the area during pedogenesis. The general lack of carbonate accumulation in the middle mudrock sequence palaeosols was probably due to a combination of the following controlling factors: a decrease in the influx of Ca^{2+}-rich dust into the basin; an increase in the frequency of flooding and sedimentation due to proximity to the channel; an increase in rainfall causing leaching of calcium from the soil profiles; and/or poorly drained, clay-rich parent material. In the upper mudrock sequence, the nodules are generally septarian, indicating formation in stagnant ponds formed in depressions on the flood basin. The influx of Ca^{2+}-rich dust was probably moderate and together proximity to the channel and/or nature of the parent sediments controlled the amount of carbonate accumulation. The calcic and petrocalcic horizons generally indicate stage II to III morphology (Gile et al., 1966) (see section 4.6).

Iron-rich nodules and concretions occur in some of the palaeosols indicating fluctuating water table conditions and/or seasonal saturation of the profiles during the wet season (see section 4.6.6). Desiccation cracks and slickensides in the palaeosol horizons indicate seasonal wetting and drying out of the palaeosol profiles while the soil structures (peds and cutans) generally indicate formation of the palaeosols in well-drained oxidised soils with a predominantly low water table (see sections 4.7, 4.8 and 4.9).

Generally the pedogenic features observed in the palaeosols suggest formation of predominantly well-drained, oxidised soils on sediments in the proximal overbank facies. Evidence of waterlogging suggests seasonal saturation of soils forming in the lower lying areas of the flood basin.

6.3 Palaeoclimatological interpretation

The interpretation of palaeoclimates is generally done using evidence accumulated from a variety of disciplines including geology (sedimentology, palaeontology, mineralogy, palaeopedology), botany (palaeobotany), geography (palaeogeography) and zoology (palaeozoology) (Bamford, 1986).

The relative positions of the continents with respect to each other and their latitudinal positions affect the temperatures and rainfall of the landmasses and the currents and winds also played a part, particularly in the shoreline regions where they helped to warm the climate (Bamford, 1986). Prior to the Cretaceous, the single continent Pangaea stretched from the north to the south pole. Ocean currents were unhindered by the continental mass and circulated as large gyres from the equator to the poles, carrying warmth from the low latitudes to the high latitudes (Francis and Frakes, 1993). Initial splitting of Gondwana began in the early Cretaceous, with the opening of the Atlantic ocean occurring later than the initial splitting (Francis and Frakes, 1993). Figure 41 shows the south pole view of the relative position of the continents during the Cretaceous.

At the end of the Jurassic, the global climate was generally warm and arid, becoming more humid in the Cretaceous (Francis and Frakes, 1993). The presence of warmth-loving flora in high latitude Cretaceous deposits suggests that the climate was warmer than it is today. The high temperatures are often attributed to high percentages of CO_2 in the atmosphere, the high sea level, and the existence of a large continental landmass with most land falling in the subtropics. The positions of the continents in the Cretaceous were also important in controlling the climate. Most authors describe the climate of the Cretaceous as warm and equable. However, recent work using oxygen isotopes from ocean sediments and high latitude deposits in the polar regions suggests that the Cretaceous was characterised by variations in warming and cooling (Francis and Frakes, 1993). The oxygen isotope work

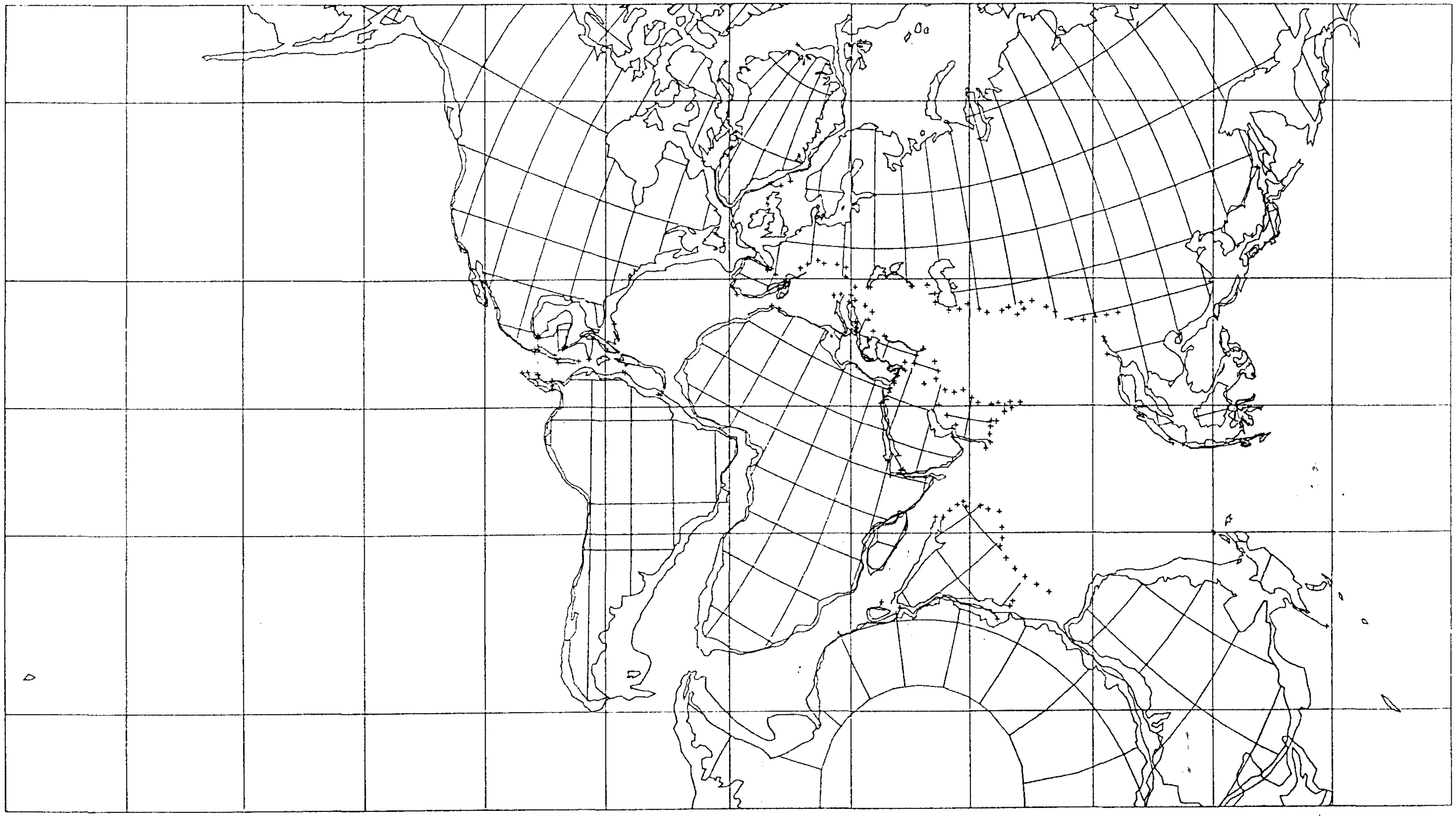

Figure 41. Mercator projection of the position of the continents in the early Cretaceous (120 million years ago) as interpreted by Smith and Briden (1977, p. 19) (N = 27; Alpha-95 = 6.2).

suggests that there was a general trend of cooling in the early Cretaceous, followed by warming in the mid Cretaceous and then cooling again towards the end of the Cretaceous (Francis and Frakes, 1993). It is thought that there was a period of aridity at the beginning of the Cretaceous (inherited from the late Jurassic) followed by a general increase in humidity through the Cretaceous.

Most authors agree that the global temperatures in the Cretaceous were generally 10°C higher than at the present day and that the temperature gradient from the equator to the poles was far less than at present (Frakes, 1979; Mack, 1992; Francis and Frakes, 1993). Previous workers have interpreted the Cretaceous climate as being generally warm and dry, with an annual seasonality and periods of warmer and cooler climates.
Schwarzbach (1963) stated that the climate of "Africa" was warm and partly arid during the Cretaceous. In the Algoa Basin, Bamford (1986) studied the palaeoflora of the Kirkwood and Sundays River Formations and concluded that the climate was temperate, warm and seasonally wet.

Palaeosols are particularly useful in the determination of palaeoclimates as their preservation potential is better than most other fossils (invertebrates, vertebrates and plants) (Mack, 1992). Generally, the type of palaeosol profile preserved reflects the climate at the time of pedogenesis. However, when using palaeosols to interpret palaeoclimates, care must be taken to evaluate other contributing factors such as the nature of the parent material, the slope, the nature of the vegetation, and the maturity of the palaeosols (Mack, 1992).

In the study area, the different types of palaeosols identified in the mudrock sequences can be used to interpret the palaeoclimate at the time of pedogenesis. As the palaeosols formed on alluvial floodplains, they are thought to have formed in areas of low slope and little topography. The entisols formed over to short a period and thus cannot be used in the interpretation of the palaeoclimate. Some of the palaeosols show features formed due to gleying. These palaeosols are not reliable indicators of palaeoclimate as the local effects of the ground-water levels and/or position close to the river channel are more important than the climatic controls. However, some of the palaeosols displaying gley effects also have desiccation cracks, slickensides, colour mottles, iron-rich concretions and soil structures (cutans and peds). These features form in response to seasonal wetting and drying of the soils, indicating a climate with definite wet and dry seasons.

Most of the palaeosols observed in the study area reflect formation above the water table, showing no evidence of gleying. The dominant maroon-brown colouration of the palaeosols, together with the presence of slickensides, root traces, burrows, and abundant calcareous nodules and hardpan layers, and evidence of clay alluviation, indicates that the palaeosols generally formed above the water table on well-drained parent materials. These palaeosols commonly occur in the proximal overbank facies reflecting formation at some distance from the stream channel.

In the lower mudrock sequences, the most prominent feature of the sequence is the presence of abundant calcareous nodules and hardpan layers and lenses. According to Mack (1992) the retention of carbonate in the soils indicates alkaline soils and an evapotranspiration rate greater than the mean annual rainfall. The amount of soil moisture is critical as there must be enough to dissolve and transport the carbonate from the upper to lower soil horizons but not enough to completely leach and remove the carbonate from the soil profile (Mack, 1992). The calcic and petrocalcic palaeosols in the lower mudrock sequence show stage II to III carbonate accumulation (Gile et al., 1966) indicating formation in well-drained soils with a sufficient supply of carbonate and a warm to hot semi-arid climate (25-30°C) with a low but seasonal rainfall (100-500mm per annum).

In the middle mudrock sequence there is a general lack of carbonate in the sequence. This need not necessarily reflect a change in climate as there are several other factors affecting the accumulation of carbonate. It is possible that the climate was slightly wetter, however, the lack of carbonate may reflect: a decrease in the influx of aeolian Ca^{2+}-rich dust into the depositional environment, a decrease in the amount of Ca^{2+} translocation in the profile due to a decrease in rainfall and/or soil moisture, or a change in the soil-moisture evaporation rate. Several palaeosols in the middle mudrock sequence contain slickensides, desiccation cracks, iron-rich concretions and nodules and soil structures (peds and cutans) indicative of a seasonal climate. The rate of sedimentation is not thought to differ markedly from the rate of sedimentation observed in the lower mudrock sequence, and is not seen as a major influencing factor in the type of soils present. Position of the profiles relative to the channel may have had some influence in the maturity of the profiles but does not account for the lack of carbonate in the profiles. It is thought that the palaeosols formed in a slightly wetter and/or cooler seasonal climate.

The upper mudrock sequence shows an increase in carbonate accumulation when compared with the middle mudrock sequence but the calcic and petrocalcic horizons observed are not nearly as abundant as in the lower mudrock sequence palaeosols. Evidence of a seasonal climate includes the presence of shrink-swell structures such as desiccation cracks and slickensides and iron-rich nodules and concretions. It is thought that the lack of carbonate accumulation reflects a decrease in the source of calcium into the depositional basin. It is thought that the palaeosols formed under conditions similar to those in the middle mudrock sequence.

Generally, the types of palaeosols are similar in all three profiles, differing only in the amount of carbonate present in the profiles. The alfisols, aridisols and vertisols are the most common palaeosols formed in the study area and all reflect formation in semi-arid seasonal climates.

The climate at the time of deposition of the sediments and formation of the palaeosols preserved in the study area is interpreted as having been warm to hot (25-30°C) with a low but seasonal rainfall (100-500mm per annum).

CHAPTER 7
CONCLUSION

A general log of all the sediments exposed in the study area shows a number of fining-upward sequences. A typical sequence comprises a conglomeratic facies overlain by a sandstone facies, which is turn fines upwards into the mudrock facies. The fining-upwards sequences exposed in the study area are interpreted as meandering river deposits comprising: channel deposits which include channel lag deposits and point bar deposits; channel-margin deposits which include crevasse splay deposits and levee deposits; and overbank deposits which include flood basin deposits and abandoned channel (channel-fill) deposits. The conglomerates were deposited as channel lag deposits, the sandstones as point bar, levee and crevasse splay deposits and the mudrocks as flood basin and channel-fill deposits.

Rare vertebrate remains were found in the conglomerates and mudrocks of the study area. Fossilised wood is more common, with large logs of unidentified conifer species occurring in many of the sandstones. The trees probably grew concentrated along the river banks, with a rapid decrease in vegetation density on to the flood basin. The flood basin was probably covered with sparse scrub and fern-like vegetation. The presence of charcoal chip lenses and layers in the conglomerates suggests that wild fires, started by lightning strikes, swept through the forests from time to time. Further fossils include flakes of black organic material, root traces and burrows which occur in the mudrock sequences.

Detailed logs of the three mudrock sequences exposed in the study area revealed a number of stacked palaeosol profiles. The palaeosols were identified by the presence of root traces and burrows, colour banding and mottles, calcareous nodules and hardpan layers and lenses, iron rich nodules and concretions, soil horizons, and soil structures (peds and cutans). The palaeosol profiles were compared with modern soils and entisols, inceptisols, ultisols, alfisols, aridisols and vertisols were recognised using the USDA Soil Taxonomy (Soil Survey Staff, 1975).

The palaeosols formed in a fairly dynamic, aggrading (vertically accreting) floodplain environment. Pedogenesis of the channel-margin and flood basin deposits occurred between floods and associated depositional events. Simple palaeosols developed in areas of frequent sedimentation, where each flood event resulted in complete burial of the soil profile and a halt in pedogenesis. Cumulative palaeosols developed on sediments further from the stream channel where sedimentation and pedogenesis could occur concurrently as the influxes of sediment during floods were too low and episodic to halt pedogenesis. The maturity of the palaeosols is related to the distance from the channel and three depositional facies and related palaeosols are observed. The channel-margin palaeosols formed on levee and proximal crevasse splay deposits and include entisols and inceptisols. The proximal flood basin palaeosols formed on interbedded distal crevasse splay and flood basin deposits and include the majority of the ultisol, alfisols, aridisols and vertisols. The distal flood basin palaeosols formed on true flood basin deposits (interbedded siltstones and claystones) and include the slightly less mature ultisols, alfisols, aridisols and vertisols.

The pedological structures observed in the palaeosols preserved in the mudrock sequences of the study area indicate formation of the palaeosols in oxidised well-drained parent materials with a generally low water table. Calcareous nodules and hardpan layers and lenses (calcic and petrocalcic horizons) indicate a warm to hot (25°-30°C) semi-arid climate and together with pedogenic features such as slickensides, desiccation cracks and iron-rich concretions, indicate a seasonal rainfall of approximately 100-500 millimetres per annum.

GLOSSARY

Definitions and explanations of terms have been taken from:
Brewer, 1964; Gile et al., 1966; Knapp, 1971; Hunt, 1972; Semeniuk and Searle, 1985; Wright, 1986; Retallack, 1990; Huggett, 1991; Soil Classification Working Group, 1991.

A

acid soil - One having a reaction less than pH 7.

aerobic - Having molecular oxygen as part of the environment. Growing or taking place only in the presence of molecular oxygen.

aerosol - Solid particles or liquid droplets dispersed in the air.

aggradation - The building upwards of a land surface owing to the accumulation of sediment deposited by geomorphological agencies such as wind, wave, and water; in the case of accumulation in a river system, alluviation.

aggregate - A single mass or cluster of soils particles such as a ped, crumb or granule.

A horizon - The upper layer in a mineral soil in which leaching is greatest, that is, a mineral horizon from which clay and free iron oxides have been removed, or in which the oxides have been segregated.

alfisols - Mineral soils that have an ochric epipedon upon an argillic horizon, moderate to high base saturation and which are moist for at least three months during the growing season. Other horizons including natric, fragipan, duripan, petrocalcic and plinthite may be present.

alkaline soil - one having a reaction more than pH 7.

alluvium - An unconsolidated stratified deposit laid down by running water; sometimes applied only to fine sediments (silt and clay), but more generally used to includes sands and gravels too.

anaerobic - Absence of molecular oxygen. As a biochemical process, occurring in or taking place in the absence of molecular oxygen.

apedal - Soil materials in which peds (soil aggregates) are absent. See ped.

argillaceous - Referring to, containing, or composed of clay. Used to describe rocks containing clay-sized material and clay minerals.

argillans - Coatings in the soil composed of clay minerals. See cutan.

argillic horizon - An horizon characterised by an illuvial accumulation of clays. It is usually a B horizon.

argillipedoturbation - The mixing of soil components caused by the shrink-swell behaviour of some clays.

aridisols - Soils of deserts and semiarid regions, and associated saline or alkaline soils. They usually have an ochric, anthropic or histic epipedon upon an argillic, natric, calcic, petrocalcic gypsic, salic, petrogypsic or cambic horizon, or a duripan, or combinations of two or more of these.

authigenic - Formed or generated in place. Applied to those constituents which came into existence with or after the formation of the rock of which they constitute a part, e.g. the cements of sedimentary rocks.

B

badlands - Land broken by an intricate pattern of narrow ravines, sharp crests and pinnacles resulting from severe erosion of soil and soft geologic materials.

base level - The level below which a land surface cannot be reduced by running water until that level is itself lowered.

base saturation - Calculated as the percentage of the total cations that are basic.

base saturation percentage - The sum of exchangeable Ca, Mg, Na and K expressed as a percentage of cation exchange capacity measured at a specified pH level.

base status - A qualitative expression of base saturation. See base saturation percentage.

basic rock - In geology, a general term for igneous rock with more than 45% but less than 66% SiO_2.

B horizon - Horizons which exhibit an illuvial concentration of silicates, iron, aluminium, or humus, or residual concentrations of sesquioxides or clays or coatings of sesquioxides.

bioturbation - The reworking of soil by organisms.

buried soil - Soil which has been covered by a deposit of unconsolidated material of whatever origin.

C

calcans - coatings in the soil composed of calcite. See cutan.

calcareous - Containing calcium carbonate.

calcic horizon - An horizon with an accumulation of alkaline earth carbonate. The carbonate is in the form of powder or isolated nodules.

calcrete - A widely used term which is much abused. It refers to a terrestrial material, composed mainly of calcium carbonate which occurs in a variety of physical states from powdery to nodular to indurated forms (petrocalcic horizons). Synonymous with caliche. Calcrete has a variety of origins from purely pedogenetic to cementation in the phreatic zone.

caliche - A layer chiefly of calcium carbonate at or near the ground surface; attributable to deposition by evaporation of ground water, soil processes, seeps, or splash at beach heads. They are characteristic of arid and semiarid regions.

cambic horizon - A depositional layer in a soil in which some mineral alteration has occurred.

catena - A sequence of soils of similar age, derived from similar parent material, and occurring under similar macroclimatic conditions, but having different characteristics due to variation in relief and drainage.

cation - A positively charged ion, for example Ca^{2+}, Mg^{2+}, K^+, Na^+, H^+, Al^{3+}, NH_4^+, and H_3O^+. The term exchangeable basic cations ordinarily refers to calcium, magnesium, potassium, and sodium.

cation exchange capacity (CEC) - By virtue mainly (silt and coarser fractions can contribute to CEC) of their colloidal components, both inorganic and organic, most soils possess a negative electrical charge which is balanced by cations so that the system as a whole is electrically neutral (see anion exchange capacity). The cations so held by a soil represent a definite quantity and can be exchanged by other cations. This quantity is used as a measure of cation exchange capacity which is given on a whole soil basis or on a clay basis as $cmol(-)kg^{-1}$, the latter being calculated using the exchange capacity of the soil and clay content. Functional groups on surfaces of organic matter, clay, and amorphous compounds tend to release protons at specific pH values and this is essentially the mechanism for pH-dependant cation exchange capacity in soils (the higher the pH, the higher the CEC). It is therefore important to choose the pH value at which CEC is to be measured so as to serve the specific objective, and then to quote this pH value when presenting the results.

cement - Chemically precipitated material occurring in the interstices between soil and rock particles therefore binding the particles together. Most common are carbonates, sesquioxides, silica and gypsum.

chelation - A chemical process involving the formation of a hetrocyclic ring compound which contains at least one metal cation or hydrogen ion in the ring.

chernozem - Any member of a group of zonal soils characterised by a dark, usually deep, humic A horizon saturated with cations of calcium and magnesium (a mollic epipedon), thin brown B horizons with clay accumulation, and a calcareous subsoil. Formed under a temperate to cool subhumid climate associated with long-grass steppe.

C horizon - A mineral horizon in the soil, which may be consolidated or unconsolidated which retains evidence of original structure and lacks properties of A and B horizons. It may possess accumulations of carbonate and other soluble salts.

clastic dykes - A tabular body of clastic material transecting the bedding of a sedimentary formation or the horizons of a soil profile, representing extraneous material that has invaded the containing formation along a crack either from below or from above.

clay coatings - Argillans. See argillans and cutans.

colour - Description of colour has been standardised through the use of Munsell notations. Accordingly colour is given in terms of a verbal description (e.g. yellowish-brown) and a notation (e.g. 10YR 5/4), the latter being compounded from notations for hue (10YR), value (5) and chroma (4). Hue refers to the dominant spectral colour which is related to the dominant wavelength of the light. Value refers to the relative lightness of colour and is a function of the amount of light. Chroma is the relative purity or strength of the spectral colour and increases with decreasing greyness. Colour usually varies with the moisture content of the soil. The moisture status (dry or moist) must always accompany colour description and the moist colour at least must always be given.

A mottled or variegated patterns of colours is common in many soil horizons. It may be the result of various processes *inter alia* hydromorphy, alluviation, biological activity, and rock weathering in freely drained conditions (i.e. saprolite). It is described by noting (i) the colour of the matrix and colour or colours of the principle mottles, and (ii) the pattern of the mottling. The latter is given in terms of abundance (few, common 2 to 20% of the exposed surface, or many), size (fine, medium 5 to 15 mm in diameter along the greatest dimension, or coarse), contrast (faint, distinct, or prominent), form (circular, elongated vesicular, or streaky) and the nature of the boundaries of the mottles (sharp, clear, or diffuse); of these, abundance, size and contrast are the most important.

concretion - Glaebules with a generally concentric fabric about a centre which may be a point, a line or a plane.

conglomerate - A coarse grained clastic sedimentary rock composed of rounded, water-worn rock fragments or pebbles set in a fine grained matrix and cemented together by another mineral substance.

crotovina - Irregular tubular streaks within one horizon of material transported from another horizon due to filling of former animal burrows with organic matter or material from another horizon, or with material from the same horizon but with an altered structure. Also known as a pedotubule. Also spelt krotovina or crotovine.

crystallaria - Single crystals or arrangements of crystals of relatively pure fractions of the plasma that do not enclose the s-matrix of the soil material but form cohesive masses; their morphology (especially shape and internal fabric) is consistent with their formation and present occurrence in original voids in the enclosing soil material. The crystals are usually calcite or gypsum.

crystal chambers - Usually prolate to equant crystallaria formed in vughs, vesicles, and chambers. They usually show evidence of crystallisation from the walls inward by preservation of a central void.

crystal sheets - Planar shaped crystallaria formed in planes. There is no need for evidence of crystallisation from the walls inward in crystal sheets because none of the possible crystal arrangements are likely to be confused with other types of crystallaria.

crystal tubes - Crystallaria that occur in channels of simple or branching acicular shape. They usually show evidence of crystallisation from the walls inward by preservation of a central void.

crystic plasmic fabric - The plasma is usually anisotropic and consists of recognisable crystals, usually of the more soluable plasma fractions. "Crystic" is derived from "crystallised".

cutan - A modification of the texture, structure, or fabric at natural surfaces in soil materials due to concentration of particular soil constituents or *in situ* modification of the plasma. Cutans can be composed of any of the component substances of the soil material, e.g. calcite (calcan or calcitan), or clay (clay cutans, clay skins or argillans), or gibbsite, gypsum, iron oxides, organic matter, or soil material.

cycad - Any gymnosperm of the family Cycadaceae looking like a palm tree but topped with compound, fern-like leaves.

D

detrital - Mineral grains transported as sediment and deposited in the surface deposit in which they are contained.

diagenesis - The changes which occur in sediments after their initial deposition and during and after lithification. These changes include compaction, replacement, cementation and recrystallisation. The rearrangement of a mineral to form a new mineral. See eogenesis, mesogenesis and telogenesis.

diagonal discrete roots - Straight, diagonal rhizocretions and root casts dipping from approximately 15-75°. Occur primarily at points of bifurcation of vertical roots.

discrete roots - see diagonal discrete roots, horizontal discrete roots, and diagonal discrete roots.

drab haloes - bluish or greenish grey haloes extending from the root traces into the surrounding palaeosol matrix.

dust - Any solid particle carried in suspension in the air. Sources include volcanic eruptions, wind erosion of silt-sized and clay-sized materials, fires, and pollution.

E

E horizon - A mineral horizon underlying the O or A horizon (if present), having a lower content of colloidal matter (clay, sesquioxides, organic matter) than the immediately overlying and\or underlying horizon, usually reflected by a pale colour and a relative accumulation of quartz and\or other resistant minerals of sand or silt sizes.

effervescence - The production of gas bubbles, e.g. when hydrochloric acid is pored on lime.

eluviation - Removal of soil material in suspension or solution from a part of or from the whole of the soil profile. Soil horizons that have lost material through eluviation are eluvial and those that have received material are illuvial. The term leaching is preferred for removal in solution. See illuviation.

entisols - Soils with little or no evidence of soil horizon development. There must be some evidence of pedogenic modification such as an ochric epidpedon. Other horizons may develop and salts may accumulate deeper in the profile. Such soils are likely to be very common in ancient continental deposits.

eogenesis - Involves changes in sediment character due to the action of surface related processes from the time of deposition until such time as the sediment body becomes more deeply buried.

epipedon - The uppermost soil horizons.

F

facies - Part of a rock body as differentiated from other parts by appearance or composition.

ferric iron - Fe^{2+}.

ferrous iron - Fe^{3+}.

flood - The result of a river overflowing its banks and covering land which is not normally submerged.

flood plain - The strip of relative smooth land adjacent to a river channel, which is built of sediments during the present regime of the stream and which is covered with water when the river overflows its banks.

fluvial, fluviatile - Of or pertaining to rivers.

friable - Crumbles readily under finger pressure.

fulgurite - Tubular masses of soil produced by lightning strikes. Occur as lumpy masses of glass with exotic high temperature minerals completely different from ordinary soil matrix.

G

gilgai - The microrelief sometimes produced by swelling clays during prolonged expansion and contraction due to changes in moisture content; usually a succession of microbasins and microknolls in nearly level areas, or of microvalleys and microridges parallel to the direction of the slope.

glaebules - Highly irregular to almost spherical naturally hardened or naturally segregated lumps of soil material with simple, distinctive mineralogical and chemical compositions. They are typically nodules or concretions which have not formed in pre-existing voids and are recognisable because they have a greater concentration of some constituent or because they have a different fabric to that of the matrix.

gley - A material that has been or is subject to intense reduction as a result of prolonged saturation with water. Grey, blue and green colours predominate, but stains of ferric and manganese oxides and hydrates (yellow, brown, red and black) may be present and indicate localised areas of better aeration. Grey colours are due to an absence of iron compounds; blue and green are due to the presence of ferrous compounds. Gleyed sands are friable and clays firm.

gleying - The reduction of iron forming grey and blue colours, associated with anaerobic conditions. Reflects poor drainage and is associated with hydromorphic soils. Surface water gleys result from poor drainage caused by impervious horizons within the profile. Groundwater gley results from impervious horizons beneath the soil.

ground water - That part of the subsurface water in the zone in which permeable rocks are saturated with water under pressure equal to or greater than atmospheric. The water may extend into overlying soil. Phreatic water.

groundwater gley - See gleying.

H

hardpan - A massive material enriched with and strongly cemented by sesquioxides, chiefly iron oxides (known as ferricrete, diagnostic hard plinthite, ironpan, ngubane, ouklip, laterite hardpan), silica (silcrete, dorbank), or lime (diagnostic hardpan carbonate horizon, calcrete). Orstein hardpans are cemented by iron oxides and organic matter.

horizon - A layer of soil approximately parallel to the soil surface with characteristics produced by pedogenetic processes which distinguish it from other horizons. This is a different usage to that in geology and confusion can result unless this distinction is made when describing palaeosols.

horizontal discrete roots - Irregular, horizontal to subhorizontal root casts and rhizocretions, less than 20 mm in diameter.

horizontal root mats - Interwoven root casts (each less than 5 mm in diameter) lying within a larger rhizocretionary root mat. Mats form laterally continuous beds.

humus - The fully decomposed organic matter of well drained soils, showing no traces of the structure of the animal or vegetable matter from which it was derived.

hydromorphy - A process of gleying and mottling resulting from the intermittent or permanent presence of free water.

hydromorphic soils - Soils developed in the presence of excess water, typified by gleying and build-up of organic matter.

I

illuviation - The movement downwards into an underlying soil layer of soil material (soluble or insoluble in the soil solution) which has been removed from the upper soil by percolating water, i.e., the movement and deposition of material from one horizon to another. See eluviation.

immature soil - A soil with weakly developed horizons because of the short time it has been subject to soil forming processes in its present environment, e.g. a recent alluvial deposit.

inceptisol - These are soils which exhibit some degree of horizon development (unlike Entisols) but do not contain features diagnostic of the other soil orders. They show evidence of leaching but also contain weatherable minerals. They usually have an ochric or umbric epipedon over a cambic horizon.

indurated - rendered hard by heat, pressure or cementation. Common cementing agents are sesquioxides, lime, and silica.

infiltration - the movement or percolation of water into the soil.

interstitial matrix - Fine sedimentary material occurring between coarser grains; maximum size 0.02mm.

interstitial waters - Water that exists in the interstices or voids in a rock, or other porous medium.

J

joint - A fissure or fracture with little or no displacement, in bedrock or in compact surface deposits.

K

K fabric - A diagnostic soil fabric in which fine-grained authigenic carbonate occurs as an essentially continuous medium. It coats or engulfs, and commonly separates and cements skeletal pebbles, sand, and silt grains"

K horizon - A type of strongly indurated calcareous horizon, petrocalcic horizon or hardpan. Sometimes referred to as a Km horizon (m is a symbol for strongly indurated horizons). Corresponds to mature calcrete horizons.

krotovina - See crotovina.

L

lattisepic fabric - The plasma generally has a flecked orientation pattern, but acicular and prolate domains occur in a lattice-like pattern; that is, there are two sets of very short, discontinuous plasma separations usually oriented approximately at right angles to each other.

leaching - The washing out of water-soluble minerals from a soil body, usually the entire solum (the genetic soil created by soil-forming processes), by the downwards movement of water.

lessivage - The mechanical transport of clay and silt particles down the soil profile from the A horizons to the B horizons. This produces an enrichment of illuvial (washed in) clay and silt in the B horizon. See eluviation and illuviation.

levee - A river or stream bank above the general level of a floodplain, containing the stream channel.

lime - Calcium oxide, CaO. Loosely used for calcium carbonate and calcium hydroxide.

M

matrix - The fine-grained material in which larger particles are found.

mature soil - Soil which has undergone most of the development that its present environment is capable of producing.

meander - One of a series of loop-like bends in the course of a stream, developed when the stream is flowing at grade, through lateral shifting of its course toward the convex sides of the original curves.

mesogenesis - Refers to diagenetic processes operating at higher temperatures and pressures during deep burial (though not sufficiently extreme to cause metamorphism).

mottling - A patchwork of colours (usually grey and orange) indicating periodic waterlogging. See colour.

N

neutral soil - One having a reaction of approximately pH 7.

nodules - Bodies of various shapes, sizes and colour that have been hardened to a greater or lesser extent by chemical compounds such as lime, sesquioxides, animal excreta and silica.

O

Ochric epipedon - A surface horizon that is light in colour and contains less than 1% organic matter.

organic matter, soil - The organic fraction of soil ranging from undecayed plant and animal tissues through ephemeral products of decomposition to fairly stable amorphous brown to black material, known as humus, which bears no trace of the anatomical structure from which it was derived.

P

palaeopedology - The study of ancient soils, with soils of the past, either buried within sedimentary sequences or persisting under changed surface conditions, being the main subject matter.

palaeosol - An old, fossil, or relict soil or soil horizon, usually buried.

papule - Glaebules composed of clay minerals, which represent disrupted clay skins (argillans). Their presence indicates pedoturbation. Term often used in cases where the origin of glaebules and their associated features are not clear enough to assign them to a genetic category.

parent material - The material from which soil has developed. One may speak of the parent material of an horizon, or of a number of horizons which constitute a profile. The term, parent rock, refers to the rock mass from which an unconsolidated parent material has been derived.

ped - an individual natural soil aggregate consisting of a cluster of primary particles, and separated from adjoining peds by surfaces of weakness which are recognisable as natural voids or by the occurrence of cutans.

pedofacies - A kind of sedimentary facies, commonly alluvial floodplain deposits, whose main features are pedogenetic rather than sedimentary. They are thus distinctive sedimentary rock units containing one or more palaeosols.

pedogenesis - Soil formation.

pedogenic - Pertaining to a soil origin.

pedology - The branch of soil science that treats soils as natural phenomena, including their morphological, physical, chemical, mineralogical and biological properties, their genesis, their classification and their geographical distribution.

pedotubule - A pedological feature consisting of soil material (skeleton grains or skeleton grains plus plasma, as distinct from concentrations of fractions of the plasma) and having a tubular external form, either single tubes or branching systems of tubes; its external boundaries are relatively sharp. Tubular form, in this context, means that the feature as a unit, or its impression in the enclosing soil material, has a relatively uniform cross-sectional size and shape, most commonly circular or elliptical; that is, the impression of the pedotubule conforms to the definition of channels. See Table 8 in text, p. 46).

pedoturbation - The mixing of soil components by various processes including bioturbation, and shrink-and-swell cycles; does not include illuviation.

percentage base saturation - See base saturation percentage.

perched water table - The surface of a zone of saturation in soil separated by a relatively impermeable unsaturated zone from the main body of groundwater.

permeability - This refers to the ease with which gases, plant roots or, more usually, liquids penetrate and pass through the soil.

petrocalcic horizon - An indurated calcic horizon, synonymous with duripan, hardpan, or Km horizon.

pH, soil - The degree of acidity (the negative logarithm to the base 10 of the hydrogen ion activity) of soil at a specified soil to suspension medium (e.g. 1 to 2,5 soil:water) ratio. The suspension medium must be specified when reporting pH-measurements.

pisolite, pisolitic - A spherical or subspherical accretionary body over 2mm in diameter; concretions about pea size

plasma - Refers to that part of the soil material which is capable of being moved, concentrated or re-organised by soil processes. This includes material of colloidal size and soluble material.

podzolisation - A process by which sesquioxides are moved through the soil profile. Acid humus, resulting from slow decomposition, results in solutions capable of breaking down clay minerals and releasing silica, aluminium and iron. Isolubles such as silica accumulate in the upper parts of the profile and result in a grey, bleached horizon (albic horizon or E horizon).

precipitation - In hydrology, the discharge of water, in liquid or solid state, out of the atmosphere, upon a land or water surface.

prismatic structure - Peds which are elongate with flat top and vertical to the land surface. See soil structure.

profile, soil - A vertical section of the soil through all the horizons that make up the solum.

R

red bed - A soil, sediment, or sedimentary rock coloured red by finely divided ferric iron oxides, mainly haematite.

relict beds - Sedimentary parent materials with associated sedimentary structures, such as planar and rippled beds and laminations, which have not been obliterated by soil formation.

rhizocretions/rhizoconcretions - Calcreted roots, root casts, and moulds which occur as extensive vertical and horizontal tube and rod structures.

rhizolith - Organo-sedimentary structures produced by roots. Defined to include accumulation and/or cementation around, cementation within, or replacement of, higher plant roots by mineral matter

rhizosphere - The zone of soil (including biological components such as fungai mycorrhiza) in the immediate vicinity of plant roots.

R horizon - Consolidated bedrock and strictly therefore, not an horizon.

root ball - Irregular, globular rhizocretions encasing vertical and horizontal roots.

S

saturate - In hydrology a soil is saturated if its total pore space is filled with water.

saturation percentage - The water content of a saturated soil paste expressed on a dry mass basis.

seasonality - The seasonal availability of water and temperature may have an appreciable effect on the development of soil features. Seasonality of rainfall, of heat, of dust influx, and of other agencies of soil formation are important to the clayeyness, redness, and base saturation of soils. Each of these features, however, is controlled by other factors that make it difficult to determine the contribution of seasonality. The nature and degree of seasonality are better revealed by other features of soils, ie. Mukkara structure, concretions, patterns of root traces, charcoal and frost cracking.

septaria - Glaebules with a series of radiating cracks crossed by a series of cracks concentric with the margins; the crack pattern is often highly irregular; they are usually spheroidal with sharp boundaries.

sesquioxide - Amorphous oxides of aluminium and iron; a binary compound of a metal and oxygen in the proportion of 2 to 3 as in Al_2O_3, Fe_2O_3. The term is also used to generally describe free iron, aluminium and manganese oxides in soil.

skeletan - Veins of skeleton grains or what a geologist would call a clastic dyke.

slickensides (stress cutans) - A common indication of stress cutans is the striated and smeared surfaces called slickensides. These form in clayey soils where peds are repeatedly heaved past one another by swell-shrink during wetting and drying episodes. Slickensides also form in palaeosols purely by the crushing of peds against one another during compaction following burial. Slickensides formed in soils or during compaction are randomly arranged along diffuse zones rather than unidirectional and concentrated in narrow bands. In thin section, on either side of the highly birefringent, striated clay of the slickensided surface, the transition outward to unorientated clay is gradational with decreasingly abundant wisps of highly birefringent clay.

soil - Rock at, or near, the land surface which has been transformed by the biosphere. See soil profile.

soil horizon - See horizon.

soil profile - All the soil horizons from the ground surface to the unaltered bedrock or parent material; usually divided into A (topsoil), B (subsoil) and C (weathered parent material) horizons, the A and B horizons together forming the solum.

soil structure - The physical constitution of a soil material as expressed by the size, shape, and arrangement of the soil particles and voids, including both the primary particles to form compound particles and the compound particles themselves; fabric is the element of structure that deals with arrangement.

solum - Upper part of the soil profile, generally the A and B horizons.

solution, soil - The aqueous liquid phase of the soil, with its solutes.

spherulite - spherical aggregates of radiating crystals

stress argillans - See slickensides and argillans.

subaerial - Occurring at the land surface.

surface water gley - See gleying.

swelling clay - Clay minerals such as the smectites that exhibit interlayer swelling when wetted, or clayey soils which, on account of the presence of swelling clay minerals, swell when wetted and shrink with cracking when dried. The latter are also known as heaving soils.

T

telogenesis - Involves changes when, after a period of burial, a sediment body is again exposed to near-surface processes by erosion of the overlying rocks.

topography - (1) The physical features of a district or region, such as are represented on maps, taken collectively, especially the relief and contour of the land. (2) The science of surveying the physical features of a district or region and the art of delineating them on maps.

V

vadose zone - Zone of aeration above the level of the water table.

vertical, discrete roots - Straight, vertical rhizocretions and root casts that reach diameters as large as 100 mm

vertisol - Clay-rich soils predominantly composed of swelling clays (smectite) in climates with alternating wet and dry seasons. As a result of seasonal shrinkage and swelling the soils undergo argillipedoturbation and commonly show gilgai.

W

Walther's Facies Law - The lateral distribution of different kinds of soils across an ancient landscape can be reconstructed from a vertical section by using a common kind of geological inference called Walther's Facies Law. This states simply that different kinds of sediment deposited side by side in nature will be preserved on top of one another in a sedimentary sequence.

waterlogged - Soil or land saturated with water.

water table - The surface defined by the height of free-standing water in fissures and pores of saturated rock and soil.

weathering - The chemical, physical, and biological processes whereby rocks decay and crumble to a material in which, unless transported, soil will form.

wildfire - A raging fire that travels and spreads swiftly.

Y

young soil - Synonymous with immature soil.

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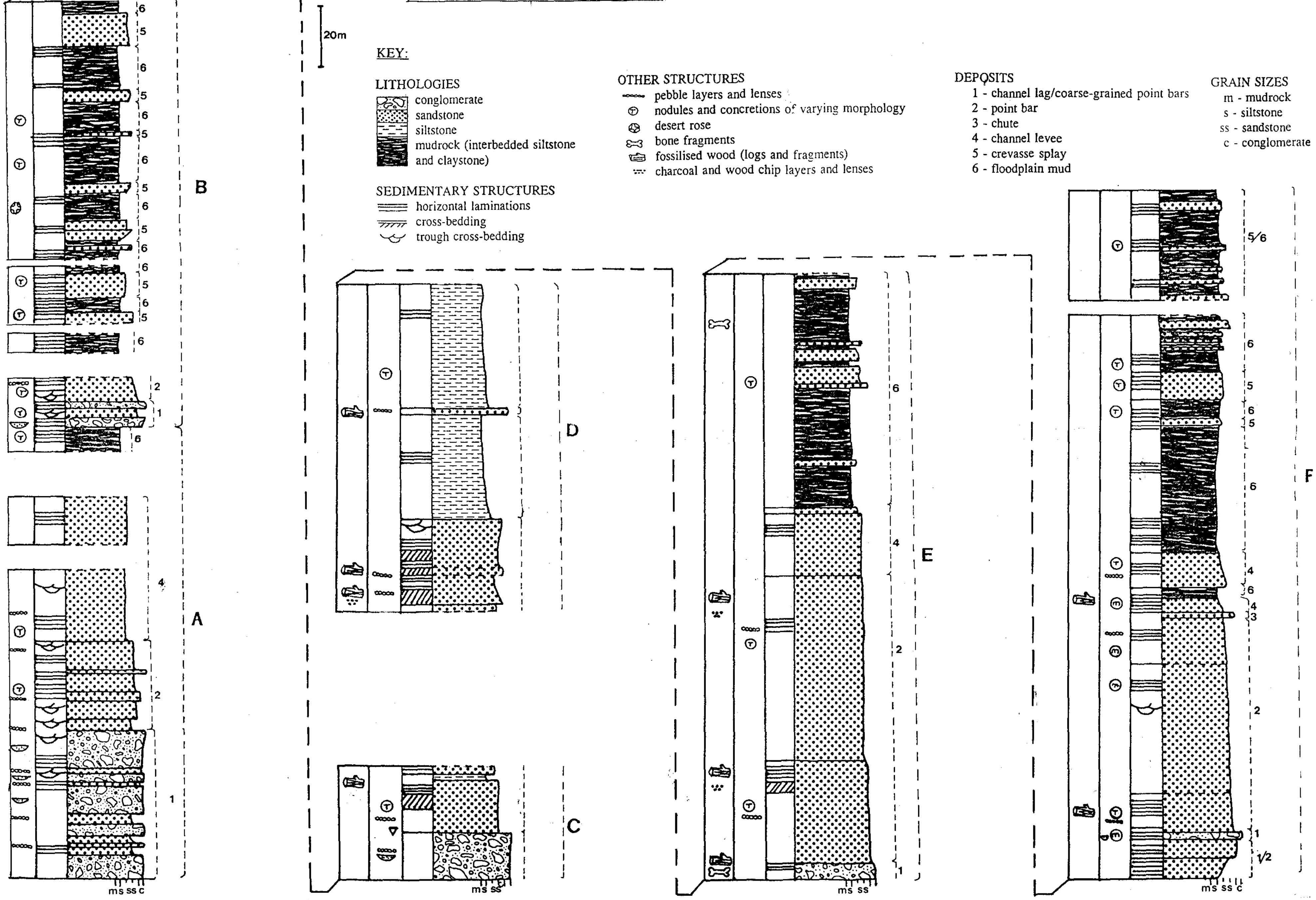
APPENDIX 1

SEDIMENTARY LOG OF THE SECTIONS EXPOSED IN THE AREA

APPENDIX 1: SEDIMENTARY LOG OF THE SECTIONS EXPOSED IN THE STUDY AREA



APPENDIX 2

DESCRIPTIONS OF THE THREE MUDROCK SEQUENCES

APPENDIX 2.1: Lower Mudrock Sequence

*In this description and in ensuing descriptions, the first number of each paragraph is the depth from the top of the palaeosol to the top of the described horizon, and the letters are its interpretation as a soil horizon. Unless otherwise stated, the grain size of the mottles and pedotubules is the same as that of the soil matrix, and the nodules, concretions and hardpan lenses are very strongly calcareous. Horizons marked with * have been combined with the horizon immediatley below them on the logs (Appendix 3) as they are too thin to represent separately.*

0 m; Bt; siltstone; dark maroon-brown, weathering dark purple-maroon; non-calcareous; common distinct, medium dark green-grey mottles vary in shape; few to common distinct, fine to medium, green clay-filled root traces, with pale green diffuse haloes, are vertically oriented; numerous vertical to subvertical, dark green clay sheets/dykes (skeletans?), <3mm in width and lined with rust orange argillans, cut through the horizon; angular blocky peds show green illuviation argillans; abrupt wavy contact to

-0.83 m; Bt; very fine-grained sandstone; dark maroon-brown, weathering light pink-maroon with orange tint; non-calcareous; common distinct, fine to medium, dark green-grey clay-filled root traces are vertically to subvertically oriented and branch outwards; numerous vertical to subvertical, dark green clay sheets/dykes (skeletans?), decreasing in width downwards and lined with rust orange argillans, cut through the horizon; subangular blocky peds show poorly developed maroon illuviation argillans; clear smooth contact to

-0.93 m; Bt; siltstone; dark maroon-brown, weathering dark maroon-pink with a light discontinuous maroon-pink band towards the base; non-calcareous; few to common distinct, fine to medium, red-brown clay-filled root traces lined with green argillans are vertically oriented and branch outwards; common distinct, fine dark green-grey clay-filled root traces are vertically oriented and branch downwards; subangular blocky peds show red-brown shiny illuviation argillans; a thin green-grey clay horizon, lined with rust orange clay, occurs parallel to the basal contact; widely dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-1.86 m; B*; silty claystone; light green-grey, weathering grey-pink; noncalcareous; common distinct, fine to medium, maroon siltstone mottles (after lithorelicts?) vary in shape; abrupt smooth contact to

-1.89 m; BCr; clayey siltstone and fine-grained sandstone in different layers; dark maroon-brown and dark grey-brown in different layers, weathering pink-maroon; non-calcareous; relict laminations planar to rippled, parallel and continuous; prismatic to angular blocky secondary peds show red-brown illuviation argillans; platy peds show red-brown illuviation argillans (after relict laminations); dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-2.05 m; Cr; fine-grained sandstone; shades of maroon in different layers, weathering grey-maroon; non-calcareous; common faint, medium dark maroon mottles are rounded to oblate; relict laminations are faint, planar and discontinuous; prismatic peds show maroon red-brown illuviation argillans; abrupt wavy contact to

-2.29 m; Cr; very fine-grained sandstone; yellow-grey and maroon-grey in different layers, weathering light pink-maroon; non-calcareous; relict beds and laminations, with clear contacts, are crudely developed, planar and discontinuous; abrupt, wavy contact to

-2.37 m; B; fine-grained sandstone; dark maroon-grey, weathering light pink-maroon; very weakly calcareous; red maroon-brown clayey siltstone skeletans occur between some joint planes; abrupt smooth contact to

-2.48 m; C; fine-grained sandstone; light grey-brown with sandy-yellow tint, weathering light grey-pink; very weakly calcareous to calcareous; red maroon-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-2.60 m; Ck; fine-grained sandstone; yellow-grey, weathering cream yellow-grey; strongly calcareous; maroon red-brown clayey siltstone skeletans occur between some joint planes; well-indurated, pink-grey crystalline nodules, weathering brown-black, occur along strike and are irregular to block shaped, and surrounded by moderately- to poorly-indurated white carbonate; abrupt wavy contact to

-3.08 m; Crt; fine-grained sandstone; sandy yellow-grey and dark grey in different layers, weathering cream brown-grey; non-calcareous; relict beds and laminations are planar, continuous and parallel; maroon red-brown skeletans occur between some joint planes; angular blocky peds show red-brown illuviation argillans; abrupt and wavy contact to

-3.97 m; Cr; fine-grained sandstone; maroon-brown, sandy yellow-brown, grey-brown and sandy-grey in different layers, weathering cream grey-pink; non-calcareous; relict laminations and thin beds are planar, parallel and continuous; black mangans occur on some ped surfaces; rare maroon red-brown skeletans occur between joint planes; abrupt and smooth contact to

-4.16 m; Cr*; clayey siltstone and fine-grained sandstone in different layers; dark maroon-brown and light grey purple-maroon in different layers, weathering light purple-maroon; non-calcareous; relict laminations and thin beds are planar, continuous, and parallel; black mangans occur on some ped surfaces; rare maroon-brown and pale green clayey siltstone skeletans occur between some joint planes; abrupt and smooth contact to

-4.47 m; C; medium-grained sandstone; grey sandy-brown, weathering sandy-cream grey-pink; non-calcareous; common distinct, medium maroon-brown very fine-grained sandstone mottles are rounded (after lithorelicts?); abrupt and wavy contact to

-4.50 m; Cr; clayey siltstone and fine- to medium-grained sandstone in different layers; light grey sandy-brown, maroon grey-brown and maroon-brown in different layers, weathering sandy-cream grey-pink; non-calcareous; relict laminations are planar, parallel and continuous and truncated by the overlying horizon; orange rust-yellow sesquans occur on some ped surfaces; abrupt smooth contact to

-4.62 m; Cr; siltstone and fine-grained sandstone in different layers; dark purple-maroon, light maroon-grey, and light grey yellow-brown grading into maroon, in different layers, weathering light pink-maroon; non-calcareous; relict laminations and thin beds are well defined, planar, parallel, and continuous; black mangans occur on some ped surfaces; dark maroon-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-5.33 m; ACr; fine-grained sandstone; sandy-brown grey and dark grey-brown in different layers, weathering light creamy grey; very weakly calcareous; relict laminations, which become indistinct and finer towards the upper contact, are planar, parallel and continuous; numerous vertical, dark grey-green clay sheets/dykes (skeletans?), <3mm in width and lined with rust orange argillans, cut through the horizon; red-brown clayey siltstone skeletans occur between some joint planes; abrupt smooth contact to

-5.63 m; Ckc; medium-grained sandstone; shades of sandy-grey-brown in different layers, weathering cream-grey with yellow tint; very weakly calcareous; very faint relict continuous, planar and parallel laminations occur towards the upper contact of the horizon; numerous vertical, dark grey-green clay sheets/dykes (skeletans?), <3mm in width and lined with rust orange argillans, cut through the horizon; well- indurated, light grey-pink, coarse-grained irregular-elongate nodules and randomly oriented hardpan veins, weathering cream, cut haphazardly down through the horizon; gradual smooth contact to

-7.08 m; Crck; coarse-grained sandstone; dark grey-green and dark maroon-grey in different layers, weathering white cream-grey; very weakly calcareous; dark maroon rounded lithorelicts are concentrated in crude layers; relict laminations are faint, crudely defined, planar and parallel; numerous vertical, dark grey-green clay sheets/dykes (skeletans?), <4mm in width, cut through the horizon; well-indurated, white crystalline, randomly oriented nodules and vertically oriented dykes, weathering cream, are irregular in shape; wavy abrupt contact to

-7.79 m; B; clayey siltstone; dark maroon-brown grading into purple-maroon upwards, weathering dark maroon-pink; non-calcareous; common distinct, medium meta-isotubules are randomly oriented and less than 0.05m long; many distinct, fine to medium, green clay-filled root traces with pale green diffuse haloes, are randomly oriented and form a dense network; black mangans occur on some ped surfaces; yellow medium-grained sandstone and red-brown sandy siltstone skeletans occur between some joint planes; angular blocky peds show maroon-purple shiny illuviation and stress argillans; irregular abrupt contact to

-8.57 m; Bt; clayey siltstone; green-grey, weathering cream pink-grey; non-calcareous; common to many distinct, coarse dark maroon-brown mottles vary in shape; few faint, fine dark green shiny clay-filled root traces are randomly oriented; sandy red-brown skeletans occur between some joint planes; subangular blocky peds show few red-maroon illuviation argillans; clear irregular to broken contact penetrating down to

-8.80 m; Bt; clayey siltstone; dark maroon-brown, weathering pink with orange tint; non-calcareous; common distinct, medium green-grey clayey siltstone meta-isotubules (after burrows? and/or roots?) are vertically oriented and are concentrated towards the upper contact; blocky peds show thick red-brown illuviation argillans which increase in abundance downwards; clear irregular contact to

-8.96 m; Bt*; silty claystone; green-grey, weathering light pink-maroon; non-calcareous; common distinct, medium maroon-brown silty claystone meta-isotubules (after burrows? and\or roots?) are vertically oriented; abrupt irregular to broken contact to

-8.99 m; Bt*; silty claystone; purple maroon-brown, weathering light pink-maroon; non-calcareous;

common distinct, medium green-grey mottles vary in shape; maroon very fine-grained sandstone skeletans occur between some joint planes; blocky peds show red-brown illuviation argillans; abrupt and wavy contact to

-9.31 m; Bt; silty claystone; pale olive-green, weathering light pink-maroon; non-calcareous; irregular in thickness along strike; abrupt irregular contact to

-9.33m; Bw; siltstone; dark maroon-brown, weathering dark maroon-pink; non-calcareous; many distinct, coarse grey-green mottles vary in shape; common distinct, medium green clay-filled root traces are vertically oriented; black mangans occur on some ped surfaces; red-brown sandy siltstone skeletans occur between some joint planes; blocky peds show rare green-black illuviation argillans; abrupt wavy contact to

-9.62 m; Cr*; siltstone; grey-green, grey-brown and light grey maroon-brown in different layers, weathering light grey with patches of maroon; non-calcareous; common distinct, medium to coarse, dark maroon-brown clayey siltstone mottles (after bioturbation?), vary in shape; common distinct, medium dark maroon clay-filled root traces are vertically oriented; faint relict laminations are crudely defined and discontinuous; black mangans and rust orange sesquans occur on some ped surfaces; secondary peds show red and green skeletans and illuviation argillans; platy peds show discontinuous planar maroon red-brown illuviation argillans (after relict laminations); abrupt wavy contact (lined with thin layer of rust orange clayey siltstone) to

-9.97 m; C; clayey siltstone; bright green, weathering white grey-green; non-calcareous; irregular in thickness along strike; black mangans present on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; subangular blocky peds show poorly developed maroon red-brown illuviation skeletans; abrupt wavy contact to

-10.00 m; ACr; clayey siltstone and sandy siltstone in different layers; dark maroon-brown and sandy grey-brown in different layers, weathering pink grey with green tint; non-calcareous; few flakes of black organic material vary in size and are randomly oriented; common distinct, medium maroon-brown clayey siltstone mottles vary in shape; few to common distinct, medium green clayey siltstone mottles vary in shape; common distinct, coarse light grey sandy siltstone mottles vary in shape; all mottles increase in abundance upwards; green clay papules are irregular in shape; few distinct, fine to medium, green clay-filled root traces are vertically oriented; faint, discontinuous and irregular, thin relict beds occur; very fine to medium, angular peds show well developed maroon red-brown and green shiny illuviation argillans; abrupt wavy contact to

-10.28 m; Cr; clayey siltstone and very fine-grained sandstone in different layers; dark maroon-brown and dark grey-green in different layers, weathering dark maroon; non-calcareous; common faint, medium very dark maroon clay-filled root traces are vertically oriented; relict laminations are planar and parallel with discontinuous lenses of dark green-grey and more continuous dark maroon-brown laminations; apedal, but discontinuous maroon-brown shiny illuviation argillans outline irregular areas; abrupt smooth to wavy contact to

-10.39 m; Ar; clayey siltstone; light grey-green and dark maroon-brown in different layers, weathering light grey-green; non-calcareous; few to common distinct, medium maroon-brown mottles vary in shape; common distinct, medium dark maroon-brown clay-filled root traces are vertically oriented; few to common distinct, fine to medium, green clay-filled root traces have pale green diffuse haloes (<10mm thick); relict planar and ripple-cross laminations are continuous at the base but become disrupted by mottling upwards; secondary peds show maroon red-brown illuviation argillans; angular blocky peds show maroon red-brown illuviation argillans (often horizontally oriented after relict laminations); abrupt wavy contact to

-10.55 m; Cr; silty claystone; dark brown-maroon and dark grey in different layers, weathering maroon; non-calcareous; few distinct, medium light grey mottles vary in shape; few distinct, fine white calcareous para-isotubules (after roots) are randomly oriented; common distinct, fine to medium, red and rust orange clay-filled root traces are vertically oriented; thin, faint, planar relict laminations are disrupted by mottling; black mangans occur on some ped surfaces; discontinuous dark maroon red-brown shiny argillans pick out relict laminations; abrupt irregular contact to

-10.78 m; AB; clayey siltstone; dark green-grey, weathering cream grey; non-calcareous; few distinct, medium red-brown mottles occur towards the basal contact; few to common distinct, fine to medium, maroon-brown and rust brown clay-filled root traces are vertically oriented; black mangans and rust yellow sesquans occur on some ped surfaces; blocky peds show green shiny illuviation argillans; red-brown argillans outline irregular areas; abrupt very irregular contact to

-10.88 m; Bt; siltstone; maroon-brown, weathering maroon-pink with orange tint; non-calcareous; many distinct, coarse blue green-grey siltstone-filled root traces are randomly oriented; subangular blocky peds show red-brown shiny argillans; abrupt irregular contact to

-11.00 m; Cr; fine-grained sandstone; light and dark grey in different layers, weathering cream grey; non-calcareous; few distinct, fine to medium, maroon clay-filled root traces are vertically oriented and concentrated towards the upper contact; very faint relict laminations are planar, parallel and continuous; maroon red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-11.28 m; A; very fine-grained sandstone; dark maroon, weathering maroon with brick red tint; many distinct, medium light grey mottles are lens-shaped and horizontally oriented; maroon red-brown clayey siltstone skeletans occur between some joint planes; subangular blocky peds show red-brown shiny illuviation argillans; abrupt smooth contact to

-11.47 m; Bt*; very fine-grained sandstone; grey-green, weathering grey-white with pink tint; non-calcareous; massive; abrupt smooth contact to

-11.49 m; Bt; siltstone; dark maroon-brown, weathering maroon; non-calcareous; common faint, medium dark maroon-grey mottles vary in shape; angular blocky peds show red-brown illuviation argillans; abrupt irregular contact to

-11.60 m; C; fine-grained sandstone; grey-brown, weathering grey-white; non-calcareous; few faint, medium dark grey maroon-brown mottles vary in shape; many distinct, medium maroon-brown siltstone mottles vary in shape; mottles increase in abundance upwards; clear wavy contact to

-11.99 m; Cr*; clayey siltstone; very dark maroon-brown, dark maroon-brown and grey-brown in different layers, weathering light maroon; non-calcareous; common distinct, medium maroon-brown mottles vary in shape and increase in abundance upwards; relict laminations are planar, continuous and parallel at the base of the horizon, but become disrupted and discontinuous upwards; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-12.41 m; Cc; fine-grained sandstone; olive-grey, weathering cream grey-brown; non-calcareous; irregular in thickness along strike; massive; well-indurated; white crystalline nodules, weathering white, are irregular in shape; abrupt wavy contact to

-12.43 m; Cr; siltstone; dark maroon-brown and dark grey maroon-brown in different layers, weathering maroon; non-calcareous; relict laminations are continuous, parallel and planar; apedal, but discontinuous red-brown shiny illuviation argillans outline irregular areas; abrupt wavy contact to

-12.61 m; Bw; clayey siltstone; dark maroon, weathering maroon; non-calcareous; common distinct, medium grey-green clay-filled root traces are vertically oriented; blocky peds show poorly developed calci-argillans; abrupt irregular contact to

-12.90 m; B*; very fine-grained sandstone; grey-brown, weathering cream-brown; very weakly calcareous; many distinct, medium to coarse, dark maroon-brown meta-isotubules (after burrows?) are vertically to subvertically oriented; abrupt irregular contact to

-12.97 m; Br; clayey siltstone; maroon-brown and dark grey-brown in different layers, weathering maroon; very weakly calcareous to calcareous in patches; common distinct, fine to medium, very dark maroon-brown meta-isotubules vary in orientation; few distinct, fine to medium, sandy brown-grey fine-grained sandstone metagranotubules (after burrows) are vertically to subvertically oriented; planar relict laminations are faint and are disrupted by the mottling; abrupt, very irregular contact to

-13.02 m; Bk; medium-grained sandstone; dark brown-grey to olive-grey, weathering white-grey; very weakly calcareous to calcareous; few distinct, medium dark maroon meta-isotubules, concentrated towards the upper contact, are vertically to subvertically oriented; red-brown very fine-grained sandstone skeletans occur between some joint planes; abrupt very irregular contact to

-13.15 m; BC*; clayey siltstone; dark maroon-brown, weathering cream grey-brown; very weakly calcareous; massive; abrupt irregular contact to

-13.19 m; BC; fine-grained sandstone; light grey-brown with green tint, weathering cream brown-grey; calcareous; few to common, faint to distinct, maroon-brown mottles vary in shape; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-13.25 m; Cr; siltstone and very fine-grained sandstone; dark maroon-brown, and light and dark grey-brown in different layers, weathering maroon; non-calcareous; few to common distinct, fine to medium, dark maroon-brown siltstone mottles (lithorelicts?) are lens-shaped, concentrated towards the upper contact, and vertically to subvertically oriented; relict laminations are planar, parallel, and continuous; brown sandy siltstone skeletans occur between some joint planes; abrupt wavy contact to

-13.31 m; R; siltstone and very fine-grained sandstone in different layers; dark maroon-brown and dark grey-brown in different layers, weathering cream grey-brown; non-calcareous; relict laminations and beds are generally planar, continuous, and parallel, with some more discontinuous dark maroon-brown laminae; abrupt wavy contact to

-13.46 m; B; sandy siltstone; dark maroon-brown, weathering maroon; non-calcareous; common faint, medium dark grey-brown mottles vary in shape; few green clay papules are irregular in shape; few distinct, fine to medium, green-grey clay-filled root traces, concentrated towards the upper contact, are vertically oriented and branch downwards; maroon clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-14.74 m; BCc; fine-grained sandstone; light grey-brown, weathering cream-brown; non-calcareous; massive; red-brown clayey siltstone and maroon sandy siltstone skeletans occur between some joint planes; well-indurated, grey crystalline cylindrical-shaped nodules, weathering dirty dark brown, are horizontally oriented; abrupt smooth contact to

-15.00 m; C; fine-grained sandstone; maroon-brown, weathering pink-maroon; non-calcareous; common faint to distinct, medium grey-brown orthogranotubules are vertically oriented; maroon clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-15.18 m; C; fine-grained sandstone; dark grey-brown, weathering light pink; very weakly calcareous; common faint, medium dark grey-brown mottles vary in shape; maroon sandy siltstone skeletans occur between some joint planes; abrupt smooth contact to

-15.40 m; Crc; very fine-grained sandstone; dark grey-brown and dark maroon-brown in different layers, weathering pink maroon; very weakly calcareous; few to common distinct, medium dark maroon-brown, clayey siltstone mottles vary in shape; few to common faint, fine to medium, light grey-brown mottles vary in shape; mottles increase in abundance upwards; few distinct, fine to medium, rust orange-brown clay-filled root traces, concentrated at the base of the horizon, are randomly oriented; faint planar relict laminations are disrupted by mottles; well-indurated, dark grey crystalline cylindrical-shaped nodules, weathering dirty dark brown, are horizontally oriented; abrupt irregular contact to

-16.23 m; Cr; medium-grained sandstone; light and dark grey-brown in different layers, weathering cream-brown; planar, parallel relict laminations become less distinguishable upwards; maroon sandy siltstone skeletans occur between some joint planes; well-indurated, light grey crystalline cylindrical-shaped nodules, weathering dirty dark brown, are horizontally oriented; abrupt wavy contact to

-16.32 m; Cr; siltstone and fine-grained sandstone in different layers; dark maroon-brown and dark grey-brown in different layers, weathering cream-maroon; very weakly calcareous; relict laminations are continuous, planar and parallel; few maroon sandy siltstone skeletans occur between joint planes; abrupt wavy contact to

-16.49 m; ACr; fine-grained sandstone; grey-brown and dark maroon-brown in different layers, weathering cream-brown; very weakly calcareous; few to common faint, medium maroon-brown mottles vary in shape; few to common distinct, medium maroon-brown clayey siltstone meta-isotubules after burrows are vertically oriented; few distinct, medium orange-yellow clay-filled root traces are subvertically oriented; planar, parallel and continuous relict laminations are faint and disrupted by mottling; few maroon sandy siltstone skeletans occur between joint planes; abrupt smooth contact to

-16.64 m; Crc; fine-grained sandstone; light grey and dark grey-brown in different layers, weathering cream-brown; very weakly calcareous; few distinct, medium maroon-brown clayey siltstone lithorelicts are lens-shaped and horizontally oriented; faint relict laminations are planar and parallel; maroon sandy siltstone skeletans occur between joint planes; well-indurated, green-white crystalline lens-shaped nodules, weathering white, are concentrated along the lower contact; abrupt, smooth to slightly irregular, contact to

-16.83 m; Cr; clayey siltstone and sandy siltstone in different layers; dark maroon grey-brown and dark red maroon-brown, and dark grey-brown in different layers, weathering darkish maroon; non-calcareous; relict laminations are irregular and continuous or discontinuous and broken; black mangans occur on some ped surfaces; pink-maroon clayey siltstone skeletans occur between some joint planes; clear wavy contact to

-17.21 m; A; clayey siltstone; dark purple-maroon, weathering light purple-grey with green tint; non-calcareous; many distinct, fine to medium, dark green-grey mottles vary in shape; angular blocky peds show poorly developed maroon illuviation and stress argillans; clear wavy contact to

-17.64 m; Bt; siltstone; dark grey-green, weathering light grey-green with patches of purple-maroon; non-calcareous; common faint, medium dark grey-purple mottles vary in shape; few distinct, fine to medium, rust orange clay-filled root traces are randomly oriented; numerous vertical to subvertical, dark purple maroon-grey clay sheets/dykes, <3mm in width, (skeletans?) cut through the horizon; abrupt irregular contact to

-18.33 m; Crc; siltstone; dark maroon-brown, weathering maroon with orange tint; non-calcareous; common distinct, coarse green-grey mottles vary in shape; few distinct, fine to medium, white calcareous para-isotubules (after roots) with pale green diffuse haloes, are randomly oriented; few distinct, fine to medium, green-grey clay-filled vein-mottles are associated with green-grey clay sheets/dykes; black mangans occur on some ped surfaces; vertical to subvertical, green-grey clay sheets/dykes, <5mm in width, (skeletans?), cut through the horizon; blocky peds show green-grey and red-brown illuviation argillans; well-indurated, white-green coarse-grained crystalline, lens-shaped nodules, weathering white, are lined with white powdery carbonate and show preserved root traces; abrupt wavy contact to

-18.83 m; Cc; siltstone; light grey-green, weathering cream grey-white; non-calcareous; few to common distinct, medium maroon-brown mottles vary in shape; common distinct, medium dark maroon-brown clay-filled root traces are vertically oriented and branch outwards; black mangans and rust-orange sesquans occur on some ped surfaces; well-indurated, white-green coarse-grained, crystalline, lens-shaped nodules, weathering white, are lined with white powdery carbonate, show preserved root traces and occur at the same level within the horizon; abrupt irregular contact to

-19.28 m; A; clayey siltstone; purple-maroon, weathering as patches of light grey and light purple-pink; non-calcareous; many distinct, medium to coarse, green-grey mottles vary in shape; common distinct, medium green clay-filled root traces are randomly oriented and branch outwards; black mangans and rust orange sesquans occur on some ped surfaces; abrupt very irregular contact to

-19.58; Bt; siltstone; dark red maroon-brown, weathering orange brown-red; non-calcareous; common distinct, medium green-grey mottles vary in shape; few distinct, fine green clay-filled root traces are randomly oriented; rust orange and iridescent purple ferri-sesquans occur on some ped surfaces; vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <5mm in width, cut through the horizon; granular peds show bright green and maroon red-brown shiny illuviation argillans; abrupt wavy to irregular contact to

-19.82 m; C; fine-grained sandstone; white green-grey, weathering grey-white; non-calcareous to very weakly calcareous; common distinct, medium purple-maroon siltstone mottles vary in shape; few distinct, fine red-brown siltstone mottles occur as small spots; black mangans and rust orange sesquans occur on some ped surfaces; secondary peds show green-grey clay argillans; abrupt irregular contact to

-19.96 m; Bt; clayey siltstone; maroon-brown, weathering dark maroon; non-calcareous; common distinct, fine to medium, green clay-filled root traces are vertically oriented and branch outwards; black mangans occur on some ped surfaces; vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <3mm in width, cut through the horizon; light maroon-brown clayey siltstone skeletans occur between some joint planes; blocky peds show dark red maroon-brown shiny illuviation argillans; clear wavy contact to

-20.31 m; Br; clayey siltstone; dark red maroon-brown and light grey-green in different layers, weathering light grey-pink; non-calcareous; common distinct, medium dark maroon-brown siltstone mottles vary in shape; relict laminations are lens-like and discontinuous along strike; angular blocky peds show poorly developed pale green illuviation argillans; abrupt, wavy to irregular contact to

-20.39 m; Bt; clayey siltstone; dark maroon-brown with purple tint, weathering dark maroon; noncalcareous; few to common distinct, medium green-grey mottles vary in shape; common distinct, fine to medium, grey-green clay-filled root traces are vertically oriented, increase in abundance upwards, and branch outwards; black mangans occur on some ped surfaces; blocky peds show red-maroon (shiny) and grey-green illuviation and stress argillans; abrupt wavy contact to

-20.58 m; Bt; silty claystone; dark grey-green, weathering grey-white with patches of rust orange; non-calcareous; few to common distinct, fine to medium, maroon clay-filled root traces are vertically to subvertically oriented; rust orange sesquans occur on some ped surfaces; granular peds show dark green illuviation argillans; abrupt wavy contact to

-20.62 m; Cr; very fine-grained sandstone; dark maroon, light maroon and light grey in different layers, weathering dark maroon; non-calcareous; few distinct, fine to medium, blue grey-green clay-filled vein-mottles are associated with the sheets/dykes; few to common distinct, fine to medium, very dark maroon-brown clay-filled root traces are vertically oriented and branch outwards; faint discontinuous relict laminations are planar and parallel; vertical to subvertical, blue grey-green clay sheets/dykes (skeletans?), <3mm in width and lined with rust orange argillans, cut through the horizon, and contain lithorelicts of host rock; wavy abrupt contact to

-21.41 m; C; fine-grained sandstone; sandy grey-brown, weathering cream orange-maroon; few distinct, medium maroon-brown clayey siltstone meta-isotubules are vertically oriented; rust orange sesquans occur on some ped surfaces; vertical to subvertical, blue grey-green clay sheets/dykes (skeletans?), <3mm in width, cut through the horizon, and contain few to common distinct, fine to medium, maroon-brown clayey siltstone mottles which vary in shape; prismatic peds show blue grey-green illuviation argillans; abrupt wavy contact to

-21.54 m; K; medium-grained crystalline; grey-white, weathering white with a thin line of rust orange material on the upper and lower contacts; very strongly calcareous; well-indurated, laterally continuous hardpan layer lined on the upper and lower contacts by rust orange sesqui-argillans; abrupt wavy contact to

-21.65 m; Cr; sandy siltstone and very fine-grained sandstone in different layers; dark maroon-brown and light cream grey-brown in different layers, weathering light pink-orange criss-crossed by grey-orange weathering lines (after sheets/dykes); non-calcareous; few distinct, fine to medium, blue grey-green clay-filled vein-mottles are associated with the sheets/dykes; planar and rippled laminations are often deformed; vertical to subvertical, grey-green clay sheets/dykes (skeletans?), <15mm in width and lined with rust orange argillans, cut through the horizon; abrupt irregular contact to

-22.21 m; Bt; siltstone; dark maroon-brown, weathering dark maroon and crisscrossed by grey-orange weathering lines (after sheets/dykes); non-calcareous; black mangans occur on some ped surfaces; numerous vertical, subvertical, and subhorizontal blue green-grey clay sheets/dykes (skeletans?), <15mm in width and lined with rust orange argillans, cut through the horizon and contain angular lithorelicts of purple-maroon clayey siltstone showing faint, planar parallel relict laminations; angular blocky peds show blue green-grey and few dark maroon illuviation argillans; abrupt irregular contact to

-22.78 m; Bt; silty claystone; dark green-grey with blue tint, weathering grey-white with rust orange-maroon at upper and lower contacts; common distinct, medium maroon-purple mottles (after lithorelicts?) vary in shape; blocky peds show rust orange illuviation sesqui-argillans, which also line the upper and lower contacts of the horizon; sharp and irregular (dykes/sheets of dark green-grey silty claystone penetrate horizon below) contact to

-22.82 m; Brt; siltstone; shades of maroon-brown in different layers, weathering dark maroon; non-calcareous to very weakly calcareous; few faint, fine-medium dark maroon-brown clayey siltstone mottles vary in shape; common distinct, fine to medium, blue-green clay-filled root traces are vertically oriented and branch outwards; faint, discontinuous and planar relict laminations occur towards the upper contact; black mangans occur on some ped surfaces; vertical to subvertical, dark blue, with green-grey tint, clay sheets/dykes (skeletans?), <8mm in width and lined with rust orange argillans, cut through the horizon; blocky peds show dark maroon red-brown illuviation argillans which become more abundant upwards; abrupt wavy contact to

-23.41 m; Btc; silty claystone; grey-blue, weathering light grey-white; non-calcareous; common distinct, fine purple-maroon mottles vary in shape; blocky peds show rust orange illuviation sesqui-argillans; well-indurated, pink-white crystalline nodules, weathering white, are irregular to lens-shaped and lined with rust orange sesqui-argillans; abrupt smooth contact to

-23.49 m; Bw; very fine-grained sandstone; dark maroon-brown, weathering maroon; non-calcareous; common faint, medium dark grey-brown mottles vary in shape; common distinct, fine to medium, blue-green clay-filled vein-mottles are randomly oriented and associated with the sheets/dykes; black mangans occur on some ped surfaces; vertical to subvertical, dark blue, with green-grey tint, clay sheets/dykes (skeletans?), <5mm in width and lined with rust orange argillans, cut through the horizon; blocky peds show maroon illuviation argillans; abrupt smooth contact to

-24.20 m; Crc*; siltstone to very fine-grained sandstone in different layers; shades of maroon-brown, grey-green, and rust orange in different layers, weathering white cream-brown with thin horizontal orange lines; non-calcareous to calcareous in patches; few to common distinct, medium green clay meta-isotubules (after roots? and/or burrows?) are randomly oriented; continuous and discontinuous, rippled and deformed relict laminations fine upwards; vertical to subvertical, dark blue, with green-grey tint, clay sheets/dykes (skeletans?), <7mm in width and lined with rust orange argillans, cut through the horizon; blocky to prismatic peds show green-blue illuviation argillans; well-indurated, cream-grey crystalline nodules, weathering brown-white, occur at the same stratigraphic level along strike and are irregular to lens-shaped; a very thin layer of fine-grained rust orange sandstone marks the contact which is abrupt and irregular to

-24.46 m; C; very fine-grained sandstone; dark maroon-brown, weathering white cream-brown with orange in patches; non-calcareous; common faint to distinct, coarse dark grey-brown mottles vary in shape; abrupt wavy contact to

-24.51 m; ACr; siltstone; shades of dark maroon-brown and light grey-brown in different layers, weathering light maroon; non-calcareous; few faint to distinct, fine maroon-brown clay-filled root traces are randomly oriented and branch outwards; relict laminations are thin, parallel, planar and continuous; few vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <2mm in width cut through the horizon; maroon-pink clayey siltstone skeletans occur between some joint plane surfaces; discontinuous green illuviation argillans outline large irregular areas; abrupt wavy contact to

-24.74; Cr; sandy siltstone and very fine-grained sandstone in different layers; dark maroon-brown and light grey-brown in different layers, weathering cream-brown with maroon tint; very weakly calcareous; few distinct, coarse dark maroon-brown clayey siltstone meta-isotubules (after burrows) are vertically oriented and concentrated at the upper contact; few distinct, medium green clay meta-isotubules (after roots? and/or burrows?) are randomly oriented; few to common distinct, fine to medium, maroon clay-filled root traces are vertically oriented and branch outwards; thin crudely-defined, relict beds are planar and parallel; few vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <2mm in width cut through the horizon; clear, wavy to irregular contact to

-24.82 m; Cc; fine-grained sandstone; dark maroon-brown, weathering dark maroon; very weakly calcareous; common faint, medium grey-brown mottles vary in shape; few faint, medium maroon grey-brown fine-grained sandstone metagranotubules are vertically oriented; few vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <2mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; well-indurated, spherical white crystalline nodules, weathering grey-white, are associated with the clay dykes; abrupt irregular contact to

-24.88 m; Cr; fine-grained sandstone; grey-brown and dark pink-maroon in different layers, weathering cream-brown; very weakly calcareous; few distinct, fine to medium, green-grey clay meta-isotubules (after roots? and/or burrows?) are randomly oriented; relict laminations are planar, continuous, parallel and become thinner and more pronounced upwards; few black mangans occur on ped surfaces; vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <6mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; abrupt wavy contact to

-24.94 m; Ctc; silty claystone; light green-grey, weathering light grey with orange lines at the lower and upper contacts; very weakly calcareous; thin horizontal rust orange silty claystone layers cut through the horizon and line the upper and lower contacts; well-indurated, light grey-pink crystalline nodules, weathering light grey-brown, are rounded to lens-shaped; well-indurated, faintly laminated medium-grained cream white crystalline nodules, weathering grey, are irregularly shaped and associated with the rounded nodules; abrupt and wavy to irregular contact to

-25.02 m; Cr*; very fine-grained and fine-grained sandstone in different layers; maroon red-brown, dark maroon-brown, and light grey-brown in different layers, weathering cream-maroon with sandy-brown tint; very weakly calcareous; common faint, medium dark maroon grey-brown mottles are lens shaped and oriented horizontally; few distinct, medium maroon-brown siltstone meta-isotubules (after burrows?) are vertically oriented; very faint crude relict laminations are planar and parallel; vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <6mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; discontinuous dark maroon red-brown argillans pick out some of the relict laminations; abrupt wavy contact to

-25.17 m; Cr; very fine-grained sandstone; dark and light maroon-brown in different layers, weathering dark maroon; very weakly calcareous; few distinct, fine to medium, grey-brown very fine-grained sandstone metagranotubules (after burrows) are vertically oriented; thick, planar to rippled, relict laminations are both continuous and parallel, and discontinuous and slightly deformed; a thin green clay layer, lined with rust orange clay, occurs at the abrupt, wavy contact to

-25.21 m; Cr; very fine-grained sandstone; very dark maroon-brown, maroon-grey and light grey-brown in different layers, weathering cream-maroon with sandy-brown tint; non-calcareous; planar and ripple cross, continuous, parallel relict laminations become less defined and coarser-grained upwards; prismatic peds show pale green illuviation argillans; abrupt wavy contact to

-25.42 m; Cr*; siltstone and medium-grained sandstone in different layers; grey-green, grey-brown, and dark maroon-brown in different layers, weathering cream-maroon with sandy-brown and orange tints; non-calcareous; few distinct, coarse grey medium-grained sandstone metagranotubules are vertically oriented and concentrated towards the upper contact; relict laminations are faint, continuous, planar and parallel; vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <4mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; wavy abrupt contact to

-25.45 m; Cr*; siltstone, fine-grained and medium-grained sandstone in different layers; dark maroon-brown, maroon-brown with grey tint and light grey-brown, and very light grey-brown in different layers, weathering cream-maroon with sandy-brown tint; non-calcareous; few distinct, coarse grey fine-grained sandstone mottles (after roots? and/or burrows?) are vertically oriented and concentrated towards the upper contact; planar to rippled and irregular relict laminations are continuous but are disrupted by mottling towards the upper contact; black mangans occur on some ped surfaces; vertical to subvertical, green-blue clay sheets/dykes (skeletans?), <5mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; abrupt wavy contact to

-25.73 m; K; fine-grained crystalline; white-grey, weathering light pink; very strongly calcareous; well-indurated, continuous hardpan horizon of coalesced rounded nodules varies in thickness along strike; abrupt wavy contact to

-25.74 m; Cr*; clayey siltstone; dark maroon-brown and dark grey-brown in different layers, weathering pink-maroon; non-calcareous; faint relict laminations occur in patches but horizon generally massive; vertical to subvertical, green-blue clay sheets/dykes (skeletans?), <4mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; blocky peds show thick blue green illuvial argillans; abrupt wavy contact to

-25.84 m; K; fine-grained crystalline; grey-white, weathering cream white; very strongly calcareous; laterally continuous well-indurated hardpan horizon with numerous horizontally oriented white, very strongly calcareous crystal tubes (after burrows? and/or roots?) running across the upper contact surface; abrupt wavy contact to

-25.89; Bt; very fine-grained sandstone; dark maroon-brown, weathering dark maroon; non-calcareous; few distinct, fine to medium, green-blue clay-filled vein-mottles are associated with green-blue clay sheets/dykes; black mangans occur on some ped surfaces; vertical to subvertical, green-blue clay sheets/dykes (skeletans?), <4mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; blocky peds show red-brown illuviation argillans; abrupt irregular contact to

-26.32 m; Bt; siltstone; dark maroon-brown, weathering grey-white with blue tint; very weakly calcareous; small (<7mm diameter) ovoid black and green-blue lithorelicts are concentrated in areas within the horizon; black mangans occur on some ped surfaces; blocky peds show well developed thick blue-green illuvial argillans; abrupt wavy contact to

-26.40 m; Btc; sandy siltstone; dark maroon-brown, weathering maroon-brown; non-calcareous; massive; black mangans occur on some ped surfaces; vertical to subvertical, blue-green clay sheets/dykes (skeletans?), <6mm in width and lined with thin rust orange sesqui-argillans, cut through the horizon; dark blue-green clay sheets <20mm thick, cut horizontally across the horizon; blocky peds show red-brown and blue-green illuviation argillans and maroon shiny illuviation and stress argillans; well-indurated, grey-white crystalline nodules (few), weathering white, are rounded; clear wavy contact to

-27.15 m; Bt; very fine-grained sandstone; dark maroon-brown with red tint, weathering maroon-brown; non-calcareous; common distinct, fine to medium, blue-green clay-filled vein-mottles are associated with blue-green clay sheets/dykes; common distinct, fine to medium, green clay-filled root traces are vertically oriented and branch outwards; black mangans occur on some ped surfaces; vertical to subvertical, blue-green clay sheets/dykes (skeletans?), <5mm in width, cut through the horizon following a very irregular path; blocky peds show thin blue-green illuviation argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-27.55 m; Bw; very fine-grained sandstone; dark maroon-brown, weathering dark maroon; non-calcareous; few to common distinct, fine to medium, copper blue clay-filled vein-mottles are associated with copper blue clay sheets/dykes; black mangans occur on some ped surfaces; vertical to subvertical, copper blue clay sheets/dykes (skeletans?), <5mm in width, cut through the horizon; widely dispersed small white powdery carbonate nodules occur; abrupt irregular contact to

-27.94 m; C; fine-grained sandstone; dark grey maroon-brown, weathering pink-maroon; non-calcareous; common faint, fine to medium, dark maroon-brown mottles vary in shape; black mangans occur on some ped surfaces; vertical to subvertical, copper blue clay sheets/dykes (skeletans?), <5mm in width, cut through the horizon; blocky peds show thick copper blue illuviation argillans; irregular abrupt contact to

-28.28 m; Cr; siltstone and very fine-grained sandstone in different layers; dark maroon-brown and maroon-brown with grey tint, and light grey-brown in different layers, weathering maroon; non-calcareous; few to common distinct, medium dark maroon-brown siltstone meta-isotubules (after burrows) are vertically oriented; relict laminations are planar, parallel and continuous and are disrupted by burrowing towards the upper contact; black mangans occur on some ped surfaces; pink-red clayey siltstone skeletans occur between some joint planes; discontinuous dark maroon-brown argillans pick out some relict laminations; abrupt irregular contact to

-28.54 m; Ctc*; medium-grained sandstone; grey-brown with green tint, weathering white cream-brown; very weakly calcareous to calcareous; few to common distinct, medium dark maroon-brown clayey siltstone mottles vary in shape; common distinct, medium grey-brown medium-grained sandstone paragranotubules, lined with maroon-brown argillans, are vertically oriented; pink-red clayey siltstone skeletans occur between some joint planes; well-indurated, grey-white crystalline hardpan lenses, weathering white, are elongate to irregularly block-shaped and concentrated at the same level along strike; abrupt wavy contact to

-28.69 m; C; fine-grained sandstone; dark maroon-brown, weathering white cream-brown; non-calcareous; massive; abrupt wavy contact to

-28.71 m; C; medium-grained sandstone; light grey-green, weathering white cream-brown; non-calcareous; few to common distinct, medium clayey siltstone mottles vary in shape; rust orange sesquans occur on some ped surfaces; angular blocky peds show red-brown illuviation argillans; abrupt smooth contact to

-28.82 m; ACr; siltstone and very fine-grained sandstone in different layers; dark and light maroon-brown, and grey-brown in different layers, weathering pink-maroon; non-calcareous; few distinct, medium grey-brown very fine-grained sandstone metagranotubules (after burrows) are vertically oriented; relict laminations at the base of the horizon are discontinuous and lens-like but become well defined, planar, parallel and continuous upwards; black mangans occur on some ped surfaces; vertical to subvertical, light green clay sheets/dykes (skeletans?), <5mm in width, cut through the horizon; pink-red clayey siltstone skeletans occur between some joint planes; secondary prismatic peds show green illuviation argillans; abrupt smooth contact to

-29.07 m; C*; medium-grained sandstone; light grey, weathering grey-white with brown tint; non-calcareous; common distinct, medium dark maroon-brown siltstone meta-isotubules (after burrows) are randomly oriented; pink-red clayey siltstone skeletans occur between some joint planes; abrupt very irregular contact to

-29.10 m; Cr*; siltstone; light grey-brown and dark maroon-brown in different layers, weathering pink-maroon; non-calcareous; crudely-defined, faint relict laminations are planar and both continuous and parallel, and discontinuous and lens-like; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-29.20 m; K; fine-grained crystalline; pink-grey, weathering light grey; very strongly calcareous; well-indurated lenses of faintly laminated hardpan occur continuously along strike; wavy abrupt contact to

-29.23 m; Bt; silty claystone; dark maroon-brown, weathering dark maroon; non-calcareous; few to common faint, medium light maroon-brown mottles vary in shape; blue-black slightly lustrous mangans and orange sesquans occur on some ped surfaces; angular blocky peds show red-brown illuviation and stress argillans; abrupt wavy contact to

-29.48 m; C; fine-grained sandstone; maroon grey-brown, weathering pink-maroon; non-calcareous; few faint, coarse light grey-brown mottles vary in shape; common distinct, coarse dark maroon-brown clayey siltstone meta-isotubules (after burrows?) are randomly oriented; few black mangans occur on ped surfaces; maroon-pink clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-29.79 m; Cc*; fine-grained sandstone; dark cream grey-brown, weathering cream maroon-brown; non-calcareous; common distinct, medium to coarse, dark maroon-brown clayey siltstone meta-isotubules (after burrows?) are vertically oriented; maroon-pink clayey siltstone skeletans occur between some joint planes; the upper contact is marked by well-indurated, grey-white medium- to coarse-grained crystalline nodules, weathering brown-white, which are horizontally oriented, irregular to lens-shaped or rounded and discontinuous along strike; abrupt irregular contact to

-29.82 m; Cr*; clayey siltstone; dark maroon-brown and very dark maroon-brown in different layers, weathering light cream maroon-brown; non-calcareous; few distinct, fine to medium, grey-brown fine-grained sandstone mottles vary in shape; relict laminations are faint, planar, discontinuous and disrupted by mottling in places; maroon-pink clayey siltstone skeletans occur on some ped surfaces; abrupt smooth to wavy contact to

-29.86 m; Cr; fine-grained sandstone; grey-brown with green tint, cream-brown, dark maroon-brown and dark grey maroon-brown in different layers, weathering cream maroon-brown; non-calcareous; few to common distinct, fine to medium, dark maroon-brown clayey siltstone meta-isotubules (after burrows?) are randomly oriented; relict planar, parallel laminations are both continuous and discontinuous and lens-like; pink-maroon clayey siltstone skeletans occur between many of the joint planes; abrupt very irregular contact to

-29.91 m; Crc; clayey siltstone and fine-grained sandstone; dark maroon-brown and light grey-brown in different layers, weathering cream maroon-brown; non-calcareous; few to common distinct, medium grey-brown fine-grained sandstone orthogranotubules (after roots? and/or burrows?) are randomly oriented and lined with maroon-brown argillans; planar, continuous and parallel relict laminations become thinner and less defined upwards; black mangans and rust yellow-orange sesquans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between many joint planes; well-indurated, grey, faintly-laminated, medium-grained crystalline hardpan lenses, weathering brown-white, are horizontally oriented and concentrated towards the upper contact of the horizon; well-indurated, grey-pink crystalline nodules, weathering brown-white, are spherical and occur individually or incorporated within the hardpan lenses; abrupt smooth contact to

-30.07 m; Cr; siltstone and fine-grained sandstone in different layers; dark maroon-brown and light grey-brown in different layers, weathering maroon; non-calcareous; few to common distinct, medium to coarse, dark grey-brown very fine-grained sandstone metagranotubules (after burrows?) are vertically oriented; relict laminations are planar, parallel and continuous but are disrupted by mottling in places; black mangans occur on many ped surfaces; pink-maroon clayey siltstone skeletans occur between some joint planes; abrupt wavy to irregular contact to

-30.18 m; Cr*; fine-grained sandstone; light grey-brown, weathering maroon; non-calcareous; few faint to distinct, fine to medium, dark grey-brown mottles, vary in shape; common distinct, fine to medium, dark maroon-brown clayey siltstone meta-isotubules (after burrows? and/or roots?) are vertically to subvertically oriented and vary in shape; maroon-pink skeletans occur between some joint planes; abrupt very irregular contact to

-30.21 m; Cr; siltstone; dark maroon-brown, weathering maroon; non-calcareous; many faint to distinct, medium dark grey maroon-brown mottles (after bioturbation?) vary in shape; few distinct, medium light grey very fine-grained sandstone mottles (after bioturbation?) vary in shape; abrupt very irregular contact to

-30.24 m; Cr; siltstone and medium-grained sandstone in different layers; dark maroon-brown and light grey-brown in different layers, weathering cream maroon-brown; non-calcareous; few distinct, fine to medium, dark maroon-brown very fine-grained sandstone metagranotubules (after burrows?) are vertically oriented; few distinct, fine to medium, grey-brown medium-grained sandstone ortho- and meta-granotubules (after burrows?) are vertically to subvertically oriented; faint relict laminations are crudely planar, parallel, and both continuous and discontinuous and lens-like, and are disrupted by granotubules; red-brown siltstone skeletans occur between some joint plane surfaces; discontinuous dark maroon argillans pick out some of the relict laminations; abrupt smooth contact to

-30.33 m; Crc; siltstone and fine- to medium-grained sandstone in different layers; dark maroon-brown, and dark and light grey-brown, and grey in different layers, weathering maroon; very weakly calcareous; few distinct, fine to medium, dark maroon-brown siltstone meta-isotubules (after burrows?) are vertically oriented; dewatering structures evident; relict laminations are planar, continuous and parallel and are disrupted by isotubules in places; black mangans occur on some ped surfaces; brown fine-grained sandstone skeletans occur between some joint planes; well-indurated, grey-white crystalline nodules, weathering white, are spherical and concentrated towards the base of the horizon; abrupt and very irregular contact to

-30.76 m; Cr; siltstone and fine-grained sandstone in different layers; dark maroon-brown, and dark and light grey-brown in different layers, weathering cream grey-brown; non-calcareous to very weakly calcareous; few to common faint, medium dark maroon-brown siltstone mottles vary in shape; relict laminations are continuous, parallel and planar or rippled, and are disrupted by mottling in places; black mangans occur on few ped surfaces; brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-30.89 m; Cr*; siltstone and fine-grained sandstone in different layers; dark maroon-brown and dark and light grey-brown in different layers, weathering maroon; non-calcareous to very weakly calcareous; few distinct, fine to medium, grey-brown fine-grained sandstone metagranotubules (after burrows?) are vertically to subvertically oriented; relict laminations are continuous, planar, and parallel; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-30.95 m; Cr*; siltstone and fine-grained sandstone in different layers; dark maroon-brown and light grey-brown in different layers, weathering maroon; very weakly calcareous; relict laminations are planar, parallel, discontinuous and lens-like; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-30.96; Cr; siltstone and fine-grained sandstone in different layers; dark maroon grey-brown and dark maroon-brown in different layers, weathering maroon; very weakly calcareous; relict laminations are discontinuous, lens-like, planar and parallel; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-30.98 m; Cr; siltstone and fine- to medium-grained sandstone in different layers; dark maroon-brown and grey-brown in different layers, weathering light orange-brown; non-calcareous; few faint, medium to coarse, dark maroon-brown siltstone meta-isotubules (after roots? and/or burrows?) are vertically oriented; relict beds and laminations are discontinuous, lens-like, planar, and parallel, with grey-brown beds at the base changing to well-defined thin laminations upwards; yellow-olive sesquans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular grey-brown material from this unit penetrates down into the unit below contact to

-31.16 m; Cr; siltstone; dark grey-brown, dark maroon-brown, and very dark maroon-brown in different layers, weathering maroon; non-calcareous; few distinct, coarse grey-brown fine-grained sandstone metagranotubules (after burrows?) are vertically to subvertically oriented; common faint, medium to coarse, dark maroon-brown siltstone para-isotubules (after burrows) are vertically oriented; irregular, rippled relict laminations are both continuous and discontinuous and lens-like; red-brown clayey siltstone skeletans occur between some joint planes; abrupt, wavy to irregular contact to

-31.26 m; AC; fine-grained sandstone; grey-brown with green tint, weathering grey-brown; non-calcareous to very weakly calcareous; common distinct, medium to coarse, maroon-brown clayey siltstone meta-isotubules (after roots and burrows) are vertically to subvertically oriented; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-31.37 m; Cr; siltstone; very dark and dark maroon-brown, and dark grey-brown in different layers, weathering maroon; very weakly calcareous; few to common distinct, medium to coarse, grey-brown fine-grained sandstone metagranotubules (after burrows) are vertically oriented; common distinct, fine to medium, dark maroon-brown clay-filled root traces are vertically oriented and concentrated towards the upper contact; relict laminations are planar, parallel, and continuous at the base but become indistinct, discontinuous and thicker upwards due to destruction by granotubules; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-31.69 m; Ckm at the top to Cr at the base; fine-grained sandstone; light grey-brown, green-brown, and dark maroon-brown in different layers, weathering light olive-brown; non-calcareous; few to common distinct, coarse dark maroon-brown clayey siltstone meta-isotubules (after burrows) are randomly oriented; relict laminations are vaguely planar to irregular and continuous; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; blocky peds show pale green-grey illuviation argillans; well-indurated grey-white, faintly laminated, coarse-grained crystalline hardpan lenses, weathering brown-white, occur in the upper 60mm of the horizon and have numerous horizontally oriented white very strongly calcareous crystal tubes (after burrows? and/or roots?) running across the upper contact surfaces; abrupt smooth contact to

-31.84 m; Crkc; siltstone and silty claystone in different layers; light and dark grey-brown and maroon-brown, and red-brown and very dark maroon-brown in different layers, weathering light maroon; non-calcareous; parallel, rippled and planar relict laminations are continuous; black mangans occur on some ped surfaces; red-brown silty claystone skeletans occur between some joint planes; blocky peds show green shiny illuviation argillans which are well-defined towards the upper contact; well-indurated, brown-white crystalline nodules, weathering dark brown-white, occur towards the upper contact and are irregular to triangular in shape; thin white calcareous filaments are associated with the nodules and cut vertically down through the horizon (after roots?); abrupt smooth contact to

-32.62 m; Cr; siltstone; dark maroon-brown and maroon-brown in different layers, weathering dark maroon; non-calcareous; faint relict laminations are planar, parallel and continuous; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-32.71 m; Bc; clayey siltstone; dark grey-green, weathering grey-pink; non-calcareous; common to many distinct, medium maroon-purple mottles vary in shape; few to common faint, medium to coarse, dark maroon-brown clay-filled root traces are randomly oriented and branch outwards; red-brown clayey siltstone skeletans occur between some joint planes; dark rust orange, iron-rich concretions, with thin pale green-white haloes, are spherical and occur throughout the horizon; gradual wavy contact to

-32.93 m; Bt; clayey siltstone; grey-green, weathering light grey-pink; very weakly calcareous; common distinct, medium purple-maroon mottles vary in shape; common distinct, fine to medium, maroon-purple clay-filled root traces are randomly oriented and branch outwards; vertical and horizontal, rust orange silty claystone dykes and sheets cut through the horizon; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-33.95 m; Bkm at top to Bkc at base; siltstone; light green-grey, weathering light grey-white; very weakly calcareous; common distinct, coarse purple-maroon and dark maroon-brown mottles (after bioturbation?) vary in shape; black mangans occur on some ped surfaces; vertical rust orange silty claystone dykes cut through the horizon; red-brown clayey siltstone skeletans occur between some joint planes; prismatic peds show purple-maroon and light grey-green diffusion and stress argillans; well-indurated, white-green crystalline hardpan, weathering white, caps the horizon and has the same internal features as the rest of the horizon; numerous crystal sheets and thinner crystal tubes, associated with the hardpan layer, cut down into the horizon, resulting in brecciation of the upper part; clear irregular contact to

-34.59 m; Bt; clayey siltstone; dark maroon-brown, weathering pink-maroon; very weakly calcareous; maroon-brown clayey siltstone lithorelicts are rounded to ovoid; common distinct, medium pale green mottles vary in shape; few dark green clay papules are irregular in shape and less than 15mm in longest diameter; common distinct, medium dark green clay-filled root traces, with pale green-white haloes (< 15mm thick), are randomly oriented and branch outwards; black mangans and rust orange sesquans occur on some ped surfaces; maroon clayey siltstone skeletans occur between some joint planes; subangular blocky peds show green shiny illuviation argillans; abrupt wavy to irregular contact to

-35.05 m; K; fine-grained crystalline; light green-white, weathering white; very strongly calcareous; lenses of dark maroon-brown mudstone (after lithorelicts?) vary in shape, size, and abundance; well-indurated, laterally continuous hardpan layer with associated white, very strongly calcareous crystal sheets and thin crystal tubes cutting through the hardpan; abrupt wavy contact to

-35.10 m; Bt; clayey siltstone; dark maroon-brown, weathering dark maroon; very weakly calcareous; few dark green clay papules are irregular in shape and less than 15mm in longest diameter; common distinct, fine to medium, dark green clay-filled root traces are randomly oriented and branch outwards; granular to subangular blocky peds show red-brown shiny illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-35.19 m; Bt; siltstone; very dark maroon-brown and light maroon-brown in different layers, weathering dark maroon; very weakly calcareous; few maroon-brown clayey siltstone lithorelicts are rounded to ovoid; common dark green clay papules are irregular in shape and less than 10mm in longest diameter; common distinct, medium maroon-brown and green clay-filled root traces, with thin pale green haloes (<2mm thick), are randomly oriented and branch outwards; very faint relict laminations are planar, parallel and disrupted by root traces; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; subangular blocky peds show green illuviation argillans; abrupt wavy contact to

-35.34 m; Bt*; claystone; bright green, weathering light maroon; non-calcareous; common distinct, fine grey-black mottles vary in shape; rust orange sesquans occur on some ped surfaces; abrupt smooth contact to

-35.36 m; Bt; siltstone; dark maroon-brown, weathering maroon; non-calcareous; few faint, medium maroon-brown siltstone ortho-isotubules (after roots? and/or burrows?), are horizontally oriented and lined with green argillans; common distinct, medium green clay-filled root traces are vertically to subvertically oriented and branch outwards; black mangans occur on some ped surfaces; subangular blocky peds show green shiny illuviation argillans; abrupt wavy contact to

-35.41 m; C; fine-grained sandstone; green grey-brown, weathering cream maroon-brown; non-calcareous; many distinct, coarse dark maroon-brown sandy siltstone mottles vary in shape; many faint, coarse light maroon mottles vary in shape; common distinct, fine to medium, green clay-filled root traces are randomly oriented and branch outwards; abrupt irregular contact to

-35.93 m; Bw; fine-grained sandstone; dark maroon-brown, weathering dark maroon; non-calcareous; few distinct, medium dark green clay-filled root traces are vertically oriented; few red-brown clayey siltstone skeletans occur between joint planes; abrupt very irregular contact to

-36.03 m; C*; medium-grained sandstone; brown-grey, weathering cream maroon-brown; non-calcareous; massive; abrupt wavy contact to

-36.09 m; C*; medium-grained sandstone; maroon-brown, weathering cream maroon-brown; non-calcareous; few distinct, fine dark maroon-brown siltstone meta-isotubules are vertically oriented and concentrated towards the upper contact; abrupt wavy contact to

-36.16 m; C; medium-grained sandstone; grey-brown, weathering cream maroon-brown; non-calcareous; few maroon-brown siltstone lithorelicts are lens-like and horizontally oriented; abrupt wavy contact to

-36.22 m; A; medium-grained sandstone; maroon grey-brown, weathering cream maroon-brown; non-calcareous; few distinct, medium dark green clay-filled root traces are vertically oriented and branch outwards; wavy abrupt contact to

-36.34 m; Bw; fine-grained sandstone; dark maroon-brown, weathering maroon-grey; non-calcareous; common faint, medium dark maroon-brown siltstone meta-isotubules (after burrows?) are vertically oriented; few distinct, medium green clay-filled root traces are vertically oriented; red-brown clayey siltstone skeletans occur on between some joint planes; abrupt irregular contact to

-36.47 m; C*; fine-grained sandstone; green-grey, weathering grey maroon-brown; non-calcareous; common distinct, fine to medium, maroon-brown mottles vary in shape; red-brown clayey siltstone skeletans occur on between some joint planes; sharp wavy contact to

-36.59 m; Ckm*; fine-grained, crystalline; grey-white, weathering white; very strongly calcareous; laterally continuous well-indurated hardpan horizon with numerous horizontally oriented white, very strongly calcareous crystal tubes (after burrows? and/or roots?) running across the upper contact surface; sharp wavy contact to

-36.61 m; C; medium-grained sandstone; green-grey, weathering grey maroon-brown; non-calcareous; common distinct, fine to medium, maroon-brown fine-grained sandstone mottles vary in shape; red-brown clayey siltstone skeletans occur between some joint plane surfaces; sharp smooth contact to

-36.67 m; Bt; fine-grained sandstone; dark maroon-brown, weathering grey maroon-brown; non-calcareous; few laminated maroon and grey-brown siltstone lithorelicts are concentrated towards the basal contact; common distinct, medium dark maroon-brown clayey siltstone meta-isotubules (after burrows?) are vertically to subvertically oriented; few distinct, fine to medium, green clay-filled root traces are randomly oriented and branch outwards; black mangans and rust orange sesquans occur on some ped surfaces; red-maroon clayey siltstone skeletans occur between some joint planes; blocky peds show red-brown shiny illuviation argillans towards the upper contact; abrupt wavy contact to

-37.35 m; Crc; fine-grained sandstone; light and dark grey-brown in different layers, weathering maroon-grey; non-calcareous; faint relict laminations are planar, parallel and discontinuous or lens-like; red-maroon clayey siltstone skeletans occur between some joint planes; well-indurated, grey-white medium-grained crystalline hardpan lenses, weathering white, are elongate to irregularly shaped and concentrated in the basal 5-10mm of the horizon; abrupt irregular contact to

-37.54 m; A; very fine-grained sandstone; dark maroon-brown, weathering cream maroon-brown; non-calcareous; very dark maroon-brown siltstone lithorelicts are lens-shaped and horizontally oriented; common distinct, medium dark grey-brown fine-grained sandstone metagranotubules (after burrows?) are vertically oriented; black mangans occur on some ped surfaces; red-brown siltstone skeletans occur between some joint panes; abrupt irregular contact to

-37.67 m; C*; fine-grained sandstone; dark maroon grey-brown, weathering grey maroon-brown; non-calcareous; common faint, medium dark maroon-brown and maroon-brown siltstone mottles vary in shape; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-37.79 m; Ckm; fine-grained crystalline; grey-white, weathering white; very strongly calcareous; well-indurated, continuous hardpan horizon of coalesced rounded nodules varies in thickness along strike; abrupt smooth to wavy contact to

-37.81 m; Cr; siltstone; dark maroon-brown and dark grey-brown in different layers, weathering maroon; non-calcareous; few faint, fine dark maroon-brown mottles vary in shape; few distinct, medium grey-brown fine-grained sandstone metagranotubules (after roots? and/or burrows?) are randomly oriented; faint relict laminations are planar, continuous and parallel; black mangans occur on some ped surfaces; red-brown siltstone skeletans occur between some joint planes; abrupt wavy contact to

-37.98 m; Cr; fine-grained sandstone; dark grey-brown and light maroon-brown in different layers, weathering light maroon; non-calcareous; common distinct, medium dark maroon-brown very fine-grained sandstone mottles vary in shape; very faint relict laminations are planar, parallel, discontinuous and interrupted by mottling; black mangans and rust orange sesquans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-38.16 m; Cr; siltstone and fine-grained sandstone in different layers; dark maroon-brown and dark grey-brown in different layers, weathering cream maroon-brown; non-calcareous; common faint, medium dark maroon-brown siltstone ortho-isotubules (after burrows?) are vertically to subvertically oriented; relict laminations are parallel, rippled and planar, and are disrupted in places by mottling; black mangans and rust orange sesquans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt, smooth to irregular in places, contact to

-38.51 m; A; fine-grained sandstone; dark grey-brown, weathering cream maroon-brown; non-calcareous; common faint, fine to medium, dark grey maroon-brown mottles vary in shape; very few distinct, fine green clay-filled root traces are randomly oriented; red-brown clayey siltstone skeletans occur between some joint planes; clear wavy contact to

-38.71 m; Cr; very fine-grained and fine-grained sandstone in different layers; dark maroon-brown and dark grey-brown in different layers, weathering cream maroon-brown; very weakly calcareous; relict laminations are planar, continuous and parallel, becoming more defined upwards; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-39.09 m; Bc; siltstone; dark maroon-brown, weathering pink-maroon; non-calcareous; few to common distinct, fine to medium, grey-brown mottles vary in shape; common faint, medium dark green clay-filled root traces are vertically oriented and branch downwards; red-brown clayey siltstone skeletans occur between some joint planes; well-indurated, pink-brown crystalline desert rose pseudomorphs, weathering light grey-pink, are concentrated at the upper contact; abrupt wavy contact to

-39.23 m; Bw; siltstone; dark maroon-brown, weathering maroon; very weakly calcareous; common faint, medium to coarse, dark grey mottles vary in shape; red-brown clayey siltstone skeletans occur between some joint planes; discontinuous dark maroon argillans are horizontally oriented (after relict laminations?); abrupt irregular contact to

-39.54 m; Cr; siltstone and very fine-grained sandstone in different layers; very dark maroon-brown, dark maroon-brown, and dark grey-brown in different layers, weathering maroon; non-calcareous; crudely defined relict laminations are planar, continuous, and oriented parallel; red-brown clayey siltstone skeletans occur between some joint planes; discontinuous dark maroon argillans pick out some relict laminations; abrupt wavy contact to

-39.63 m; Cr; siltstone and very fine-grained sandstone in different layers; very dark maroon-brown, light maroon-brown, and dark grey-brown in different layers, weathering maroon; non-calcareous; few distinct, medium dark maroon-brown clayey siltstone meta-isotubules (after burrows) are vertically oriented; relict laminations are well-defined, thin, planar, continuous, and parallel; red-brown clayey siltstone skeletans occur between some joint planes; discontinuous dark maroon argillans pick out some relict laminations; abrupt wavy contact to

-39.75 m; Cr; fine-grained sandstone; light grey-maroon and grey-brown in different layers, weathering maroon-grey; non-calcareous; faint relict laminations are planar, continuous and parallel; black mangans occur on few ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-39.90 m; Cr; fine- and medium-grained sandstone in different layers; light maroon-brown and green-grey in different layers, weathering green grey-brown; non-calcareous; planar relict beds and laminations show green-grey beds with thin discontinuous lenses and laminations of maroon-brown; black mangans occur on few ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-40.09 m; ACr*; siltstone and very fine-grained sandstone in different layers; dark maroon-brown and dark grey-brown in different layers, weathering maroon; non-calcareous; crudely- defined relict laminations are discontinuous, and rippled to irregular, with lenses of dark maroon-brown mudstone; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-40.14 m; C; medium-grained sandstone; dark grey sandy-brown, weathering cream maroon-brown; non-calcareous; massive; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-40.16 m; Cr; siltstone and very fine-grained sandstone in different layers; dark maroon-brown, and grey-brown and dark grey-brown in different layers, weathering cream maroon-brown; non-calcareous; crudely-defined, faint relict laminations vary upwards, occurring as lenses of fine-grained grey-brown sandstone set in dark maroon-brown very fine-grained sandstone, or as planar, continuous and parallel laminations; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-40.30 m; Crc; siltstone; very fine-grained and medium-grained sandstone in different layers; dark maroon-brown, rust orange and bright green-grey in different layers, weathering green-grey; very weakly calcareous; crudely-defined relict laminations are planar, parallel and discontinuous or lens-like; red-brown clayey siltstone skeletans occur between some joint planes; well-indurated, green-white coarse-grained crystalline hardpan lenses, weathering white, are elongate to irregular in shape and concentrated at the same level along strike; abrupt irregular to broken contact to

-40.42 m; ACr; siltstone and very fine-grained sandstone in different layers; dark maroon-brown, sandy-brown and dark grey-maroon in different layers, weathering maroon cream-brown; non-calcareous; common faint, coarse dark grey-maroon siltstone mottles vary in shape; common distinct, coarse sandy-grey fine-grained sandstone metagranotubules (after burrows?) are randomly oriented; relict laminations are planar, parallel and continuous, becoming poorly defined and discontinuous or lens-like upwards; red-brown clayey siltstone skeletans occur between some joint planes; abrupt irregular to broken contact to

-40.72 m; Crc; siltstone and medium-grained sandstone in different layers; dark maroon-brown and grey sandy-brown in different layers, weathering green grey-brown; non-calcareous; flakes of black organic material vary in size and are randomly oriented; few distinct, medium to coarse, maroon-brown siltstone meta-isotubules (after burrows? and/or roots?) are vertically oriented; planar, continuous to discontinuous, and parallel relict laminations are disrupted in places by isotubules; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; discontinuous dark maroon argillans pick out some of the relict laminations; well-indurated, grey-white crystalline nodules, weathering white, occur as lenses along strike; abrupt to clear, irregular to broken contact to

-40.82 m; Cr; siltstone and medium-grained sandstone in different layers; grey-maroon and dark maroon-brown, and light grey sandy-brown in different layers, weathering cream maroon-brown; non-calcareous to calcareous laminations; planar, parallel relict laminations are lenticular and discontinuous along strike; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; discontinuous dark maroon argillans pick out some of the relict laminations; abrupt wavy contact to

-40.89 m; Bt; clayey siltstone; dark maroon-brown, weathering cream maroon-brown; very weakly calcareous; common distinct, medium to coarse, green clay-filled root traces are randomly oriented and branch outwards; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; angular blocky peds show maroon red-brown illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; gradual wavy contact to

-41.03 m; Bw; very fine-grained sandstone; dark maroon-brown, weathering maroon with cream-brown tint; non-calcareous; common distinct, fine to medium, green clay-filled root traces, with pale green diffuse haloes (<3mm thick), are randomly oriented and branch outwards; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; abrupt smooth contact to

-41.28 m; Bht; siltstone; dark maroon-brown, weathering maroon with cream-brown tint; non-calcareous; flakes of black organic material vary in size and are randomly oriented; common distinct, medium light green clay-filled root traces are randomly oriented but become more vertically oriented and abundant upwards; black mangans occur on some ped surfaces; maroon-brown clayey siltstone skeletans occur between some joint planes; blocky peds show green illuviation argillans; wavy abrupt contact to

-42.18 m; Btc; siltstone; dark maroon-brown, weathering maroon with cream-brown tint; non-calcareous; flakes of black organic material vary in size and are randomly oriented; common distinct, fine to medium, green clay-filled root traces are randomly oriented and branch outwards; black mangans occur on some ped surfaces; maroon-brown clayey siltstone skeletans occur between some joint planes; well-indurated, pale grey-green and light maroon laminated crystalline nodules, weathering white, are thin (<8mm thick) and lens-shaped; abrupt, irregular to broken contact to

-42.23 m; SCREE; abrupt, irregular to broken contact to

-43.31 m; Bw; siltstone; dark maroon-brown, weathering maroon; non-calcareous; few faint to distinct, medium to coarse, dark grey-brown very fine-grained sandstone orthogranotubules (after burrows?) are vertically oriented; black mangans occur on some ped surfaces; brown clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-43.53 m; BC; very fine-grained sandstone; dark grey-brown, weathering brown with cream tint; very weakly calcareous; common faint to distinct, medium dark maroon-brown siltstone meta-isotubules (after burrows?) are vertically oriented; sandy-brown very fine-grained sandstone skeletans occur between some joint planes; discontinuous dark maroon argillans are horizontally oriented (after relict laminations?); clear wavy contact to

-43.74 m; C; very fine-grained sandstone; maroon grey-brown, weathering maroon; very weakly calcareous; many distinct, coarse grey-brown mottles vary in shape; few distinct, coarse grey-green fine-grained sandstone mottles vary in shape; common distinct, medium dark maroon-brown siltstone meta-isotubules (after burrows) are randomly oriented; very thin relict laminations of grey and maroon siltstone occur at the upper contact; sandy-brown very fine-grained sandstone skeletans occur between some joint planes; abrupt, irregular to broken contact to

-44.21 m; C; very fine-grained sandstone; green grey-brown, weathering maroon; non-calcareous; common to many distinct, medium to coarse, dark maroon-brown siltstone meta-isotubules (after burrows) are randomly oriented; few to common distinct, medium green grey-brown fine-grained sandstone metagranotubules (after burrows), are vertically oriented and lined with maroon argillans; sandy-brown very fine-grained sandstone skeletans occur between some joint planes; thick, discontinuous maroon argillans are horizontally oriented (after relict laminations?); abrupt wavy contact to

-44.40 m; Ac; fine-grained sandstone; grey-brown, weathering pink grey-brown; very weakly calcareous; flakes of black organic material vary in size and are horizontally oriented; common faint to distinct, medium to coarse, maroon-brown mottles vary in shape; black mangans occur on few ped surfaces; sandy-brown very fine-grained sandstone skeletans occur between some joint planes; subangular blocky peds show maroon illuviation argillans; well-indurated grey, coarse-grained crystalline nodular lenses, weathering brown, are elongate to irregular in shape and horizontally oriented; abrupt irregular contact to

-45.19 m; ABc; medium-grained sandstone; dark kakhi-grey, weathering green-grey with yellow tint; very weakly calcareous; dark maroon-brown siltstone lithorelicts, showing internal stress argillans, are ovoid, lined with rust orange argillans, and horizontally oriented; few faint, coarse maroon grey-orange mottles vary in shape; rust orange veins, of the same grain size as the host rock, cut down through the horizon; well-indurated grey, fine-grained crystalline nodules, weathering dark brown, contain maroon-brown clayey siltstone lithorelicts and occur as numerous coalesced rounded nodules, as log-shaped nodules extending back into the outcrop, or as thin horizontally-oriented, continuous hardpan layers; abrupt wavy contact to

-47.03 m; Crc; fine-grained and medium-grained sandstone in different layers; dark maroon-brown and green grey-brown in different layers, weathering maroon-grey with brown patches; very weakly calcareous; flakes of black organic material vary in size and are horizontally oriented; very faint, planar, continuous relict beds and laminations become thicker and more defined upwards; well-indurated, grey-cream, coarse grained crystalline nodules, weathering brown, are irregularly shaped; abrupt wavy contact to

-48.34 m; Bt*; silty claystone; maroon-brown, weathering light maroon-brown; non-calcareous; massive; black mangans occur on some ped surfaces; blocky peds show maroon-red illuviation and stress argillans and maroon-brown diffusion argillans; abrupt wavy contact to

-48.45 m; Bk; siltstone; maroon-brown, weathering light grey-brown; very weakly calcareous; massive; subangular blocky peds show well developed calcans, forming a "boxwork" structure; abrupt wavy contact to

-48.50 m; Cr; silty claystone and clayey siltstone in different layers; dark maroon-brown and light grey-brown in different layers, weathering maroon-brown; non-calcareous; relict laminations are planar, continuous and parallel; black mangans occur on some ped surfaces; abrupt wavy contact to

-48.58 m; Bt; silty claystone; dark maroon-brown, weathering maroon-brown; non-calcareous; massive; lustrous blue-black mangans occur on some ped surfaces; fine subangular blocky peds show well developed illuviation and stress argillans; abrupt smooth contact to

-48.67 m; Crt; siltstone to very fine-grained sandstone in different layers; shades of maroon and grey in different layers, weathering maroon-brown; non-calcareous; relict laminations are planar, parallel and continuous at the base of the horizon but become planar, discontinuous and lenticular upwards; black mangans occur on some ped surfaces; platy peds show maroon shiny illuviation argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-49.00 m; Bc; siltstone; dark maroon-brown, weathering maroon-brown; non-calcareous; common faint, coarse maroon clay-filled root traces are vertically oriented; black mangans occur on some ped surfaces; angular blocky peds show maroon illuviation argillans; well-indurated, brick red and red-pink ferric nodules, weathering dark brown, are irregular to oblate in shape and lined with rust orange argillans; abrupt smooth contact to

-49.36 m; Cr; very fine-grained sandstone; dark maroon-brown and grey-brown in different layers, weathering light maroon-brown; non-calcareous; flakes of black organic material vary in size and are horizontally oriented; faint crude relict laminations are planar, discontinuous and lenticular, with slight deformation in places; black mangans occur on some ped surfaces; maroon-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-49.50 m; Cr; siltstone; dark and light maroon-brown, and grey in different layers, weathering maroon-brown; non-calcareous; relict laminations are rippled and planar, discontinuous and continuous, and parallel; black mangans occur on some ped surfaces; dark maroon-red argillans are horizontally oriented and pick out relict laminations; platy to granular peds show red-brown and orange-brown illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-49.68 m; Brc; clayey siltstone; dark and light maroon-brown, and grey in different layers, weathering maroon-brown; non-calcareous; common faint to distinct, medium grey-brown mottles vary in shape; common distinct, fine to medium, white calcareous para-isotubules (after roots) are randomly oriented and branch outwards; relict laminations are rippled, discontinuous and deformed in places; black mangans occur on some ped surfaces; dark maroon-red argillans are horizontally oriented and pick out relict laminations; platy to granular peds show red-brown and orange-brown illuviation and stress argillans; well-indurated, brick red and red-pink ferric nodules, weathering dark brown, are irregular to oblate in shape and lined with rust orange argillans; dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-49.79; Crt*; siltstone; dark and light maroon-brown, and grey in different layers, weathering maroon-brown; non-calcareous; relict laminations are rippled and planar, discontinuous and continuous, and parallel; black mangans occur on some ped surfaces; dark maroon-red argillans are horizontally oriented and pick out relict laminations; platy to granular peds show red-brown and orange-brown illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-49.88 m; Bk; fine-grained crystalline; grey-brown, weathering pink-grey; very strongly calcareous; well-indurated, laterally continuous hardpan layer; abrupt smooth to wavy contact to

-49.89 m; Cr*; silty claystone and clayey siltstone in different layers; dark and light maroon in different layers, weathering pink-brown; non-calcareous; faint relict laminations are planar, parallel and continuous or discontinuous and lenticular; black mangans occur on some ped surfaces; granular to subangular blocky peds show red-maroon shiny illuviation and stress argillans, increasing in definition and abundance upwards; abrupt wavy contact to

-49.95 m; Cr*; clayey siltstone; dark red-maroon and dark maroon-brown in different layers, weathering pink-brown; very weakly calcareous; crude faint relict laminations are lenticular and discontinuous; black mangans and rust orange sesquans occur on some ped surfaces; granular primary peds and subangular blocky secondary peds show red-maroon shiny illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-50.03 m; Cr; silty claystone and siltstone in different layers; dark maroon-brown and light grey-brown in different layers, weathering pink-brown; non-calcareous to calcareous laminations; thin relict laminations are planar, parallel and continuous but become deformed and convolute upwards, and then rippled and/or planar, continuous and parallel at the upper contact; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; subangular blocky peds show red-maroon shiny illuviation and stress argillans; abrupt smooth contact to

-50.45 m; A; very fine-grained sandstone; dark maroon-brown, weathering maroon-brown; non-calcareous; flakes of black organic material vary in size and are randomly oriented; brown clayey siltstone skeletans occur between some joint planes; well-indurated, brick red iron-rich nodules, weathering brown, are rounded to irregular in shape; abrupt wavy contact to

-51.05 m; Bt; clayey siltstone; dark maroon-brown, weathering maroon; non-calcareous; few faint, medium maroon mottles vary in shape; black mangans and rust orange sesquans occur on some ped surfaces; subangular blocky peds show maroon shiny illuviation and stress argillans; abrupt smooth contact to

-51.42 m; Cir; fine-grained sandstone; dark maroon-brown and dark grey-brown in different layers, weathering grey-pink; very weakly calcareous; numerous flakes of black organic material vary in size and are randomly oriented; common distinct, medium to coarse, maroon-brown mottles vary in shape; few distinct, coarse green grey-brown very fine-grained sandstone mottles vary in shape; green and maroon clay papules are irregular in shape; few distinct, medium green clay-filled root traces, lined with maroon argillans, are randomly oriented; very faint relict laminations are planar and parallel where visible; numerous small unidentifiable chips of bone are present; pink-red clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-51.74 m; K; coarse-grained crystalline; grey-white, weathering light grey; very strongly calcareous; well-indurated, laterally continuous hardpan layer; abrupt wavy contact to

-51.87 m; A; fine-grained sandstone; grey-brown, weathering pink-grey; very weakly calcareous; numerous large flakes of black organic material and small wood and charcoal chips vary in size and are randomly oriented; green clayey siltstone lithorelicts are angular, randomly oriented and lined with maroon argillans; common faint, medium maroon green-grey mottles vary in shape; maroon and green clay papules are irregular in shape; abrupt wavy contact to

-51.96 m; AC; medium-grained sandstone; grey brown-green, weathering green-grey; very weakly calcareous; numerous flakes of black organic material and small wood and charcoal chips vary in size and are randomly oriented; lens-shaped dark green-grey clayey siltstone lithorelicts are horizontally oriented, lined with red-brown argillans, and show common distinct, medium dark maroon-brown siltstone meta-isotubules (after burrows) of unknown original orientation, within; few distinct, medium rust brown fine-grained sandstone mottles vary in shape; few to common distinct, medium to coarse, maroon-brown fine-grained sandstone metagranotubules (after burrows) are vertically oriented; red-brown clayey siltstone skeletans occur between joint planes; abrupt, irregular to broken contact to

-52.98 m; SCREE; abrupt, irregular to broken contact to

-54.43 m; Bt; siltstone; dark maroon purple-brown, weathering grey purple-maroon; very weakly calcareous; common faint to distinct, fine to medium, dark grey-green siltstone meta-isotubules (after burrows) are vertically oriented; angular blocky peds show thick red-brown illuviation and stress argillans; gradual irregular contact to

-54.75 m; Bt; siltstone; purple maroon-brown, weathering purple maroon-grey; non-calcareous; green clay papules are irregular in shape; many distinct, medium green-grey clay-filled root traces are vertically oriented and branch outwards, forming dense networks; black mangans occur on few ped surfaces; light pink clayey siltstone skeletans occur between some joint planes; abrupt irregular contact to

-55.13 m; Bk; crystalline; white, weathering white; very strongly calcareous; continuous soft white powdery crystal sheet with associated small spherical aggregates of radiating crystals (spherulites); very strongly calcareous; irregular abrupt contact to

-55.23 m; Bt*; siltstone; dark purple maroon-brown, weathering purple-grey; non-calcareous; common distinct, fine to medium, green-grey clay-filled root traces are vertically oriented and branch outwards; secondary subangular blocky peds show thick red-brown shiny illuviation and stress argillans; primary granular peds show grey-green illuviation argillans; abrupt smooth contact to

-55.55 m; Bt; silty claystone; green, weathering grey green-white; non-calcareous; few distinct, fine purple mottles vary in shape; abrupt irregular contact to

-55.58 m; Bt; clayey siltstone; purple-maroon, weathering purple-grey; non-calcareous; many distinct, medium green clay-filled root traces are vertically to subvertically oriented and branch outwards; granular to blocky peds show green and purple maroon illuviation argillans; abrupt wavy contact to

-55.86 m; Bw; silty claystone; dark green-grey, weathering green-white; non-calcareous; few faint, fine dark grey-black mottles vary in shape; few distinct, fine to medium, maroon mottles are rounded; granular to blocky peds show green shiny illuviation argillans; abrupt irregular contact to

-55.91 m; Bw; siltstone; dark maroon-brown with purple tint, weathering maroon-purple; very weakly calcareous; common distinct, medium green clay-filled root traces are randomly oriented and branch outwards; granular to blocky peds show maroon-brown and green illuviation argillans; abrupt wavy contact to

-56.04 m; Bt; clayey siltstone; dark green-grey, weathering green-grey; non-calcareous; small flakes of black organic material vary in size and are randomly oriented; few to common distinct, medium to coarse, dark maroon-red mottles vary in shape; granular to blocky peds show maroon-red and green illuviation argillans; abrupt wavy contact to

-56.23 m; Bt; siltstone; dark maroon-brown with purple tint, weathering purple-maroon; small flakes of black organic material vary in size and are randomly oriented; common distinct, medium green clay-filled root traces are randomly oriented and branch outwards; two green clay (5mm thick) horizontal layers are present; granular to blocky peds show maroon-brown and green illuviation argillans; well-indurated white crystalline nodules, weathering white, are spherical and small (<20mm diameter); abrupt wavy contact to

-57.30 m; A; silty claystone; dark green-grey, weathering white grey-green; non-calcareous; granular peds show green-grey shiny diffusion and illuviation argillans; clear very irregular contact

-57.38 m; Bt; clayey siltstone; dark maroon-brown, weathering grey-maroon; non-calcareous; common distinct, medium green clay-filled root traces are randomly oriented and branch outwards; granular peds show green and maroon-brown shiny diffusion, illuviation and stress argillans; abrupt, irregular to broken contact to

-57.51 m; SCREE COVER - ALLUVIUM

APPENDIX 2.2: Middle Mudrock Sequence

0 m; Bt; clayey siltstone; red to dark maroon-brown, weathering dark maroon; non-calcareous; common distinct, fine to medium, bright green-grey clay-filled root traces are vertically to subvertically oriented and may be single or branched; coarse, subangular blocky peds show common illuviation argillans; well-indurated, pink maroon iron-rich crystalline nodules, weathering dark brown, occur randomly throughout the horizon and are cylindrical in shape; abrupt smooth contact to

-0.99 m; Cr; fine-grained sandstone; grey-green, weathering grey-white; non-calcareous; common to many distinct, medium to coarse, maroon siltstone mottles (after bioturbation), which decrease in abundance in the middle portion of the horizon and then increase upwards, are irregular in shape; common distinct, medium to coarse, light maroon-grey siltstone mottles (after bioturbation) are irregular in shape; common distinct, medium pale green clay-filled root traces, with maroon haloes of irregular width, are vertically oriented and branch downwards; faint planar and parallel relict laminations are evident in areas of no bioturbation; the horizon lenses out laterally; smooth gradual contact to

-1.21 m; C; fine-grained sandstone; grey, weathering light grey; non-calcareous; many distinct, coarse grey-brown and green-grey mottles are irregular in shape; few distinct, coarse green clay-filled root traces are randomly oriented; few faint to distinct, coarse maroon clay-filled root traces are vertically oriented and branch downwards; sandy-brown, sandy-siltstone calci-skeletans occur between some joint planes; massive and apedal, but discontinuous green illuviation argillans (<5mm long) outline irregular areas; wavy abrupt contact to

-1.96 m; Bt; clayey siltstone; dark maroon-brown, weathering maroon; non-calcareous; few distinct, fine to medium, green-grey clay-filled root traces are vertically oriented; subangular blocky peds show maroon-brown illuviation argillans; abrupt wavy contact to

-2.04 m; Bt; claystone; very dark maroon, weathering dark maroon; non-calcareous; rust orange sesquans and black mangans occur on some ped surfaces; granular to platy peds show maroon shiny illuviation and stress argillans; abrupt wavy contact to

-2.28 m; Bw; clayey siltstone; dark maroon-brown, weathering maroon with red-brown tint; common distinct, coarse dark green clay-filled root traces, with pale green haloes (<7mm thick), are vertically to subvertically oriented and branch downwards; contact is marked by a thin continuous rust orange red layer, abrupt planar contact to

-3.10 m; Cr; siltstone and clayey siltstone in different layers; light maroon-grey, dark grey and grey-green, and dark maroon in different layers, weathering light pink-maroon; non-calcareous; few distinct, medium dark maroon clayey siltstone mottles are rounded and occur on lamination planes; relict laminations are both continuous, planar and parallel and discontinuous, wavy and/or lens-like and irregular in thickness along strike; abrupt planar contact to

-3.43 m; R; very fine-grained sandstone; dark maroon, white-grey, and orange-maroon in different layers, weathering maroon; non-calcareous; thin relict laminations are planar, lens-like and discontinuous; rust orange sesquans occur on some ped surfaces; sandy-brown, very fine-grained sandstone calci-skeletans occur between some joint planes; abrupt wavy contact to

-3.63 m; Be*; fine-grained sandstone; maroon-brown, rust orange, yellow, and red in different layers, weathering light orange-maroon; non-calcareous; red rust orange forms a definite layer with diffuse orange and yellow contacts on either side of the layer; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-3.65 m; Be; clayey siltstone; dark maroon-brown, weathering maroon; non-calcareous; flakes of black organic material, with thin rust orange haloes, vary in size and are randomly oriented; few distinct, fine green mottles (after bioturbation) are randomly oriented and rounded; many faint, medium grey-maroon mottles (after bioturbation) vary in shape; dark maroon-brown diffusion cutans define secondary subangular blocky peds; abrupt wavy contact to

-3.77 m; Bht; siltstone; dark grey with green tint, weathering grey-white; non-calcareous; abundant flakes of black organic material vary in size and orientation and are found throughout the horizon; many faint, fine dark grey-green and black-grey mottles vary in shape; common distinct, medium brick-red mottles are irregular in shape; common distinct, medium to coarse, green-grey clay-filled root traces are randomly oriented and branch outwards; common faint, medium red-brown clay-filled root traces are vertically to subvertically oriented; red-brown siltstone skeletans occur between some joint plane surfaces; dispersed white powdery carbonate nodules occur; small (<8mm diameter) rust brown and dull grey, spherical iron-rich concretions and nodules, with thin (<2mm) diffuse haloes, are associated with the root traces and become more abundant upwards; abrupt, very irregular (consists of deep v-shaped pockets cutting down into the horizon below for as much as 0.55m) contact to

-4.19 m; B; clayey siltstone; dark maroon-brown, weathering maroon; non-calcareous; common faint, medium dark grey-brown mottles are irregular in shape; common distinct, fine to medium, green cay-filled root traces are vertically to subvertically oriented and branch downwards; mottling and root traces are more prolific above a rust red planar to wavy, horizontal, continuous layer which cuts across the horizon: abrupt planar contact (marked by a thin continuous green grey clay layer) to

-4.74 m; Bt; very fine-grained sandstone; dark maroon-brown, weathering dark maroon; non-calcareous; common distinct, medium light grey-green mottles vary in shape; platy to blocky secondary peds show dark grey-green illuviation argillans; sparse discontinuous dark grey-green illuviation argillans outline irregular areas (possible primary peds); clear wavy contact to

-5.05 m; Bt; sandy siltstone; dark maroon, weathering light pink with grey tint; non-calcareous; common distinct, medium grey-green and grey-brown very fine-grained sandstone mottles (after burrows? and bioturbation?) are rounded to irregular in shape; common faint, medium light maroon-grey clayey siltstone ortho-isotubules are vertically to subvertically oriented; common distinct, fine to medium, maroon clay-filled root traces, with pale green diffuse haloes, are randomly oriented and branch outwards; subangular blocky peds show maroon-red shiny illuviation argillans; gradual irregular contact to

-5.30 m; BCr; sandy siltstone; light and dark maroon-brown and grey-brown in different layers, weathering light pink-grey; non-calcareous; common distinct, medium grey-brown mottles (after bioturbation), vary in shape; common to many distinct, medium to coarse, maroon-brown clayey siltstone ortho- and meta-isotubules (after burrows) are vertically to subvertically oriented and are lined in places by red-brown argillans; relict laminations are planar, rippled, and convolute and are disrupted by burrowing and bioturbation; apedal, but some discontinuous red-brown illuviation argillans are concentrated in irregular lenses along lamination planes; abrupt smooth contact to

-5.65 m; Cr; siltstone; light and dark maroon-brown and grey-brown in different layers, weathering light pink with grey tint; non-calcareous; light maroon-grey and grey-brown mottles (after bioturbation) vary in shape; faint relict laminations are planar, continuous and parallel; subangular blocky peds show thin maroon-brown illuviation argillans; abrupt wavy contact to

-5.93 m; Bht at top to C near base; sandy siltstone; dark maroon-brown, weathering light maroon; flakes of black organic material vary in size and are randomly oriented; grey-green and dark grey mottles (after burrowing and bioturbation) are randomly oriented and irregular in shape; few distinct, medium pale-green clay-filled root traces, with white diffuse haloes, are vertically oriented; subangular blocky to rounded peds show maroon illuviation and diffusion argillans; abrupt wavy contact to

-6.98 m; A; clayey siltstone; grey-green, weathering light grey; non-calcareous; randomly-oriented flakes and chips of black and brown organic material vary in size and increase in abundance towards the upper contact of the horizon; prominent, coarse maroon clayey siltstone meta-isotubules vertically oriented and slightly irregular in shape; many faint, fine dark green mottles (after bioturbation) vary in shape and increase in abundance upwards; many distinct, coarse red clay-filled root traces are randomly oriented; numerous vertical to subvertical, red clay sheets/dykes (<15mm thick) cut through the horizon; angular blocky peds show thick red shiny illuviation argillans; abrupt broken to irregular contact to

-7.61 m; B; clayey siltstone; maroon red-brown, weathering orange-maroon; non-calcareous; common to many distinct, medium to coarse, bright green clay-filled root traces are vertically to subvertically oriented and branch downwards; gradual irregular contact to

-7.79 m; Bw; clayey siltstone; dark maroon-brown, weathering light maroon; non-calcareous; common distinct, medium green mottles vary in shape; subangular blocky peds show green illuviation argillans; wavy abrupt contact to

-8.27 m; Bk; clayey siltstone; dark maroon-brown, weathering light maroon; non-calcareous; many faint to distinct, maroon grey-brown siltstone mottles vary in shape; few distinct, fine to medium, white calcareous para-isotubules (after roots) with pale green diffuse haloes (<10mm thick), are randomly oriented and branch outwards; dispersed white powdery filamentous carbonate occurs; gradual irregular contact to

-8.67 m; Bk; clayey siltstone; dark maroon-brown, weathering light maroon; very weakly calcareous to very strongly calcareous in patches; common distinct, coarse grey-brown medium-grained sandstone metagranotubules (after burrows? and/or roots?) vary in size; common distinct, fine to medium, white calcareous para-isotubules (after roots) with pale green diffuse haloes (<10mm thick), are randomly oriented and branch outwards, forming a dense network; fine subangular blocky peds show well developed calcans; dispersed white powdery to indurated filamentous carbonate occurs; abrupt wavy to irregular contact to

-8.87 m; Bw; clayey siltstone; dark maroon with red-brown tint, weathering light maroon; non-calcareous; common faint to distinct, medium maroon-grey mottles vary in shape; common distinct, medium dark maroon clay-filled root traces are vertically oriented; abrupt irregular contact to

-9.77 m; Bk; fine-grained sandstone; dark grey-green with brown tint, weathering light grey; calcareous; many faint, medium dark maroon-brown sandy siltstone orthogranotubules show vague vertical orientation and are slightly irregular in shape; abrupt wavy to irregular contact to

-9.90 m; Bw; very fine-grained sandstone; dark maroon-brown, weathering maroon; non-calcareous; common faint to distinct, medium grey-brown mottles vary in shape; common distinct, medium to coarse, grey-green clay-filled root traces (<15mm wide by >15mm long) are vertically to subvertically oriented becoming more horizontally oriented towards the base of the horizon, and branch downwards; few to common distinct, fine to medium, bright green clay-filled root traces are vertically oriented; abrupt irregular contact to

-11.33 m; C; very fine-grained sandstone; dark green-grey, weathering light grey; very weakly calcareous; common faint to distinct, medium dark maroon-brown mottles are randomly oriented; black mangans occur on some ped surfaces; abrupt wavy contact to

-11.51 m; Ck; medium-grained sandstone; green-grey, weathering light grey; very strongly calcareous; massive; black mangans occur on some ped surfaces; abrupt to gradual irregular (marked by 0.08m thick mottled zone) contact to

-11.94 m; Bkc; siltstone; dark maroon-brown, weathering maroon; very weakly calcareous; common distinct, medium grey-brown, very fine-grained mottles (after bioturbation?) vary in shape and increase in abundance towards upper contact; poorly preserved bone material occurs in the contact zone with the overlying horizon; angular blocky peds show calcans with evidence of stress calci-argillans in places; well-indurated crystalline, grey-brown thick (<0.20m thick) hardpan lenses, weathering dark brown and maroon-brown, occur continually along strike, with some smaller blocky nodules also present; abrupt wavy contact to

-12.30 m; BCr; very fine- to fine-grained sandstone and silty claystone in different layers; grey-brown, maroon-brown and dark maroon-brown in different layers, weathering maroon; non-calcareous; common distinct, medium to coarse, grey-brown fine-grained sandstone mottles increase in abundance upwards, disturb the laminations in places, and vary in shape; relict laminations are planar, parallel and either continuous or discontinuous and lens-like; abrupt wavy contact to

-12.70 m; Ck; medium-grained sandstone; dark grey-green, weathering grey; very strongly calcareous; few to common, faint to distinct, medium maroon-brown mottles are concentrated in the upper part of the horizon and vary in shape; few to common distinct, fine to medium, maroon-brown clayey siltstone meta-isotubules (after burrows) are vertically oriented; abrupt, irregular to broken contact to

-12.82 m; Bw; very fine-grained sandstone; dark maroon-brown, weathering light maroon; non-calcareous; few to common faint, medium grey-maroon mottles vary in shape; contact is marked by a thin orange layer which is laterally continuous, abrupt wavy contact to

-13.04 m; Bht; fine-grained sandstone; grey green-blue, weathering light grey with blue tint; non-calcareous; very few flakes of black organic material vary in size and are randomly oriented; many faint, coarse purple maroon-brown mottles vary in shape; rounded secondary peds show poorly developed red-brown illuviation argillans; discontinuous very dark maroon-brown argillans are oriented horizontally (after relict laminations?); abrupt wavy contact to

-13.26 m; Cr*; very fine-grained sandstone and siltstone in different layers; light and dark maroon in different layers, weathering faint maroon-orange; non-calcareous; few to common faint to distinct, medium green-grey and/or maroon fine-grained sandstone metagranotubules (after burrows) are vertically oriented; relict laminations are planar, continuous and parallel; abrupt wavy contact to

-13.28 m; Cr; medium-grained and fine-grained sandstone; grey green-blue and grey-brown in different layers, weathering light grey-blue; few flakes of black organic material vary in size and are randomly oriented, occurring towards the upper contact of the horizon; many faint, coarse purple maroon-brown fine-grained sandstone mottles vary in shape; common distinct, medium dark maroon-brown clayey-siltstone mottles vary in shape and orientation; relict laminations are planar, continuous and parallel, and disrupted by mottling; subangular blocky to rounded peds show red-brown illuviation argillans; gradual smooth contact to

-14.07 m; A; fine-grained sandstone; light maroon, weathering light maroon orange-brown; flakes of black organic material vary in size and are randomly oriented; many faint to distinct, medium grey-brown and grey-green mottles are randomly oriented and irregular in shape; few to common faint, medium dark maroon-brown mottles are randomly oriented and irregular in shape; mottles increase in abundance upwards; gradual very irregular contact to

-14.14 m; Ar*; siltstone; dark and light maroon-brown in different layers, weathering light maroon orange-brown; non-calcareous; few distinct, medium green-grey fine-grained sandstone metagranotubules (after burrows) are vertically oriented; faintly-defined relict laminations are planar, continuous and parallel, and disrupted by burrowing; abrupt wavy contact to

-14.15 m; Ar; fine-grained sandstone; green-grey, weathering green-grey; non-calcareous; flakes of black organic material occur concentrated in patches, vary in size and are oriented horizontally; common distinct, medium to coarse, maroon mottles are rounded; common distinct, medium maroon clayey-siltstone filled root traces are vertically to subvertically oriented; red-brown sandy siltstone skeletans occur between some of the joint planes; abrupt irregular contact to

-14.23 m; Cr; clayey siltstone and fine-grained sandstone in different layers; dark maroon-brown, and light maroon-brown and dark grey-brown in different layers, weathering maroon; non-calcareous; few faint to distinct, coarse maroon-brown clayey siltstone mottles vary in shape; few distinct, medium dark orange clayey siltstone mottles vary in shape; few distinct, medium dark maroon clayey siltstone meta-isotubules (after burrows and/or roots) are vertically to subvertically oriented and irregular in shape; wavy to irregular relict laminations are generally layer parallel and continuous, however, the dark grey-brown fine-grained sandstone laminations are more lens-like and discontinuous; abrupt smooth contact to

-14.62 m; Cr*; fine-grained sandstone; grey with green tint, weathering light grey; non-calcareous; few distinct, medium to coarse, maroon-brown siltstone meta-isotubules (after burrows), are vertically oriented; abrupt wavy contact to

-14.65 m; Cr; sandy siltstone, very fine-grained sandstone and fine-grained sandstone in different layers; maroon-brown, dark maroon-brown, and grey-green in different layers, weathering light maroon; non-calcareous; common faint, medium very dark maroon-brown siltstone mottles vary in shape; common faint to distinct, coarse green-grey fine-grained sandstone mottles vary in shape; relict laminations are planar to wavy/rippled, parallel and continuous; apedal, but discontinuous dark maroon-brown illuviation argillans are horizontally oriented along lamination planes; abrupt wavy to irregular contact (marked by fine white powdery carbonate in patches, and apparent slump features in other areas) to

-14.74 m; Ck*; fine-grained sandstone; grey-green, weathering grey; very strongly calcareous; few faint, medium maroon mottles vary in shape and are concentrated towards the upper contact; the horizon is stained light green-yellow in large patches; red maroon-brown sandy siltstone skeletans occur between some of the joint planes; abrupt very irregular contact to

-14.87 m; Cr; sandy siltstone and very fine-grained sandstone; light maroon-brown, maroon, and very dark maroon, and grey-green in different layers, weathering grey with maroon tint; non-calcareous; relict laminations are wavy to rippled and irregular, discontinuous and lens-like, with lenses of lithorelicts in places; abrupt intertongued wavy contact to

-14.90 m; Cr; fine-grained sandstone; grey, weathering light grey; non-calcareous; very few flakes of black organic material vary in size and are randomly oriented; few distinct, medium to coarse, light maroon very fine-grained sandstone mottles vary in shape; red-brown very fine-grained sandstone calcan skeletans occur between some of the joint planes; apedal, but discontinuous dark maroon-brown illuviation argillans are horizontally oriented (after relict laminations?); widely dispersed white powdery carbonate nodules occur; wavy abrupt contact to

-14.99 m; Cr; siltstone and very fine-grained sandstone in different layers; dark maroon and light maroon-grey in different layers, weathering maroon; non-calcareous; grey-brown very fine-grained sandstone metagranotubules (after roots and burrows) are randomly oriented; relict laminations are planar, continuous and parallel; abrupt smooth contact to

-15.19 m; E; medium-grained sandstone; light green; weathering light grey-green; non-calcareous; many distinct, coarse maroon very fine-grained sandstone mottles with diffuse contacts, vary in shape; few distinct, coarse maroon sandy siltstone metagranotubules (after burrows) are vertically oriented; few to common distinct, medium maroon clay-filled root traces with maroon diffuse haloes, are vertically oriented and branch downwards; abrupt smooth contact to

-15.57 m; Bw; sandy siltstone; dark maroon-brown, weathering light maroon-brown; few faint, medium light maroon mottles vary in shape; abrupt irregular contact to

-15.66 m; E; fine-grained sandstone; green-grey, weathering grey; non-calcareous; many distinct, medium maroon-brown fine-grained sandstone metagranotubules, lined with rust orange sesquans, are vertically to subvertically oriented; maroon sesquans present on some ped surfaces; irregular abrupt contact to

-16.05 m; Bw; fine-grained sandstone; maroon, weathering maroon-brown; non-calcareous; very few red-maroon clayey-siltstone skeletans occur between some of the joint planes; medium subangular blocky peds show poorly developed maroon-brown illuviation argillans; abrupt wavy contact to

-16.21 m; E; fine-grained sandstone; light grey-green, weathering grey with brown tint; non-calcareous; many distinct, medium maroon-brown siltstone mottles with slightly diffuse contacts vary in shape; black mangans occur on some ped surfaces; red-maroon clayey siltstone skeletans occur between some of the joint planes; abrupt smooth contact to

-16.41 m; Bk; fine-grained sandstone; grey-green, weathering light grey; very strongly calcareous; few to common distinct, fine to medium, maroon-brown clayey siltstone meta-isotubules (after burrows? and/or roots?) are vertically oriented; maroon-orange sesquans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint plane surfaces; abrupt wavy contact to

-16.48 m; Bw; fine-grained sandstone; maroon, weathering orange-maroon; non-calcareous; common distinct, medium grey-green fine-grained sandstone metagranotubules (after burrows) are vertically oriented and increase in abundance upwards; black mangans occur on few ped surfaces; maroon-brown silty claystone skeletans occur between some joint plane surfaces; dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-16.64 m; E; fine-grained sandstone; light grey-green, weathering light grey with pink tint; non-calcareous; many distinct, medium to coarse, maroon sandy siltstone mottles vary in shape and are randomly distributed; black mangans occur on some joint plane surfaces; abrupt smooth contact to

-16.75 m; Bw; very fine-grained sandstone; dark maroon-brown, weathering maroon; non-calcareous; common faint, medium light maroon mottles vary in shape and orientation; dull black mangans occur on some ped surfaces; abrupt irregular contact to

-17.01 m; AB; fine-grained sandstone; light grey-green with brown tint, weathering grey; non-calcareous; few to common distinct, medium maroon-brown mottles vary in shape and have slightly diffuse contacts; rust orange-red ferri-sesquans occur on some ped surfaces; abrupt clear contact to

-17.52 m; K; crystalline; dark brown, weathering brown (elephant skin type); very strongly calcareous; round, knobbly to irregularly shaped, well-indurated nodules are coalesced and arranged in lenses along strike, forming an almost continuous hardpan layer; abrupt clear contact to

-17.62 m; Cr; very fine-grained sandstone; very dark maroon-brown and maroon-brown in different layers, weathering maroon; non-calcareous; common distinct, medium light grey-brown mottles are rounded to ovoid in shape; relict laminations are vague, discontinuous to lens-like, and irregular and are interrupted by mottles; black mangans occur on some ped surfaces; red maroon-brown clayey siltstone skeletans occur between some joint plane surfaces; dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-19.54 m; Bw; very fine-grained sandstone; dark maroon-brown, weathering dark maroon; non-calcareous; black mangans occur on some ped surfaces; abrupt wavy contact to

-19.62 m; Btc; silty claystone; very dark green-grey, weathering light grey-brown; non-calcareous; common faint to distinct, fine to medium, very dark maroon mottles vary in shape and orientation; common distinct, medium pale green clay-filled root traces are randomly oriented and branch outwards; common distinct, medium rust orange clay-filled root traces are vertically oriented and branch downwards; dull and lustrous blue black mangans occur on many ped surfaces; secondary subangular blocky peds show poorly developed green illuviation argillans; granular peds show maroon illuviation and stress argillans; dispersed white powdery carbonate nodules occur; numerous dark orange brown iron-rich concretions (<5mm diameter) have thin white haloes; gradual smooth contact to

-20.55 m; Bt; sandy siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; common faint to distinct, medium white calcareous para-isotubules (after roots) with pale green diffuse haloes (<2mm thick), are randomly oriented and branch outwards; common distinct, coarse (<30mm diameter) very strongly calcareous dark grey-pink crystal tubes (rhizoconcretions) are vertically oriented, elongate, irregular to knobbly in shape, and lined with red-brown clay; common distinct, medium green clay-filled root traces, with diffuse pale green haloes, are randomly oriented and branch outwards, forming a dense network; black mangans occur on some ped surfaces; subangular blocky to granular peds show maroon-brown shiny illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-21.22 m; Bt; siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; common distinct, medium green fine-grained sandstone mottles (after bioturbation and burrowing) are randomly oriented and decrease rapidly in abundance upwards from the basal contact; common distinct, fine to medium, white calcareous para-isotubules (after roots) with pale green diffuse haloes (<3mm thick), are randomly oriented and branch outwards; common to many distinct, medium green clay-filled root traces, which become more abundant upwards, are randomly oriented and branch outwards, forming dense networks concentrated in patches; blue-black mangans occur on many ped surfaces; subangular blocky to granular peds show maroon-brown illuviation and stress argillans, which increase in abundance upwards; dispersed white powdery carbonate nodules occur; gradual smooth contact to

-23.50 m; Bw; siltstone; dark maroon-brown, weathering dark pink-maroon; non-calcareous; common distinct, medium grey-green clay-filled root traces are vertically oriented and branch downwards; black mangans occur on some ped surfaces; subangular blocky to granular peds show faint, poorly developed maroon-brown shiny illuviation and stress argillans; abrupt smooth contact to

-24.20 m; Cr; fine-grained sandstone and siltstone in different layers; light and dark grey-green, and dark maroon-brown in different layers, weathering light grey-green; flakes of black organic material are horizontally oriented; common distinct, medium maroon grey-green siltstone mottles are rounded to irregular in shape and randomly oriented; few distinct, fine green clay-filled root traces are randomly oriented; light and dark grey-green relict laminations are planar, continuous, and parallel, whereas maroon-brown laminations are planar, discontinuous and lens-like, both types are disrupted by mottling; discontinuous dark maroon and green argillans follow relict lamination planes; abrupt smooth contact to

-24.53 m; AB; very fine-grained sandstone; dark maroon-brown, weathering grey-maroon; non-calcareous; flakes of black organic material are randomly oriented and vary in size; common faint to distinct, medium grey maroon-brown mottles vary in shape and orientation; few distinct, fine to medium, green clay-filled root traces are vertically oriented; subangular blocky peds show red-brown illuviation and stress argillans; abrupt smooth contact to

-24.90 m; Bw; siltstone; dark maroon with brown tint, weathering light maroon; non-calcareous; common distinct, medium green-grey clay-filled root traces, with thin pale green haloes (<2mm thick) are randomly oriented and branch outwards; blue black and grey mangans occur on some ped surfaces; dark maroon clayey siltstone diffusion cutans define subangular blocky peds; abrupt smooth contact to

-25.30 m; Bt; clayey siltstone; dark maroon-brown, weathering light maroon; non-calcareous; many distinct, fine to medium, green clay-filled root traces are randomly oriented and branch outwards, forming a dense network; blue grey mangans occur on some ped surfaces; subangular blocky peds show poorly developed illuviation argillans; abrupt wavy contact to

-25.75 m; Bt; clayey siltstone; dark blue green-grey, weathering grey maroon; non-calcareous; few faint to distinct, fine dark orange clay-filled root traces with thin white haloes (<1mm thick) are randomly oriented and branching; rust orange sesquans and black mangans occur on some ped surfaces; abrupt, irregular wispy contact to

-25.93 m; Bt; siltstone; dark maroon, weathering light maroon; non-calcareous; common distinct, medium dark green clay-filled root traces, with pale green diffuse haloes (<3mm thick) are vertically oriented and branch downwards; blue black lustrous mangans occur on some ped surfaces; angular blocky peds show some maroon shiny illuviation and stress argillans; abrupt wavy contact to

-26.12 m; Bt; clayey siltstone; grey-green, weathering light grey-green; non-calcareous; few to common distinct, medium purple-maroon mottles vary in shape, have diffuse contacts, and occur near the base of the horizon; few distinct, fine to medium, maroon clay-filled root traces are vertically oriented; rust orange sesquans occur on some ped surfaces; yellow-olive clayey siltstone skeletans occur between some joint planes; angular to subangular blocky peds show dark green shiny illuviation and stress argillans; abrupt irregular contact (streamers of material from the lower unit are incorporated in the upper horizon) to

-26.89 m; Btc; silty claystone; purple-maroon, weathering maroon; non-calcareous; common distinct, medium green clay-filled root traces with thin (<2mm thick) pale green white haloes, increase in abundance towards the upper contact, and are vertically oriented, branching downwards; granular to subangular blocky peds show purple maroon and green shiny illuviation and stress argillans; dark rust orange, iron-rich nodules are spherical and occur in association with the root traces; gradual smooth contact to

-27.09 m; Btc; siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; common dark green clay papules are irregular in shape and less than 10mm in longest diameter; common distinct, fine white calcareous para-isotubules (after roots) with pale green diffuse haloes (<3mm thick), are vertically to subvertically oriented, increase in abundance upwards to form a dense network at the horizon contact; common distinct, medium green clay-filled root traces, with pale green to white diffuse haloes over 8mm, are randomly oriented and branch outwards; subangular blocky to granular peds show green illuviation and stress calci-argillans; dispersed white powdery carbonate nodules occur; well-indurated, grey to white crystalline disk- to irregular-shaped nodules, weathering white, are randomly oriented; abrupt smooth contact to

-28.36 m; AB; very fine-grained sandstone; maroon, weathering dark maroon; non-calcareous; few flakes of black organic material are randomly oriented; common distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; clear wavy to irregular contact to

-28.62 m; Bt; siltstone; dark maroon-brown, weathering maroon-brown; non-calcareous; common to many distinct, medium green clay-filled root traces, with thin white diffuse haloes (<3mm thick), are vertically to subvertically oriented and branch downwards; few blue grey mangans occur on ped surfaces; granular to subangular blocky peds show green illuviation argillans; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-29.49 m; Bt; fine-grained sandstone; grey-green, weathering light grey; non-calcareous; common distinct, medium maroon-brown very fine-grained sandstone mottles vary in shape and orientation; common distinct, coarse orange-yellow mottles are irregular in shape with diffuse contacts; few to common distinct, fine to medium, maroon and green clay-filled root traces are vertically to subvertically oriented; strong yellow diffuse staining in places; few black mangans occur on ped surfaces; angular to subangular blocky peds show maroon and green illuviation argillans; abrupt irregular contact to

-29.62 m; Bw; siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; common to many distinct, fine to medium, yellow-green and dark orange-brown clay-filled root traces, with pale green to white haloes (<3mm thick), are vertically to subvertically oriented and branch downwards; blue-black mangans occur on some ped surfaces; apedal, but maroon illuviation argillans (<20mm long) outline irregular areas; abrupt very irregular contact to

-29.95 m; Bt; fine-grained sandstone; grey-green, weathering light grey-brown with maroon tint; non-calcareous; common faint, medium grey-brown and yellow mottles vary in shape and have diffuse contacts; common distinct, medium maroon sandy siltstone mottles (after lithorelicts) have sharp contacts and are randomly oriented; common distinct, medium maroon-red clay-filled meta-isotubules, lined with green argillans, are vertically and horizontally oriented; common distinct, fine to medium, maroon clay-filled root traces, lined with green argillans, are vertically oriented and branch downwards; blocky peds show thick, discontinuous, maroon illuviation and stress argillans; abrupt very irregular bioturbated contact to

-30.11 m; B; very fine-grained sandstone; dark maroon with orange tint, weathering light grey-brown with maroon tint; non-calcareous; many faint to distinct, medium light grey-brown mottles vary in shape and orientation; few to common distinct, fine to medium, maroon and green clay-filled root traces are vertically to subvertically oriented, increase in abundance upwards, and branch outwards; dispersed white powdery carbonate associated with light grey-brown mottles; abrupt irregular contact (which cuts down into unit below) to

-30.25 m; Br*; very fine-grained sandstone; grey, weathering grey-white; non-calcareous; common faint to distinct, medium maroon-brown and grey-brown mottles vary in shape; few to common faint, medium purple mottles vary in shape; few to common distinct, medium maroon clay-filled root traces lined with green argillans, are vertically to subvertically oriented; few faint relict laminations; dispersed white powdery carbonate nodules occur; abrupt to gradual irregular contact to

-30.36 m; B; very fine-grained sandstone; grey, weathering grey; non-calcareous; common to many distinct, medium dark maroon mottles vary in shape; abrupt irregular contact to

-30.39 m; Cr; very fine-grained sandstone; grey, weathering grey; common distinct, fine to medium, red-maroon and green clay-filled root traces are randomly oriented; few faint, relict laminations; rounded to subangular blocky peds lack argillans; abrupt irregular to broken contact to

-30.69 m; Brt; very fine-grained and fine-grained sandstone in different layers; dark grey-brown and maroon-brown, and light grey-brown in different layers, weathering light grey-pink; non-calcareous; few to common faint, medium to coarse, grey-purple very-fine grained sandstone mottles vary in shape; an irregularly shaped wedge of maroon-brown siltstone, truncated at the upper contact, contains dark green clay papules which are irregular in shape and less than 10mm in longest diameter, and many distinct, fine to medium, light green and red-brown clay-filled root traces which are randomly oriented and branch outwards; host rock shows planar, parallel, continuous relict laminations; few black mangans and rust orange sesquans occur on ped surfaces; abrupt irregular contact to

-30.99 m; Cr; fine-grained sandstone and very fine-grained sandstone in different layers; grey and maroon-purple in different layers, weathering grey-pink; non-calcareous; common distinct, fine to medium, maroon clay-filled root traces are vertically oriented and branch downwards; relict laminations are both planar, parallel and continuous, and discontinuous and lense-like; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; dispersed white powdery carbonate nodules occur; wavy abrupt contact to

-31.19 m; Ckr; fine-grained sandstone; grey and light pink-maroon in different layers, weathering maroon; calcareous; few to common faint, medium maroon grey-brown mottles vary in shape and occur near the upper contact; few distinct, medium maroon clay-filled root traces, lined with green argillans and showing pale green haloes, are vertically oriented and branch downwards; common distinct, fine to medium, white calcareous para-isotubules (after roots), lined with green argillans and showing pale green haloes (<1mm thick) in places, are vertically oriented and branch downwards; poorly defined, faint relict laminations are planar, continuous and parallel; black mangans occur on some ped surfaces; dispersed white powdery carbonate nodules occur; clear wavy contact marked by thin green clay lens in places, to

-31.29 m; Cr; fine-grained sandstone; dark maroon-brown, light maroon-pink and grey-pink in different layers, weathering light maroon; very weakly calcareous; few to common distinct, medium maroon-red clay-filled root traces lined with green argillans, are randomly oriented; relict laminations are planar, parallel and laterally continuous; clear wavy contact to

-31.38 m; A; very fine-grained sandstone; grey-green, weathering grey; calcareous in patches; few to common distinct, medium red-brown clay-filled root traces lined with green argillans and showing thin white haloes (<3mm thick), are randomly oriented and branch outwards; common distinct, fine to medium, white calcareous para-isotubules (after roots) lined with green argillans and showing diffuse white haloes, are randomly oriented and branch downwards; dispersed white powdery carbonate nodules occur; smooth gradual contact to

-31.55 m; Cr; very fine-grained sandstone; dark and light maroon in different layers, weathering maroon-grey; few to common distinct, medium very dark maroon-brown clay-filled root traces with rust orange brown haloes (<4mm thick), are vertically oriented; many distinct, fine to medium, green clay-filled root traces are vertically oriented and branch outwards, forming dense networks; faint relict laminations are parallel, continuous and discontinuous or lens-like, and rippled to irregular; discontinuous blue black mangans occur on some ped surfaces; discontinuous maroon-brown illuviation argillans outline irregular areas; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-31.84 m; Cr; very fine-grained sandstone; dark grey-green and dark maroon-brown in different layers, weathering light grey-green; common distinct, medium green clay-filled root traces are vertically to subvertically oriented and branch downwards; parallel, continuous coarsening-upward relict laminations are generally planar or rippled but are irregular where disturbed by root traces; blue-black mangans occur on some ped surfaces; blocky peds show red-brown illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; gradual to abrupt irregular intertongued contact to

-32.21 m; Cr; very fine-grained sandstone; light maroon-pink, dark maroon, and grey in different layers, weathering grey-pink; non-calcareous; common distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; relict laminations are parallel and both planar and rippled; black mangans occur on some ped surfaces; towards the upper contact, angular blocky peds show red-brown illuviation argillans; clear abrupt contact to

-33.13 m; Bt; clayey siltstone; dark maroon, weathering light maroon-pink; non-calcareous; few distinct, fine to medium, green clay-filled root traces are vertically oriented; blue-black mangans occur on some ped surfaces; subangular blocky peds show dark maroon illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-33.75 m; Bt; siltstone; dark maroon-brown, weathering light pink maroon; non-calcareous; common faint, fine light maroon mottles vary in shape; common distinct, fine to medium, green clay-filled root traces are vertically oriented and branch downwards; blue-black lustrous mangans occur on some ped surfaces; platy to blocky peds show maroon-brown shiny illuviation and stress argillans which increase in abundance upwards; clear smooth contact to

-34.87 m; Bw; clayey siltstone; dark maroon-brown, weathering light maroon; non-calcareous; few to common distinct, fine green clay-filled root traces are vertically oriented and branch downwards; smooth gradual contact to

-35.53 m; B; siltstone; dark maroon-brown, weathering light grey; non-calcareous; common distinct, fine maroon red-brown clay-filled root traces lined with green argillans are vertically oriented; many distinct, fine to medium, rust orange and yellow clay-filled root traces with cream and pale green haloes (<2mm thick), are randomly oriented, branching outwards to form a dense network; smooth gradual contact to

-35.89 m; Bh; siltstone; dark maroon-brown, weathering maroon; non-calcareous; flakes of black organic material are present; common distinct, fine to medium, green clay-filled root traces, with pale green to white diffuse haloes, are vertically to subvertically oriented and branch downwards; blue-black mangans occur on some ped surfaces; subangular blocky to granular peds show orange-brown illuviation and stress argillans; clear wavy contact to

-37.02 m; Bt; clayey siltstone; dark maroon-brown, weathering maroon; non-calcareous; common distinct, fine to medium, white calcareous para-isotubules (after roots), with pale green diffuse haloes, are vertically oriented and branch downwards; common distinct, fine to medium, green clay-filled root traces are vertically oriented and branch downwards; blocky peds show orange illuviation argillans; dispersed white powdery carbonate nodules and filamentous carbonate occur; wavy clear contact to

-37.10 m; Bt; clayey siltstone; dark maroon-brown, weathering light maroon; non-calcareous; many distinct, medium to coarse, green clay-filled root traces are randomly oriented and branch outwards, forming a dense network; black mangans occur on some ped surfaces; granular peds show maroon-brown illuviation argillans; clear broken bioturbated contact to

-37.38 m; Cr; fine-grained sandstone; grey-green and maroon-brown in different layers, weathering grey with slight brown tint; non-calcareous; common faint, medium light maroon mottles vary in shape; few distinct, fine to medium, dark maroon-brown very fine-grained sandstone mottles vary in shape; faint relict laminations are layer parallel and continuous; apedal, but sparse discontinuous maroon-brown illuviation argillans outline irregular areas; abrupt wavy contact to

-38.10 m; Bw; silty claystone; green, weathering grey-maroon; non-calcareous; common distinct, coarse maroon mottles vary in shape; rust yellow sesquans occur on some ped surfaces; subangular blocky peds show red maroon-brown illuviation argillans; clear gradational bioturbated contact to

-38.22 m; Bt; fine-grained sandstone; maroon-brown, weathering light grey-maroon; non-calcareous; few dark green clay papules are irregular in shape; few distinct, fine green and dark maroon clay-filled root traces with maroon grey-brown diffuse haloes (<5mm thick), are vertically oriented; rust orange sesquans and black mangans occur on some ped surfaces; poorly defined subangular blocky peds show maroon illuviation argillans; widely dispersed white powdery carbonate nodules occur; abrupt clear irregular contact to

-38.37 m; C; fine-grained sandstone; green grey-brown, weathering light grey-maroon; non-calcareous; few distinct, fine dark maroon clay-filled root traces are vertically oriented; massive and apedal, but sparse discontinuous green illuviation argillans (<5mm long) outline irregular areas; widely dispersed white powdery carbonate nodules occur; smooth abrupt contact, marked by a very thin continuous rust orange layer, to

-38.49 m; C; fine-grained sandstone; grey-brown, weathering green-brown with maroon tint; non-calcareous; few distinct, fine dark maroon clay-filled rootlet traces are vertically oriented; dispersed white powdery carbonate nodules occur; irregular abrupt contact to

-39.44 m; SCREE COVER - ALLUVIUM

APPENDIX 2.3: Upper Mudrock Sequence

+0 m; SCREE - irregular contact to

0 m; Bt; clayey siltstone; green-grey, weathering grey-white; non-calcareous; common distinct, medium rust orange mottles vary in shape; many distinct, fine to medium, dark brown to rust orange clay-filled root traces are vertically to subvertically oriented and branch prolifically, forming a dense network throughout the horizon; simple, granular peds show many very moist, shiny green argillans; secondary coarse, subangular blocky peds show grey cream-brown siltstone illuviation cutans; abrupt irregular contact to

-0.6 m; Bt; siltstone; dark maroon with purple tint, weathering maroon; non-calcareous; abundant distinct, fine dark charcoal-green clay vein-mottles (after rootlets?) are randomly oriented; common distinct, fine to medium, dark brown-orange clay-filled root traces, with pale green-grey haloes (<2mm in diameter), are vertically to subvertically oriented; vertical green-grey clay sheets/dykes, (skeletans?) cut through the horizon; poorly developed, subangular blocky to granular peds show common green-grey illuviation argillans; the horizon becomes more clay rich upwards, with an increase in the number of root traces, the purple colouration, and the density of the clay sheets/dykes; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-1.28 m; Cr; fine-grained sandstone; light and dark green grey in different layers, weathering cream green-grey; non-calcareous; few dark green clay papules are irregular in shape; common distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; relict laminations are very faint and discontinuous; rust orange mangans occur on some secondary ped surfaces; numerous vertical to subvertical, dark green clay sheets/dykes (skeletans?), <3mm in width, cut through the horizon; poorly developed dark green argillans, defining platy peds, pick out some of the relict laminations; poorly defined secondary subangular blocky peds show light pink-grey and dark maroon siltstone illuviation cutans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-2.36 m; A; very fine-grained sandstone; grey-green, weathering cream grey; non-calcareous; few to common distinct, coarse light maroon-grey mottles vary in shape; few distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; black mangans occur on some secondary ped surfaces; sandy grey-green diffusion cutans define secondary subangular blocky peds; vertical to subvertical, green clay sheets/dykes (skeletans?), <2mm in width, cut through the horizon; moderately-defined, coarse to medium subangular blocky peds show common green illuviation argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-2.48 m; Cr; siltstone; dark maroon brown, light maroon brown, and light grey maroon in different layers, weathering pink maroon; non-calcareous; common distinct, fine to medium, green clay-filled root traces are vertically to subvertically oriented and branch downwards; relict laminations are very thin (<2mm), planar and parallel; black mangans occur on some secondary ped surfaces; sandy-brown siltstone diffusion cutans define very coarse secondary subangular blocky peds; medium subangular blocky peds show poorly defined (<1cm long) green illuviation argillans; dispersed white powdery carbonate nodules occur and are generally associated with diffusion cutans; abrupt irregular contact to

-2.71 m; Bt; silty claystone; purple-maroon, weathering light purple; non-calcareous; many distinct, fine to medium, green clay-filled root traces with pale green diffuse haloes (<1mm thick), are randomly oriented and form a dense network; few distinct, fine thin white calcareous para-isotubules (after roots), with pale green diffuse haloes (<1mm thick), are randomly oriented and branch outwards; vertical to subvertical, green-grey clay sheets/dykes (skeletans?), <2mm in width, cut through the horizon; light grey brown clayey-siltstone skeletans occur between some of the joint planes; medium to coarse angular blocky peds show common shiny purple illuviation and stress argillans and very poorly developed, minor red-maroon argillans; dispersed white powdery carbonate is common; abrupt wavy to irregular contact to

-3.70 m; Bt; siltstone; red maroon-brown, weathering dark maroon brown with tint of orange; non-calcareous; few faint to distinct, medium dark olive orange-brown glaebules are oval in shape (maximum diameter 7mm); green-grey friable, irregularly-shaped papules are present; common distinct, medium green clay-filled root traces are vertically to subvertically oriented and branch slightly; very thin green argillans occur as horizontally-oriented sheets which lens out laterally; medium to coarse angular blocky peds show common maroon-brown shiny, well-defined illuviation and stress argillans; dispersed white powdery filaments (up to 5mm long) of carbonate are present; abrupt irregular contact to

-5.17 m; BCr; sandy siltstone; dark maroon-brown, maroon-brown and light grey-green in different layers, weathering light grey green with patches of maroon weathering; non-calcareous; common distinct, medium to coarse, blue green-grey siltstone mottles (after bioturbation?) vary in shape; very few distinct, fine green-grey clay-filled root traces are randomly oriented and branch slightly; relict laminations are crudely defined and are interrupted by bioturbation and mottling; thick platy peds show dark maroon brown illuviation argillans; dispersed white powdery carbonate nodules occur; abrupt broken contact to

-5.26 m; Cr; siltstone; maroon-brown and shades of grey-green, with blue tint in different layers, weathering light grey-green with patches of maroon weathering; non-calcareous; few distinct, medium to coarse, red maroon-brown mottles vary in shape; few distinct, coarse red maroon-brown clayey siltstone meta-isotubules (after burrows) are randomly oriented; thin planar, parallel and poorly defined relict laminations are dominated by faint laminations of different shades of green-grey, with thin discontinuous lenses of maroon-brown; light red-brown siltstone skeletans occur between some of the joint planes; dispersed white powdery carbonate is common; abrupt broken contact to

-5.36 m; A; siltstone; blue grey-green, weathering as patches of white grey-green and light pink; non-calcareous; abundant distinct, medium to coarse, maroon mottles are randomly oriented (after bioturbation); light red-brown clayey siltstone skeletans occur between some of the joint planes; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-5.64 m; Bw; siltstone; dark maroon-brown, weathering light grey-maroon; non-calcareous; few distinct, fine to medium, dark green-grey siltstone metagranotubules are vertically and horizontally oriented; red-brown sandy siltstone skeletans occur between many of the joint planes; very coarse angular blocky peds show light maroon, poorly developed argillans; widely dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-5.89 m; Bw; sandy siltstone; green-blue, weathering light grey blue-green; non-calcareous; few distinct, coarse maroon mottles vary in shape; few faint, fine maroon-green clay mottles vary in shape; angular blocky peds show moist maroon red-brown poorly developed argillans; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-6.07 m; Bw; siltstone; dark maroon-brown, weathering light maroon; non-calcareous; common faint to distinct, medium light grey-green and light grey-maroon mottles (after bioturbation) occur in equal proportions; prismatic peds show few moist maroon red-brown poorly developed argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-6.64 m; Cr; siltstone and clay in different layers; blue-green, dark maroon-brown, and dark grey-brown in different layers, weathering light blue-green grey; non-calcareous; few distinct, medium light maroon-brown meta-granotubules (after roots/burrows?) are randomly oriented; relict laminations are parallel but discontinuous and lens-like, varying in thickness along strike; thin green-brown argillans are discontinuous and are parallel to the relict laminations (<2cm long); coarse angular blocky peds show few moist maroon red-brown poorly developed argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-6.75 m; Cr; clayey siltstone; dark maroon brown and maroon brown in different layers, weathering light maroon; non-calcareous; relict laminations are generally continuous, planar and parallel to the upper and lower contacts of the horizon; very thick platy peds show blue green-grey argillans with associated patchy black mangans; secondary coarse angular blocky peds show few poorly developed moist maroon red-brown argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-7.17 m; Bt; silty claystone; dark maroon-brown, weathering grey purple-maroon; non-calcareous; common distinct, fine light grey-green clay-filled root traces are randomly oriented and branch outwards; black mangans are present on some of the peds surfaces, especially towards the base of the horizon; coarse angular to subangular blocky peds show common maroon red-brown illuviation and stress cutans; dispersed white powdery carbonate nodules occur; abrupt wavy contact (marked by a thin continuous light green-grey clay layer) to

-8.52 m; Bw; clayey siltstone; dark maroon-brown, weathering maroon; non-calcareous; common distinct, coarse very dark grey-green sandy siltstone mottles vary in shape (after bioturbation?); black mangans occur on some ped surfaces; light grey-pink clayey siltstone skeletans occur between some of the joint planes; widely dispersed white powdery carbonate nodules occur; abrupt very irregular contact to

-8.80 m; Ck; medium-grained sandstone; green-grey, weathering white grey-green; calcareous; few to common distinct, coarse dark maroon-brown clayey siltstone ovoid clasts are present in the upper part of the horizon; angular blocky peds show few poorly developed moist red-brown argillans; abrupt wavy contact to

-9.12 m; AB; silty claystone; dark maroon-brown, weathering dark pink-maroon; non-calcareous; black mangans occur on some ped surfaces; blocky peds show poorly developed red-brown argillans; abrupt wavy contact to

-9.40 m; Cr; silty claystone and fine-grained sandstone in different layers; dark maroon-brown and green-grey in different layers, weathering maroon with light grey-green horizontally-oriented lenses; non-calcareous; few to common distinct, coarse dark maroon ortho-isotubules (after burrows?) cut vertically through the green-grey laminations; planar, lens-like relict laminations are crudely defined and discontinuous, often pinching out or bifurcating laterally; blocky peds show few, poorly developed red-brown argillans; abrupt irregular to broken contact to

-9.85m; Bt; silty claystone; dark maroon-brown with purple tint, weathering dark maroon; non-calcareous; few distinct, fine to medium, red clay mottles, generally concentrated towards the centre of the horizon, vary in shape; few to common distinct, medium green clay-filled root traces are horizontally oriented; black mangans occur on some ped surfaces; sandy-yellow brown fine-grained sandstone skeletans form thin dykes which cut vertically down through the horizon; secondary blocky peds show few poorly developed light maroon-pink argillans; abrupt irregular contact to

-12.32 m; Cr; fine-grained sandstone; dark grey-brown and dark brown in different layers, weathering cream grey-brown; non-calcareous; common to many distinct, coarse dark maroon-brown siltstone mottles vary in shape; faint laminations are parallel and planar; poorly developed subangular blocky peds show shiny maroon-brown illuviation argillans; very coarse secondary prismatic to blocky peds show few poorly developed pink maroon-brown argillans; abrupt irregular contact to

-12.81 m; Bw; siltstone; dark maroon-brown, weathering dark pink-maroon; non-calcareous; few distinct, fine dark green-grey clay-filled root traces are randomly oriented; very coarse secondary prismatic to blocky peds show few poorly developed light pink maroon-brown argillans; abrupt wavy contact to

-13.25 m; B; siltstone; dark maroon-brown, weathering maroon; non-calcareous; few distinct, coarse dark grey-green clay mottles vary in shape; black mangans occur on some ped surfaces; coarse subangular blocky peds show shiny red-brown, poorly developed illuviation argillans; very coarse secondary blocky peds show few poorly developed light pink maroon-brown argillans; widely dispersed white powdery carbonate nodules occur; abrupt irregular bioturbated contact to

-14.04 m; C; fine-grained sandstone; green-grey, weathering white grey-green; non-calcareous; small poorly developed green illuviation argillans are present; secondary, coarse subangular blocky peds show maroon red-brown poorly developed argillans; abrupt irregular contact to

-14.64 m; Bt; siltstone; very dark maroon-brown, weathering dark maroon; very weakly calcareous; black mangans occur on some ped surfaces; medium to coarse subangular blocky peds show common maroon red illuviation argillans; abrupt wavy contact to

-15.23 m; Cr; very fine-grained sandstone; light pink grey-brown and pink-brown in different layers, weathering light pink grey; very weakly calcareous; common distinct, coarse dark maroon clayey siltstone mottles vary in shape and disrupt the relict laminations; very faint relict laminations are discontinuous, planar and generally parallel; black mangans occur on some peds; very dark maroon-brown siltstone skeletans occur between many of the joint planes; coarse subangular blocky peds lack argillans; widely dispersed white powdery carbonate nodules occur; clear irregular to wavy bioturbated contact to

-15.71 m; Bt; clayey siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; few distinct, medium (less than 15 mm diameter) brick red-pink calcite crystal tubes (after roots/burrows?) are vertically oriented and lined with shiny red-brown stress argillans; subangular blocky peds show common shiny red-brown illuviation argillans; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-15.91 m; B*; sandy siltstone; light grey-brown, weathering cream maroon; non-calcareous; common faint, medium light pink-grey mottles vary in shape; blocky peds show few weakly-developed light pink-maroon argillans; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-15.93 m; Bk; siltstone; dark maroon-brown, weathering cream maroon; very weakly calcareous; common faint to distinct, medium light grey maroon-brown mottles vary in shape; few distinct, coarse (less than 40 mm diameter) calcite brick red-maroon crystal tubes, after large roots, are vertically oriented and lined with dark maroon-brown stress argillans; black mangans occur on some ped surfaces; widely dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-16.21 m; Cr; siltstone; dark maroon-brown and light pink-grey in different layers, weathering maroon; non-calcareous; few distinct, fine to medium, dark brown clay-filled root traces, with rust yellow-orange diffuse haloes, are vertically oriented and branch downwards; relict laminations are planar, parallel and continuous; maroon clayey siltstone skeletans occur between some of the joint planes; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-16.47 m; Cr; very fine-grained sandstone; light grey, grey-brown and light maroon-brown in different layers, weathering grey-white; non-calcareous; few distinct, fine pink-maroon mottles are rounded but flat in shape; rippled and planar relict laminations are discontinuous (lens-like), and generally parallel; poorly defined subangular blocky peds show few moist maroon argillans; abrupt wavy contact to

-16.79 m; Crc; siltstone; dark maroon-brown and dark kakhi-grey in different layers, weathering pink-grey; non-calcareous; planar and parallel relict laminations are both continuous and discontinuous, some being more lens-like; black mangans occur on some ped surfaces; angular blocky peds show common dark maroon red-brown illuviation and stress argillans; well-indurated, pink-maroon crystalline coalesced nodules, weathering dark dirty brown, occur throughout the horizon and are irregular, cylindrical and rounded in shape; abrupt, irregular to broken contact to

-17.04 m; Cc; fine-grained sandstone; dark olive grey-brown, weathering cream grey; non-calcareous; black mangans and rust orange and red-pink sesquans occur on some ped surfaces; white spherical crystalline nodules, weathering dark brown, are generally cemented together in clumps; abrupt wavy contact to

-17.78 m; Crv; medium-grained sandstone; rust orange, and light and dark green grey-brown in different layers, weathering light cream yellow-grey; non-calcareous; few distinct, fine dark brown mottles vary in shape; relict laminations are very faint and poorly defined, with the rust orange horizon being darker in the centre with diffuse upper and lower contacts, and highly indurated and iron-rich; abrupt broken contact to

-17.97 m; SCREE; abrupt broken contact to

-19.86 m; Bw; siltstone; maroon-brown, weathering maroon; non-calcareous; common faint, fine to medium, dark grey-brown mottles vary in shape; coarse poorly developed peds lack argillans; abrupt wavy contact to

-20.50 m; Cr; medium-grained sandstone fining upwards to fine-grained sandstone; dark dirty olive-orange, light sandy-grey, dark grey-purple, olive-grey and dark grey-brown in different layers, weathering light yellow-brown with an olive tint; calcareous in patches, generally non-calcareous; thin planar, continuous laminations of different grain sizes, with some claystone lenses, show varying degrees of cementation; dispersed white powdery carbonate nodules and filamentous carbonate occur; abrupt wavy contact to

-22.25 m; Cr; siltstone; light and dark olive-green, and maroon-brown in different layers, weathering light cream grey; non-calcareous; dark red-brown meta-isotubules, with a faint diffuse red-brown halo, are vertically oriented; relict laminations are faint, planar, and poorly defined, with discontinuous lenses of maroon-brown; very coarse prismatic peds show black mangans on most ped surfaces; abrupt smooth contact to

-22.47 m; Cr; siltstone and fine-grained sandstone in different layers; maroon and maroon-grey, and khaki grey-brown in different layers, weathering pink-maroon; non-calcareous; few to common distinct, coarse maroon-grey siltstone meta-granotubules (after burrows?) are vertically to subvertically oriented; planar relict laminations are generally lens-like and discontinuous along strike, but are well defined; abrupt wavy contact to

-22.55 m; Cr; siltstone and fine-grained sandstone in different layers; light maroon grey-brown, and rust orange and grey sandy-brown in different layers, weathering light cream grey sandy-brown; non-calcareous; few to common distinct, coarse maroon-brown siltstone meta-granotubules are vertically to subvertically oriented and have thin, branching maroon-red clay-filled root traces within; few to common distinct, coarse maroon-brown clayey siltstone meta-isotubules (after burrows) are vertically to subvertically oriented; wavy to irregular, parallel relict laminations and thin beds have gradual to abrupt contacts, and are disrupted by burrowing in places; black mangans occur on some ped surfaces; abrupt wavy contact to

-22.74 m; Cr; fine-grained sandstone; dark dirty olive sandy-brown and dark brown in different layers, weathering creamy sandy-brown with a yellow tint; non-calcareous; common distinct, medium to coarse, olive green-grey medium-grained sandstone-filled meta-granotubules (after roots?/burrows?) are faint; indistinct relict laminations are planar, continuous and parallel; black mangans, with rust orange sesquan haloes, occur on some ped surfaces; coarse poorly developed prismatic peds lack argillans; abrupt wavy contact to

-22.92 m; Cr; fine-grained sandstone; pink grey-brown and dark maroon in different layers, weathering light pink-grey; non-calcareous; very faint relict laminations are generally planar, parallel and continuous; poorly developed, discontinuous dark maroon argillans pick out some of the relict laminations; abrupt smooth contact to

-23.01 m; Cr; very fine- to fine-grained sandstone; dirty olive-grey brown, light rust orange, and dark brown in different layers, weathering light cream-grey; non-calcareous; very faint relict laminations are crudely planar and parallel; light pink-maroon clayey-siltstone skeletans occur between some of the joint planes; abrupt irregular contact to

-23.13 m; A*; medium-grained sandstone; orange sandy yellow-brown, weathering cream brown with a bright orange tint; non-calcareous; dark orange laminations, up to 3mm thick, occur at the upper and lower contacts of the horizon and are laterally continuous; abrupt irregular contact to

-23.18 m; A; medium-grained sandstone; yellow sandy-brown with a grey tint, weathering cream sandy-brown; non-calcareous; light pink maroon-grey clayey-siltstone skeletans occur between some of the joint planes; abrupt wavy contact to

-23.33 m; Cr; siltstone and fine-grained sandstone in different layers; dark maroon and dark dirty sandy grey-brown in different layers, weathering cream grey-brown with a pink tint; non-calcareous; few to common distinct, coarse olive-yellow sandy-brown medium-grained sandstone meta-granotubules, lined with dark orange sesquans (after burrows), are vertically oriented; parallel, planar to rippled relict laminations are generally discontinuous, lensing out along strike; abrupt wavy contact to

-23.47 m; B/C; fine-grained sandstone; grey-brown and lighter grey-brown in different layers, weathering cream sandy grey-brown; non-calcareous; very faint planar relict laminations are rarely preserved; rust orange sesquans occur on many ped surfaces; abrupt very irregular contact to

-23.52 m; C*; fine-grained sandstone; dark orange sandy-brown, weathering cream brown with an orange tint; non-calcareous; few faint, coarse light grey-brown siltstone-filled meta-granotubules (after burrows?) are vertically to subvertically oriented; dark orange laminations occur at the upper and lower contacts of the horizon; the upper contact is marked by thin lenses of grey-brown siltstone (which also occurs as burrow-fill); abrupt and very irregular contact to

-23.56 m; C*; fine-grained sandstone; dark khaki-grey, sandy-brown and dark grey-brown in different layers, weathering light grey; non-calcareous; very faint, planar, parallel relict laminations occur as continuous laminations or as lenses; rust orange sesquans occur on some secondary ped surfaces; abrupt wavy contact to

-23.61 m; C; fine-grained sandstone; sandy brown-grey, weathering light cream grey; non-calcareous; very faint relict laminations are rarely observed; rust orange sesquans are present on some secondary ped surfaces; very abrupt wavy contact to

-23.87 m; K; crystalline; light grey-pink, weathering dark maroon-brown; very strongly calcareous; very hard, well-indurated hardpan layer; laterally continuous although slightly irregular in thickness along strike; abrupt smooth contact to

-24.04 m; Bw; siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; common faint, medium olive-maroon mottles vary in shape; black mangans occur on some ped surfaces; abrupt smooth contact to

-24.37 m; Crc; fine-grained sandstone; kakhi grey-brown, grey-brown and very dark grey-brown in different layers, weathering light cream grey; non-calcareous; planar parallel and continuous relict laminations and beds, less than 4cm thick, are well defined with the upper contact marked by a band of dark brown and very dark brown-grey very fine-grained sandstone laminations; sandy-brown very fine-grained sandstone skeletans occur between some of the joint planes; well-indurated, spherical grey crystalline nodules, weathering dark brown, occur in spaced intervals at the same stratigraphic level along strike; abrupt wavy contact to

-25.08 m; Cr; siltstone and very fine-grained sandstone in different layers; grey-green and dark brown, and light and dark grey-brown in different layers, weathering cream grey with slight khaki tint; non-calcareous; relict laminations are generally continuous, planar, and parallel with discontinuous lenses of grey-green and dark brown siltstone; sandy-brown very fine-grained sandstone skeletans occur between some of the joint planes; wavy abrupt contact to

-25.31 m; A; sandy siltstone breccia; dark grey-brown, weathering light pink-grey; non-calcareous; siltstone clasts are maroon-brown; sandy brown very fine-grained sandstone and light grey very fine-grained sandstone skeletans occur between some of the joint planes; massive and apedal, but sparse discontinuous maroon-brown illuviation argillans (<5mm long) outline irregular areas; abrupt wavy contact to

-25.43 m; Cr; siltstone and fine-grained sandstone in different layers; dark maroon-brown and maroon-brown, and grey-brown and sandy brown in different layers, weathering cream grey with slight kakhi tint; non-calcareous; few distinct, medium dark maroon-brown clay-filled, ovoid to irregularly- shaped mottles (after lithorelicts) occur towards the upper contact; relict laminations of dark maroon-brown, maroon-brown and grey-brown are well defined at the base of the horizon but become fainter upwards, with sandy-brown and grey-brown sandstone laminations dominant; sandy-brown very fine-grained sandstone skeletans occur between some of the joint planes; abrupt wavy contact to

-25.56 m; Cr; fine-grained sandstone; grey and dark brown in different layers, weathering cream grey; non-calcareous; very faint, rippled continuous relict laminations are rarely observed; red-brown very fine-grained sandstone skeletans occur between some of the joint planes; coarse prismatic peds lack argillans; abrupt smooth contact to

-25.85 m; Crk; siltstone and clayey siltstone in different layers; light and dark grey-brown, maroon grey-brown and maroon, and dark maroon, dark maroon-brown, and dark grey in different layers, weathering cream pink-grey; non-calcareous; planar and rippled, continuous parallel relict laminations of siltstone are common, with discontinuous lenses of clayey siltstone; numerous filaments of dispersed white powdery carbonate are present; abrupt smooth contact to

-26.14 m; Cr; siltstone and clayey siltstone in different layers; maroon-brown and dark maroon-brown in different layers, weathering light maroon-pink; non-calcareous; relict laminations are crudely defined, lens-like, planar, and discontinuous; creamy grey very fine-grained sandstone skeletans occur between some of the joint planes; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-26.25 m; Cr; siltstone; grey-brown and dark maroon-brown in different layers, weathering white cream-grey; non-calcareous; few to common distinct, coarse grey-brown mottles vary in shape; very faint poorly defined relict laminations are parallel, discontinuous and rarely observed; black mangans occur on some secondary ped surfaces; cream grey very fine-grained sandstone skeletans occur between some of the joint planes; very few, poorly developed, discontinuous dark maroon argillans pick out faint relict laminations; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-26.34 m; Cr; siltstone; dark maroon-brown and light maroon brown-grey in different layers, weathering maroon-pink; non-calcareous; few distinct, fine to medium, green clay- filled root traces, with pale green diffuse haloes (<1mm thick) are randomly oriented and branch outwards; few distinct, fine thin white calcareous para-isotubules (after roots), with pale green diffuse haloes (<1mm thick), are randomly oriented and branch outwards; disrupted faint planar and parallel relict laminations are observed towards the top of the horizon; black mangans occur on some secondary ped surfaces; medium subangular blocky peds show common maroon-brown shiny illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-26.72 m; A; siltstone; grey-green with brown tint; weathering cream white-grey; non-calcareous; massive and apedal, but sparse discontinuous pink-red illuviation argillans (<5mm long) outline irregular areas; abrupt smooth contact to

-26.88 m; Cr; siltstone; dark and light maroon, dark brown, and dark and light grey-brown in different layers, weathering dark maroon; non-calcareous; few to common distinct, medium light grey-brown very fine-grained sandstone-filled metagranotubules (after burrows?) are vertically oriented; common distinct, fine to medium, thin white calcareous para-isotubules (after roots?) are vertically oriented and branch downwards, forming networks in patches; planar parallel continuous relict laminations and thin beds are well defined and vary in thickness upwards; abrupt smooth contact to

-26.96 m; Cr; siltstone; grey-brown, dark grey-brown and dark brown in different layers, weathering cream-grey; non-calcareous; well defined relict laminations are very thin, continuous, planar, and parallel; black mangans occur on some ped surfaces; abrupt smooth contact to

-27.12 m; Cr*; clayey siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; few distinct, fine dusty pink para-granotubules, with white diffuse haloes, are irregular in shape; common distinct, medium grey-brown siltstone ortho-isotubules (after burrows?) are horizontally oriented; black mangans occur on some ped surfaces; medium subangular blocky to granular peds show dark maroon-red illuviation and stress argillans; dispersed white powdery carbonate nodules and filamentous carbonate occur; abrupt smooth contact to

-27.13 m; Cr*; siltstone; grey-brown, dark grey-brown and dark brown in different layers, weathering cream grey; non-calcareous; relict laminations are very thin, well defined, continuous, planar, and parallel; black mangans are present on some ped surfaces; widely dispersed white powdery carbonate nodules and filamentous carbonate occur; abrupt smooth contact to

-27.23 m; Cr; clayey siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; few distinct, fine dusty pink para-granotubules, with white diffuse haloes, are irregular in shape; common distinct, medium grey-brown siltstone ortho-isotubules (after burrows?) are horizontally oriented; black mangans occur on some ped surfaces; medium subangular blocky to granular peds show dark maroon-red illuviation and stress argillans; dispersed white powdery carbonate nodules and filamentous carbonate occur; abrupt smooth contact to

27.24 m; R; sandy siltstone; grey-brown, dark grey-brown and dark brown in different layers, weathering cream grey; non-calcareous; well defined relict laminations are very thin, continuous, planar, and parallel; black mangans occur on some ped surfaces; abrupt smooth contact to

-27.39 m; Btc; clayey siltstone; dark maroon grey-brown, weathering dark maroon; non-calcareous; common distinct, fine to medium, thin white calcareous para-isotubules (after roots?) are randomly oriented and branch outwards; blue black mangans are present on some ped surfaces; platy to granular peds show abundant dark maroon-brown shiny clay illuviation and stress argillans, many of which are horizontally oriented and define relict laminations; well-indurated, pink-grey, crystalline elongate nodules and hardpan lenses (up to 2.5m long), weathering pink maroon-brown, occur at the same level along strike and have very strongly calcareous crystal tubes (after root traces) along their upper surfaces; abrupt wavy contact to

-27.57 m; Cr; clayey siltstone to siltstone; light grey-green, dark maroon-brown, light maroon-brown, and light maroon-grey in different layers, weathering light maroon-pink with lighter grey weathering horizontal layers; non-calcareous; few distinct, coarse maroon-brown siltstone mottles vary in shape; dark green clay papules disturb relict laminations; common distinct, medium thin pink-red calcareous para-isotubules (after roots), with pale green to white diffuse haloes (<2mm thick), are randomly oriented and increase in abundance towards the upper contact; relict laminations are both planar and rippled and are parallel and continuous; dull black mangans occur on some ped surfaces; subangular blocky peds show red-brown and blue black shiny illuviation and stress argillans; dispersed white powdery carbonate nodules and filamentous carbonate occur; abrupt and wavy to irregular contact to

-28.22 m; Btc*; silty claystone; pink maroon-brown, weathering dark pink; non-calcareous; rust orange sesquans and black mangans occur on some ped surfaces; coarse prismatic peds show red-brown shiny illuviation and stress argillans; dispersed white powdery carbonate nodules occur; well-indurated, irregularly-shaped light pink-maroon crystalline nodular layers and lenses, weathering white, are randomly oriented and form networks in places; abrupt wavy contact to

-28.24 m; Br; silty claystone; maroon grey-brown and dark maroon-brown in different layers, weathering light pink-maroon; non-calcareous; relict laminations are parallel, planar, and continuous; black mangans occur on some ped surfaces; widely dispersed white powdery carbonate nodules occur; abrupt smooth to wavy contact to

-28.38 m; Bt*; clayey siltstone; maroon grey-brown, weathering dark maroon-pink; non-calcareous; black mangans occur on some ped surfaces; medium to coarse subangular blocky peds show abundant red-brown shiny illuviation and stress argillans; abrupt wavy contact to

-28.41 m; Br; clayey siltstone; dark grey-brown, dark maroon-brown and dark maroon-grey in different layers, weathering light maroon-pink; non-calcareous; relict laminations are parallel, planar or rippled, thin, and well defined; subangular blocky peds show maroon-brown shiny illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-28.53 m; Btc; siltstone; dark grey-green, weathering white grey-green; non-calcareous; maroon-brown very fine-grained sandstone lithorelicts are subrounded to subangular; many distinct, fine to medium, dark rust orange to brown clay-filled root traces, with white diffuse haloes, are randomly oriented and branch outwards, forming a dense network; black mangans occur on some ped surfaces; light pink red-brown siltstone skeletans occur between some of the joint planes; granular peds show green and maroon-red illuviation and stress argillans; dispersed white powdery carbonate nodules and filamentous carbonate occur; small (<12 mm diameter) rust orange, spherical iron concretions and nodules, with thin (<2mm) diffuse haloes, are associated with the root traces and become more abundant upwards; abrupt very irregular contact to

-28.79 m; Btk; very fine-grained sandstone; dark maroon-brown with purple tint, weathering pink-maroon with patches of white grey-green; calcareous; many distinct, fine thin white calcareous para-isotubules (after roots) with pale green diffuse haloes (<5mm thick), are randomly oriented, branching outwards to form a dense network; common distinct, fine to medium, rust orange clay-filled root traces, with thin (<3mm) diffuse pale green haloes, are randomly oriented and branch outwards, forming a dense network; rust orange illuviation sesquan argillans occur on some ped surfaces; numerous vertical to subvertical, dark green clay sheets/dykes (skeletans?) cut through to the base of the horizon where they amalgamate to form a thin 20 mm layer; abrupt very irregular contact to

-29.43 m; Bt; sandy siltstone; dark green with slight olive tint, weathering light grey with patches of maroon; non-calcareous; subangular blocky to granular peds show many bright green shiny illuviation and stress argillans; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-29.54 m; BC; fine-grained sandstone; olive-yellow and olive-green in patches, weathering cream olive-grey; non-calcareous; many distinct, fine maroon-purple clayey siltstone mottles vary in shape; medium, distinct, common maroon clay-filled root traces are randomly oriented and branch outwards; subangular blocky peds show poorly developed maroon red illuviation argillans; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-29.70 m; C; very fine-grained sandstone; olive green-yellow with orange tint, weathering cream olive-grey; calcareous; few faint, fine maroon siltstone mottles vary in shape and have very diffuse contacts; towards the upper contact, the horizon is tinted maroon; lilac-maroon very fine-grained sandstone skeletans occur between some joint planes; widely dispersed white powdery carbonate nodules occur; clear irregular contact to

-29.90 m; C; fine-grained sandstone; dark orange olive-yellow, weathering sandy yellow with orange-olive tint; non-calcareous; rust orange sesquans occur on some ped surfaces; lilac-maroon very fine-grained sandstone skeletans occur between some joint planes; abrupt smooth contact to

-33.99 m; Cr; very fine-grained sandstone; shades of khaki grey-brown in different layers, weathering light sandy grey-brown; non-calcareous; coarse, faint, common dark khaki grey-brown mottles vary in shape; very faint relict laminations are planar, continuous, and parallel; light sandy brown siltstone skeletans occur between some joint planes; abrupt to clear smooth contact to

-35.28 m; Cr; siltstone and fine-grained sandstone in different layers; light grey-brown and olive sandy-brown in different layers, weathering sandy grey-brown; non-calcareous; relict beds and laminations, visible in patches, are planar, continuous and parallel; red brown siltstone skeletans occur between some joint plane surfaces; creamy grey-brown siltstone diffusion cutans define poorly developed very coarse blocky peds; abrupt smooth contact to

-35.61 m; ACr; sandy siltstone to very fine-grained sandstone; dark and light grey-brown, dark maroon-purple, dark brown, and green grey-brown in different layers, weathering sandy brown-grey; non-calcareous; common to many distinct, coarse metagranotubules (after burrows) are vertically to subvertically oriented and are concentrated towards the upper contact of the horizon; thin, planar, parallel and continuous relict laminations occur, however there are some wavy and discontinuous lens-shaped grey-brown siltstone laminations; rust orange and dark red-black sesquans and/or ferrans occur on some ped surfaces; creamy grey-brown, fine-grained, very strongly-calcareous sandstone skeletans occur between some joint planes; coarse subangular blocky peds show poorly developed maroon-red illuviation argillans; widely dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-36.50 m; Cr; fine-grained sandstone; dark grey sandy-brown and dark grey-black in different layers, weathering light grey-brown; non-calcareous; faint to indistinguishable relict laminations are planar, parallel and often discontinuous; black mangans occur on some ped surfaces; creamy grey brown sandstone skeletans occur between some joint planes; subangular blocky peds lack argillans; abrupt smooth contact to

-37.73 m; ACr; siltstone; dark maroon-brown, light and dark grey-brown and light maroon grey-purple in different layers, weathering cream grey with pink tint; non-calcareous; few to common distinct, coarse dark maroon-red clay-filled root traces are vertically to subvertically oriented and branch downwards; relict laminations are planar, parallel and continuous, and become fainter upwards; light grey-pink siltstone diffusion cutans define poorly developed coarse blocky peds; dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-39.05 m; Cr; silty claystone and siltstone in different layers; maroon red-brown and dark grey-black, dark maroon-brown, light maroon-brown, and light grey-brown in different layers, weathering light grey-pink with horizontal brick red lines; non-calcareous; relict laminations are planar, parallel and continuous, with the maroon red-brown silty claystone laminations showing common argillans; creamy grey-brown, fine-grained sandstone calcans occur parallel to the laminations; angular blocky peds show maroon red-brown illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-39.43 m; ACr; siltstone; light maroon-grey, pink-maroon, and dark maroon-brown in different layers, weathering light grey-pink; non-calcareous; few to common distinct, fine to medium, dark maroon clay-filled root traces are randomly oriented and branch outwards; relict laminations are parallel, continuous and both planar and rippled; grey-brown siltstone skeletans occur between some joint planes; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-39.81 m; Bw; siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; black mangans occur on some ped surfaces; grey-brown siltstone skeletans occur between some joint planes; angular blocky peds show few, poorly developed dark maroon illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-40.12 m; Btc; clayey siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; rust orange sesquans occur on some ped surfaces; thick platy peds show maroon red-brown illuviation and stress argillans, often occurring as thick horizontal layers; platy peds show poorly defined (<10 mm long) green illuviation argillans oriented horizontally; dispersed white powdery carbonate nodules occur; few well-indurated, brick pink-red, iron-rich crystalline nodules, weathering dark maroon-brown, are ovoid (<15 mm wide and 10 mm thick) and randomly oriented; abrupt irregular contact to

-40.84 m; C; fine-grained sandstone; dark grey-green, weathering white grey-green; non-calcareous;

poorly developed black mangans occur on a few ped surfaces; light maroon red-brown siltstone skeletans occur between some joint planes; widely dispersed white powdery carbonate nodules occur; abrupt irregular contact to

-41.12 m; Crc; siltstone; dark maroon-brown and grey maroon-brown in different layers, weathering dark maroon-pink; non-calcareous; common faint, medium to coarse, grey-brown siltstone orthogranotubules (after burrows?) are vertically oriented; rippled and planar relict laminations which become less defined upwards, are continuous but show varying thickness along strike; light maroon red-brown clayey siltstone skeletans occur between some joint planes; subangular blocky peds show poorly developed dark maroon-brown illuviation argillans; dispersed white powdery carbonate in present; well-indurated, ovoid dark maroon-brown crystalline nodules, weathering brown-black, occur throughout the horizon; abrupt wavy contact to

-41.57 m; Cr; siltstone and very fine-grained sandstone in different layers; dark and light maroon-brown, and light grey-brown in different layers, weathering light maroon-pink; non-calcareous; few faint, fine to medium, maroon-brown siltstone orthogranotubules (after burrows?) are vertically oriented; few distinct, fine to medium, dark brown clay-filled rootlets are vertically oriented and branch and downwards; relict laminations are planar, parallel and continuous; maroon red-brown siltstone skeletans occur between some joint planes; dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-41.87 m; Cr; fine-grained sandstone; grey-green, purple-maroon, dark maroon-brown, dark grey, and light maroon-grey in different layers, weathering white-grey; non-calcareous; few faint, coarse maroon-grey siltstone mottles vary in shape; few distinct, fine dark maroon-brown clayey siltstone mottles are found in the basal section of the horizon; faint to distinct relict laminations are planar and parallel, with the darker-coloured laminations dominant at the base and the lighter-coloured laminations becoming more dominant upwards; maroon red-brown siltstone skeletans occur between some joint planes; massive and apedal, but sparse discontinuous maroon-brown illuviation argillans ($<$15mm long) outline irregular areas; abrupt very irregular contact to

-42.83 m; Btc; clayey siltstone; dark purple-maroon, weathering purple-maroon; very weakly calcareous; many distinct, fine to medium, thin white calcareous para-isotubules (after roots) with pale green diffuse haloes ($<$10 mm thick), are randomly oriented and branch outwards, forming a dense network; red-brown clayey siltstone skeletans occur between some joint planes; blocky peds show maroon-red illuviation and stress argillans; brick red nodules occur at a certain laterally-continuous level within the horizon as well as in association with root traces; well-indurated, spherical ($<$2cm diameter), rust orange crystalline nodules, weathering dark orange, occur in association with the very strongly calcareous root traces and become more prolific towards the upper contact, with their distribution following the path of the root traces; abrupt irregular contact to

-44.44 m; Btk; silty claystone; dark grey-green, weathering light grey-green with pink tint; non-calcareous to very strongly calcareous in patches; many faint to distinct, fine purple-maroon claystone mottles vary in shape; common distinct, medium dark maroon-brown mottles vary in shape; many distinct, medium, very strongly calcareous, white crystal tubes, after root systems, are lined with green-grey and green-purple illuviation argillans, and are vertically oriented, branching downwards to form extremely dense networks of crystal tubes; common distinct, medium dark maroon clay-filled root traces are vertically oriented and branch downwards; purple-black mangans and rust orange sesquans occur on ped surfaces; abrupt very irregular contact to

-44.75 m; Bw; clayey siltstone; dark maroon-brown, weathering dark maroon; non-calcareous; few distinct, medium dark green clay-filled root traces are vertically oriented and branch downwards; light red-brown clayey siltstone skeletans occur between some joint plane surfaces; granular peds show maroon red-brown illuviation argillans; abrupt irregular contact to

-45.21 m; Cr; siltstone and clayey siltstone in different layers; light green-grey and dark maroon-brown in different layers, weathering light grey-pink; non-calcareous; common distinct, medium dark maroon-brown siltstone meta-isotubules (after burrows?) are randomly oriented and slightly irregular in shape; relict laminations are both continuous, planar and parallel, and discontinuous, lens-like and planar parallel; pink maroon-red clayey siltstone skeletans occur between some joint planes; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-45.43 m; Bt; siltstone; dark maroon-brown with purple tint, weathering maroon; non-calcareous; common distinct, medium green clay-filled root traces are vertically oriented and branch downwards; granular peds show maroon illuviation and stress argillans; abrupt smooth contact to

-45.63 m; Bt; claystone; dark grey-brown with green tint, weathering light grey-pink; non-calcareous; abrupt smooth contact to

-45.68 m; Bt; sandy siltstone; maroon-brown with purple tint, weathering maroon; non-calcareous; common distinct, medium green clay meta-isotubules (after roots? and/or burrows?) are randomly oriented; subangular blocky peds show maroon illuviation and stress argillans; abrupt irregular contact to

-46.10 m; Bw; siltstone; dark maroon-brown, weathering maroon; non-calcareous; many faint to distinct, medium, light maroon-brown mottles vary in shape (after bioturbation); common distinct, medium dark green clay-filled root traces are vertically oriented and branch downwards; maroon-brown clayey siltstone skeletans occur between some joint plane surfaces; abrupt wavy contact to

-46.40 m; C; very fine-grained sandstone; dark grey-green with brown tint, weathering light grey-pink; very weakly calcareous; common faint, fine to medium, maroon sandy siltstone mottles vary in shape, and have both diffuse and sharp contacts; maroon red-brown clayey siltstone skeletans occur between some joint planes; massive and apedal, but sparse discontinuous red-brown illuviation argillans (<5mm long) outline irregular areas; abrupt irregular contact to

-46.54 m; C; very fine-grained sandstone; green-grey, weathering light grey with green tint; non-calcareous; few to common distinct, medium, light and dark maroon-brown siltstone mottles vary in shape; maroon red-brown clayey siltstone skeletans occur between some joint plane surfaces; dispersed white powdery carbonate nodules occur; abrupt very intermottled irregular to broken contact to

-47.01 m; C; fine-grained sandstone grading upwards to very fine-grained sandstone; grey maroon-brown grading upwards to maroon-brown, weathering maroon; non-calcareous; common distinct, medium, dark grey-brown and dark maroon-brown very fine-grained sandstone mottles vary in shape; subangular blocky peds show moderately-developed maroon red-brown illuviation argillans; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-47.56 m; Bw; siltstone; dark maroon-brown, weathering maroon-pink with orange tint; non-calcareous; red-brown clayey siltstone skeletans occur between some joint plane surfaces; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-48.18 m; Bw; siltstone; dark grey-brown with green tint, weathering cream grey-green; non-calcareous; few faint, medium light green sandy siltstone mottles occur at the upper contact; red-brown clayey siltstone skeletans occur between some joint plane surfaces; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-48.83 m; Bw; silty claystone; dark maroon-brown, weathering dark maroon-pink; non-calcareous; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-49.13 m; Crk; very fine-grained and fine-grained sandstone in different layers; very dark grey-green and maroon, and dark grey with green tint in different layers, weathering grey-green with brown tint; strongly calcareous; few faint, medium, very dark green-grey clay-filled root traces are vertically oriented; relict laminations are faint with thin continuous maroon and grey laminations and discontinuous lens-shaped green-grey laminations; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-49.28 m; Cr; fine-grained sandstone; light and dark grey-green in different layers, weathering light green-grey; non-calcareous; faint relict laminations are planar, continuous and parallel; red-brown clayey siltstone skeletans occur between some joint planes; dispersed white powdery carbonate nodules occur; abrupt smooth contact to

-49.67 m; E; siltstone; dark green grey-brown, weathering grey-green with brown tint; non-calcareous; red-brown clayey siltstone skeletans occur between some joint planes; abrupt wavy contact to

-49.80 m; Bw; siltstone; dark maroon-brown, weathering maroon; non-calcareous; black mangans occur on some ped surfaces; red-brown clayey siltstone skeletans occur between some joint planes; poorly developed platy peds show sparse discontinuous green illuviation argillans (<10 mm long), which are horizontally oriented; wavy contact to

-51.32 m; Bt; very fine-grained sandstone; dark green-grey, weathering grey-white with patches of maroon; non-calcareous; common distinct, coarse dark maroon-brown mottles vary in shape; numerous vertical to subvertical, dark maroon red-brown clay sheets/dykes (skeletans?), <5 mm in width, cut through the horizon and contain common distinct, fine green clay-filled vertical root traces; angular blocky peds show dark maroon-brown illuviation argillans; dispersed white powdery carbonate nodules occur; abrupt wavy contact to

-51.92 m; C; very fine-grained sandstone; dark green-grey with blue tint, weathering grey-white; non-calcareous; few to common distinct, medium to coarse, maroon orange-brown mottles vary in shape; black mangans occur on some ped surfaces; maroon red-brown clayey siltstone skeletans occur between some joint planes; subangular blocky peds show poorly developed purple-maroon illuviation argillans; abrupt very irregular contact to

-52.21 m; Bt; siltstone; dark maroon-brown, weathering maroon; non-calcareous; few distinct, fine grey-green siltstone mottles vary in shape; red sesquans and black mangans occur on some ped surfaces; subangular blocky peds show red-brown shiny illuviation and stress argillans; dispersed white powdery carbonate nodules occur; abrupt wavy contact (marked by a thin green discontinuous friable clay layer) to

-53.12 m; Bt; sandy siltstone; dark blue grey-green, weathering cream blue-grey with purple-maroon patches; non-calcareous; many distinct, medium to coarse, maroon-brown mottles vary in shape; rust orange and red sesquans occur on some ped surfaces; pink-maroon clayey siltstone skeletans occur between some joint planes; subangular blocky peds show dark blue-green-grey and maroon-brown shiny illuviation argillans; abrupt irregular contact to

-53.51 m; Bt; siltstone; dark maroon-brown, weathering light maroon-pink with purple tint; non-calcareous; few green clay papules are irregular in shape; common distinct, medium maroon red-brown clay-filled root traces are vertically oriented; common distinct, and fine green clay-filled root traces are vertically oriented and branch downwards; subangular blocky peds show maroon red-brown illuviation and stress argillans; abrupt irregular contact to

-53.68 m; B; siltstone; green blue-grey, weathering white green-grey; non-calcareous; common distinct, medium to coarse, maroon siltstone metagranotubules (after branching root systems and burrows) are randomly oriented; light maroon-brown clayey siltstone skeletans occur between some joint planes; granular peds lack argillans; clear wavy contact to

-53.86 m; Bt; silty claystone; green-grey, weathering grey-white with green-blue tint; non-calcareous; many distinct, medium to coarse, maroon-purple mottles vary in shape; coarse granular peds show dark grey-green and maroon-purple shiny illuviation and stress argillans; clear irregular contact to

-55.07 m; Btk; silty claystone; maroon-purple, weathering rust orange and maroon-purple in patches; non-calcareous; many distinct, fine rust orange clay-filled mottles vary in shape and distribution; many faint to distinct, fine to medium, dark green and red-brown clay-filled root traces are randomly oriented and branch outwards, forming a muddled network; many distinct, fine thin white calcareous para-isotubules (after roots) with pale green diffuse haloes, are vertically to subvertically oriented and branch downwards; pink-red clayey siltstone skeletans occur on some joint planes; granular peds show maroon red-purple and dark green-grey shiny illuviation and stress argillans, and poorly developed rust orange illuviation argillans; dispersed white powdery carbonate nodules occur; clear irregular contact to

-55.74 m; Bt; claystone; dark blue green-grey, weathering white blue-grey; non-calcareous; common distinct, medium, maroon-brown clay-filled root traces are vertically oriented and branch downwards; rust orange sesquans occur on some ped surfaces; granular peds show dark blue-green-grey illuviation and stress argillans; abrupt smooth contact to

-59.11 m; SANDSTONE.

APPENDIX 3

DETAILED LOGS OF THE MUDROCK SEQUENCE PALAEOSOLS

APPENDIX 3: KEY TO LOGS OF PALAEOSOL MUDROCK SEQUENCES

LITHOLOGIES

- claystone
- silty claystone
- clayey siltstone
- siltstone
- sandy siltstone
- sandstone
- K (calcareous hardpan)

COLOURS

- maroon-brown
- grey-green, green, white-green-grey
- light shades of grey-brown, grey, and olive grey brown
- dark shades of grey-brown, grey, and olive grey brown
- shades of yellow, olive and orange
- shades of kakhi grey and kakhi grey-brown
- maroon-purple-brown
- black grey
- yellow-brown to grey-orange
- green-grey-brown
- maroon-grey-brown
- blue-grey
- grey-green-blue
- olive yellow green

FOSSILS AND MOTTLES

- root traces
- burrows
- pedotubules
- bones
- organic flakes
- colour mottles

GRAIN SIZES

c - claystone
s - siltstone
ss - sandstone

SOIL STRUCTURE

- blocky peds
- prismatic peds
- blocky to prismatic peds
- blocky to granular peds
- granular peds
- clastic dykes

CONTACTS

- smooth
- wavy
- irregular

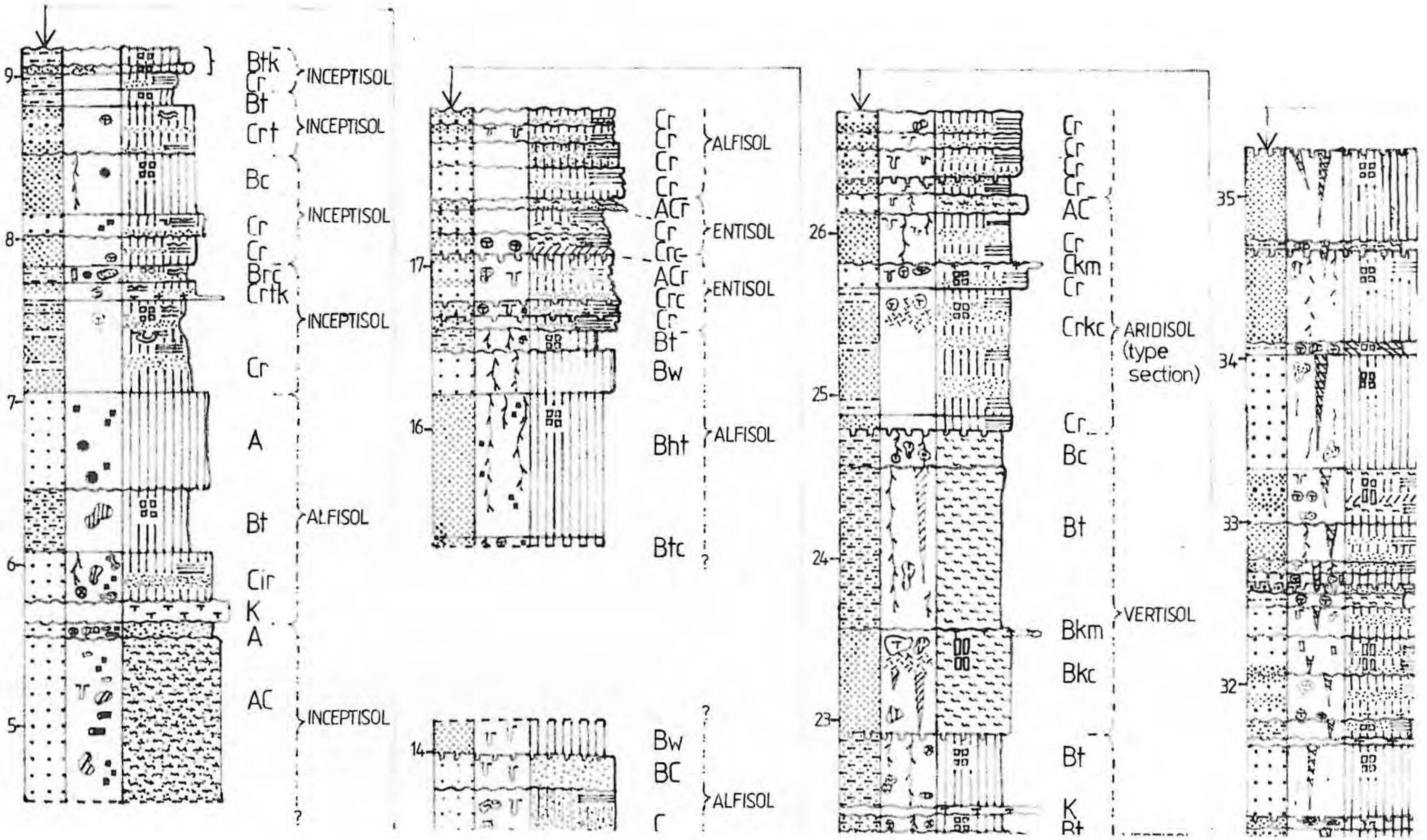
GLAEBULES AND CRYSTALS

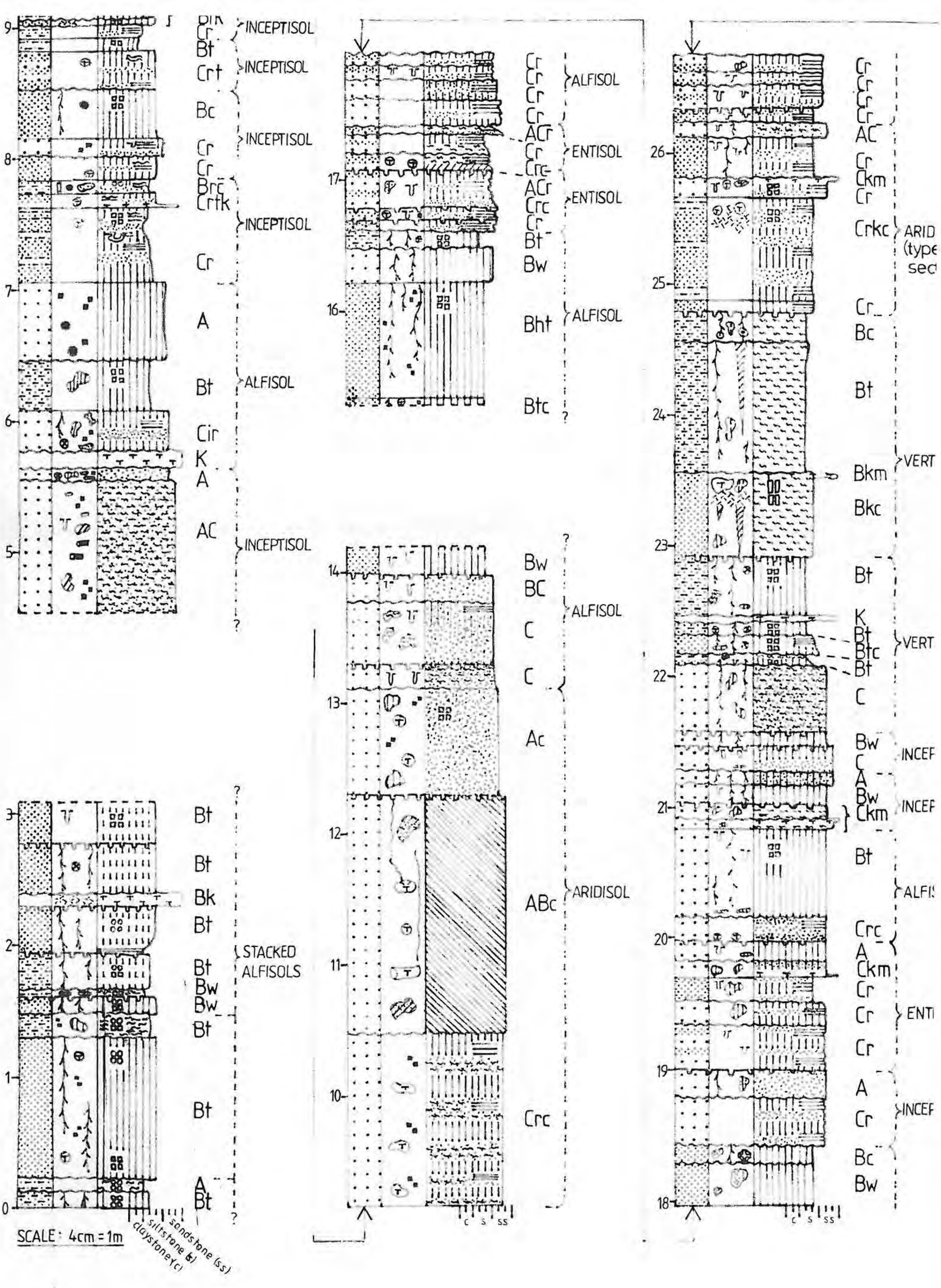
- lithorelicts
- charcoal
- papules
- ferric nodules
- ferric concretions
- calcareous nodules
- coalesced nodules
- cylindrical nodules
- desert roses
- calcareous veinlets

SEDIMENTARY STRUCTURES

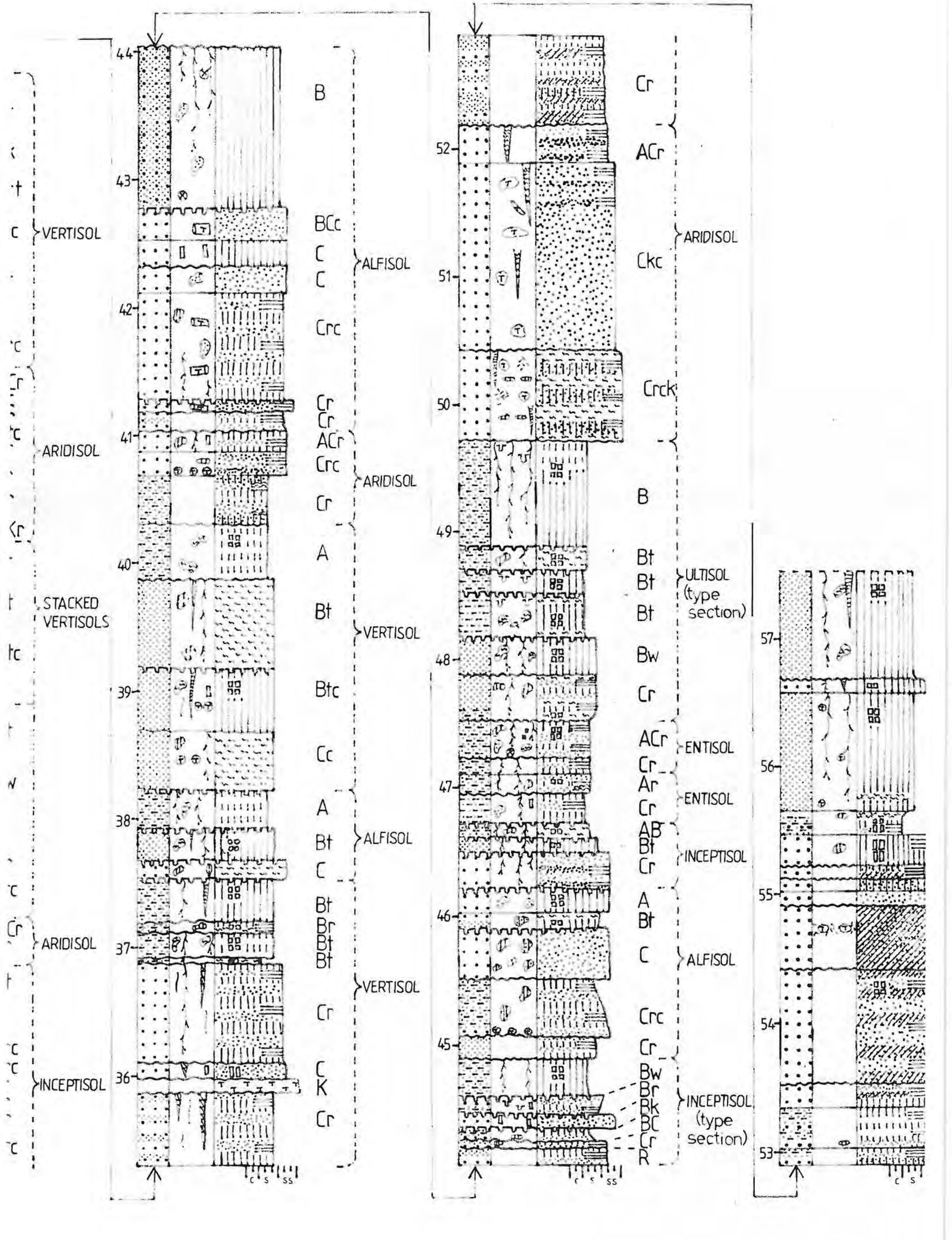
- horizontal lamination
- wavy/rippled lamination
- planar cross-bedding
- slumped/convoluted bedding
- veins
- dewatering structures

APPENDIX 3.1: DETAILED LOG OF THE LOWER MUDROCK SEQUENCE PALAEOSOLS



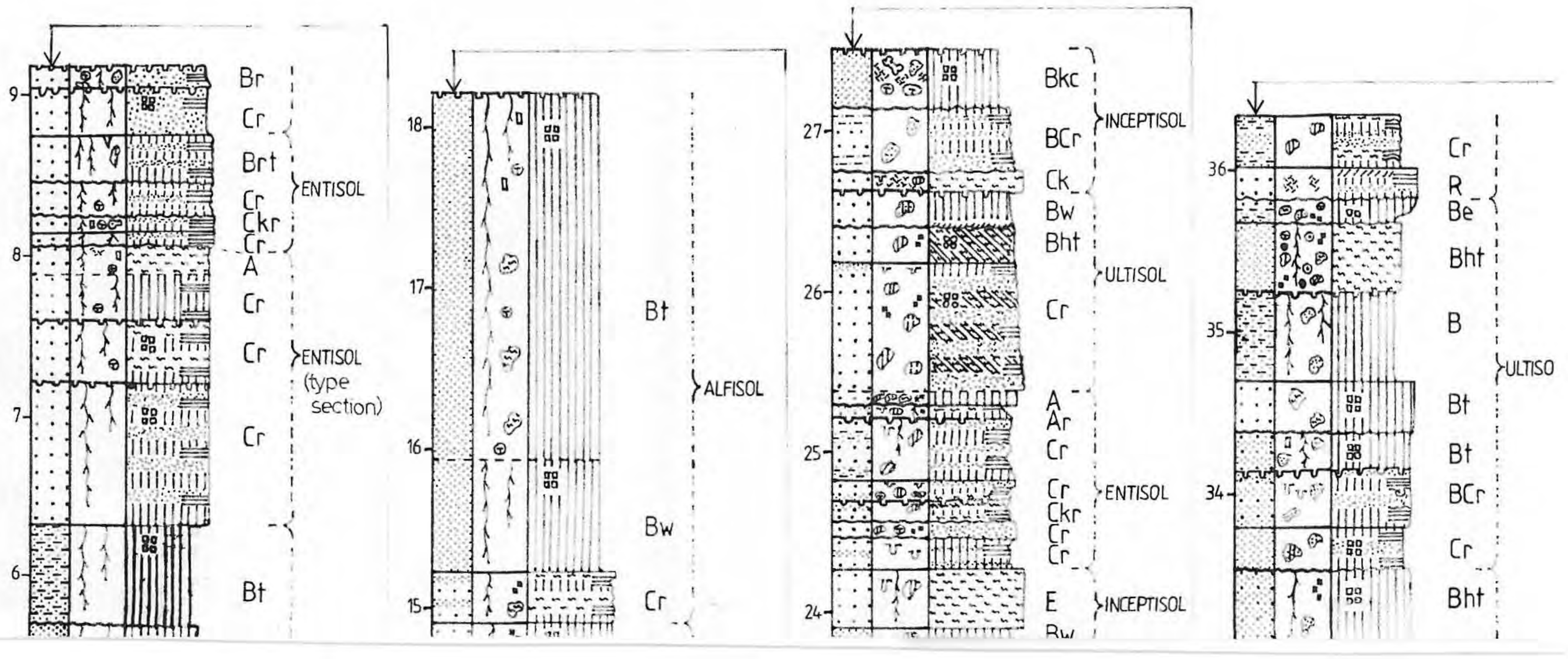


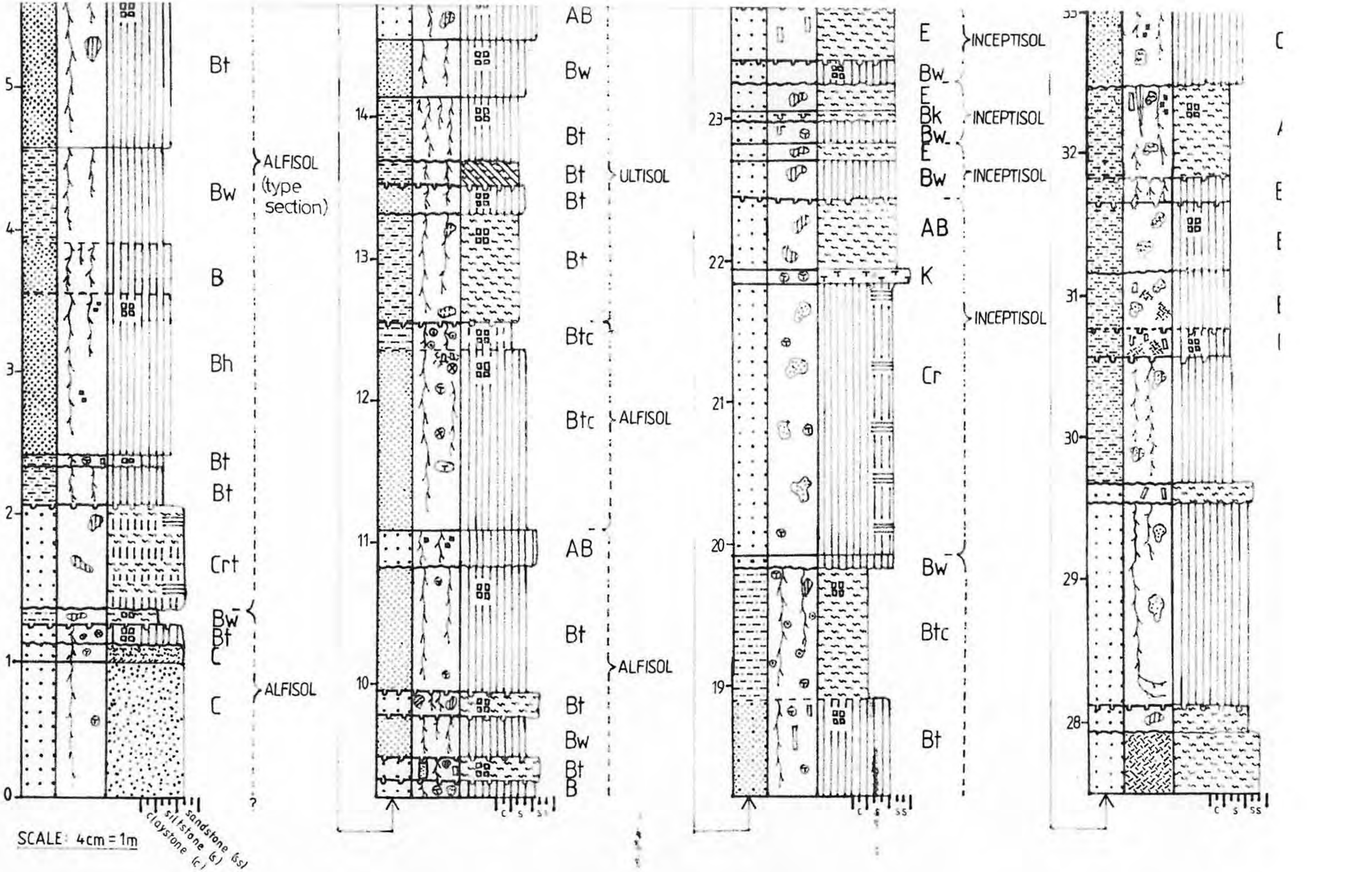
INCEPTISOL
INCEPTISOL
INCEPTISOL
INCEPTISOL
ALFISOL
INCEPTISOL
STACKED ALFISOLS
SCALE: 4cm = 1m
claystone (c)
siltstone (s)
sandstone (ss)
ALFISOL
ENTISOL
ENTISOL
ALFISOL
ALFISOL
ARIDISOL
c s ss
ARID (type sec
VERT
VERT
INCEF
INCEF
ALFI
ENTI
INCEF
c s ss



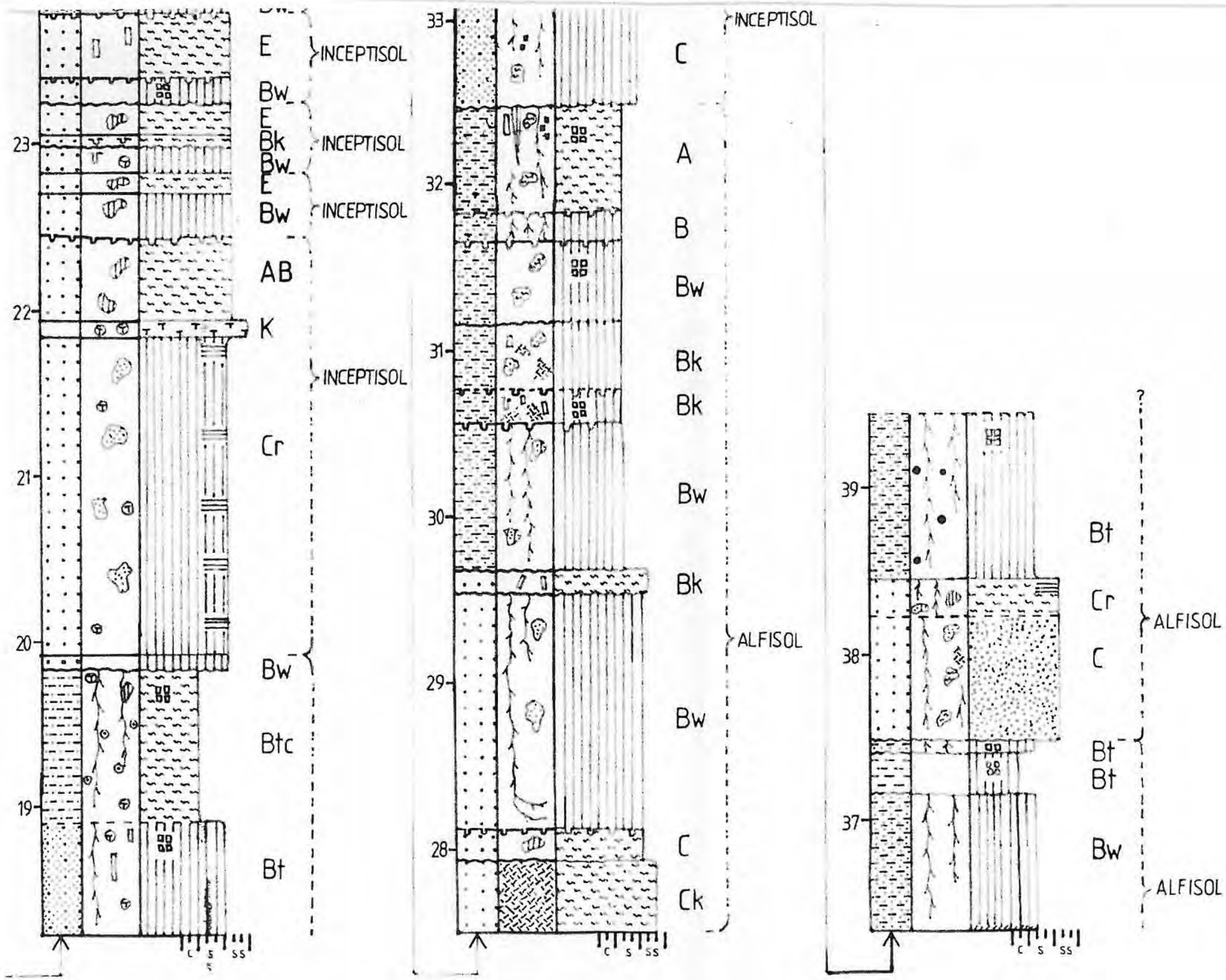
VERTISOL
ARIDISOL
STACKED VERTISOLS
ARIDISOL
INCEPTISOL
44
43
42
41
40
39
38
37
36
B
BCc
C
C
Crc
Cr
Cr
ACr
Crc
Cr
A
Bt
Btc
Cc
A
Bt
C
Bt
Br
Bt
Bt
Cr
C
K
Cr
ALFISOL
ARIDISOL
VERTISOL
ALFISOL
VERTISOL
c s ss
52
51
50
49
48
47
46
45
Cr
ACr
Ckc
Crck
B
Bt
Bt
Bt
Bw
Cr
ACr
Cr
Ar
Cr
AB
Bt
Cr
A
Bt
C
Crc
Cr
Bw
Br
Bk
BC
Cr
R
ARIDISOL
ULTISOL (type section)
ENTISOL
ENTISOL
INCEPTISOL
ALFISOL
INCEPTISOL (type section)
c s ss
57
56
55
54
53
c s

APPENDIX 3.2: DETAILED LOG OF THE MIDDLE MUDROCK SEQUENCE PALAEOSOLS





ALFISOL (type section)
ALFISOL
ULTISOL
ALFISOL
ALFISOL
INCEPTISOL
INCEPTISOL
INCEPTISOL
INCEPTISOL
sandstone (ss)
siltstone (s)
claystone (c)
SCALE: 4cm = 1m


E
INCEPTISOL
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E
23
Bk
INCEPTISOL
Bw
E
Bw
INCEPTISOL
AB
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K
INCEPTISOL
Cr
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20
Bw
Btc
19
Bt
c s ss
33
INCEPTISOL
C
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32
B
Bw
31
Bk
Bk
Bw
30
Bk
ALFISOL
29
Bw
C
28
Ck
c s ss
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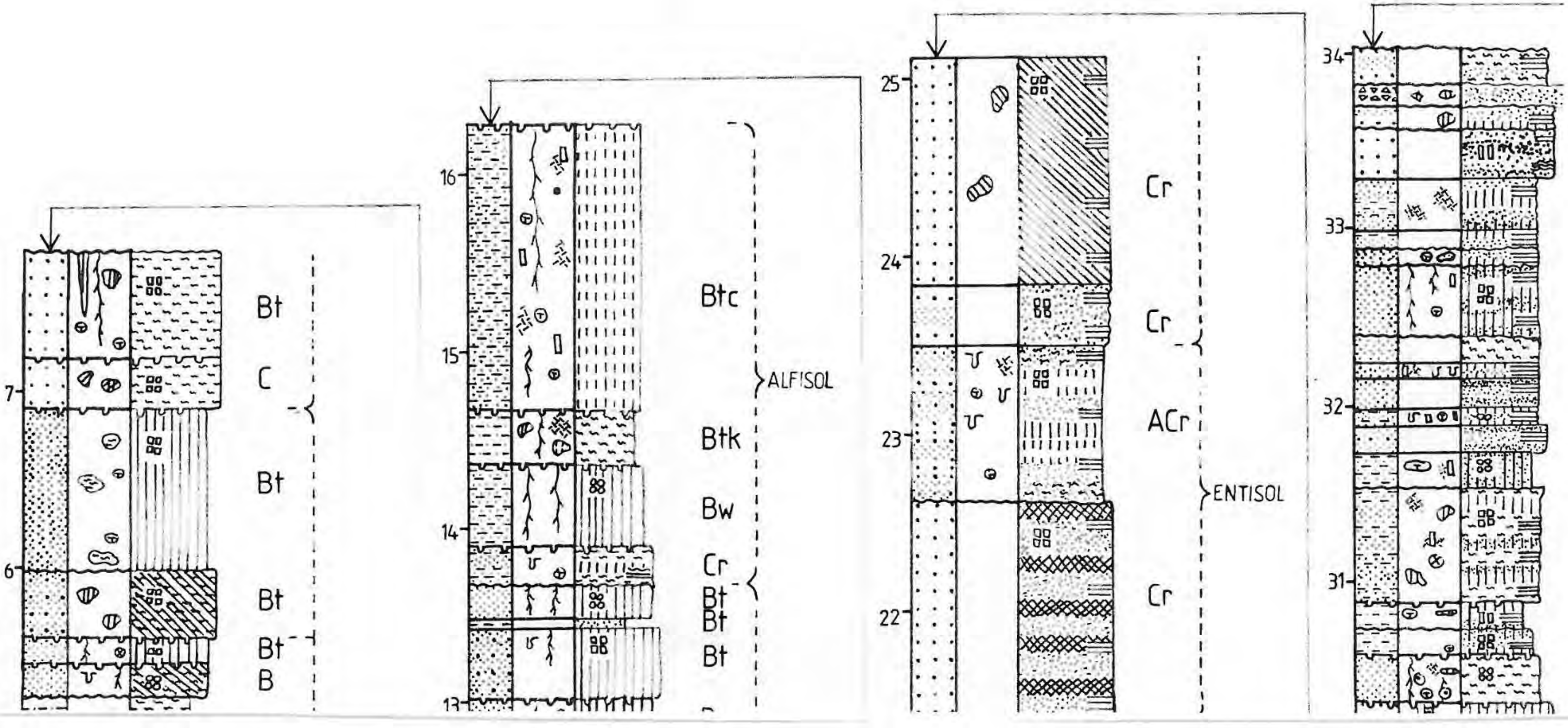
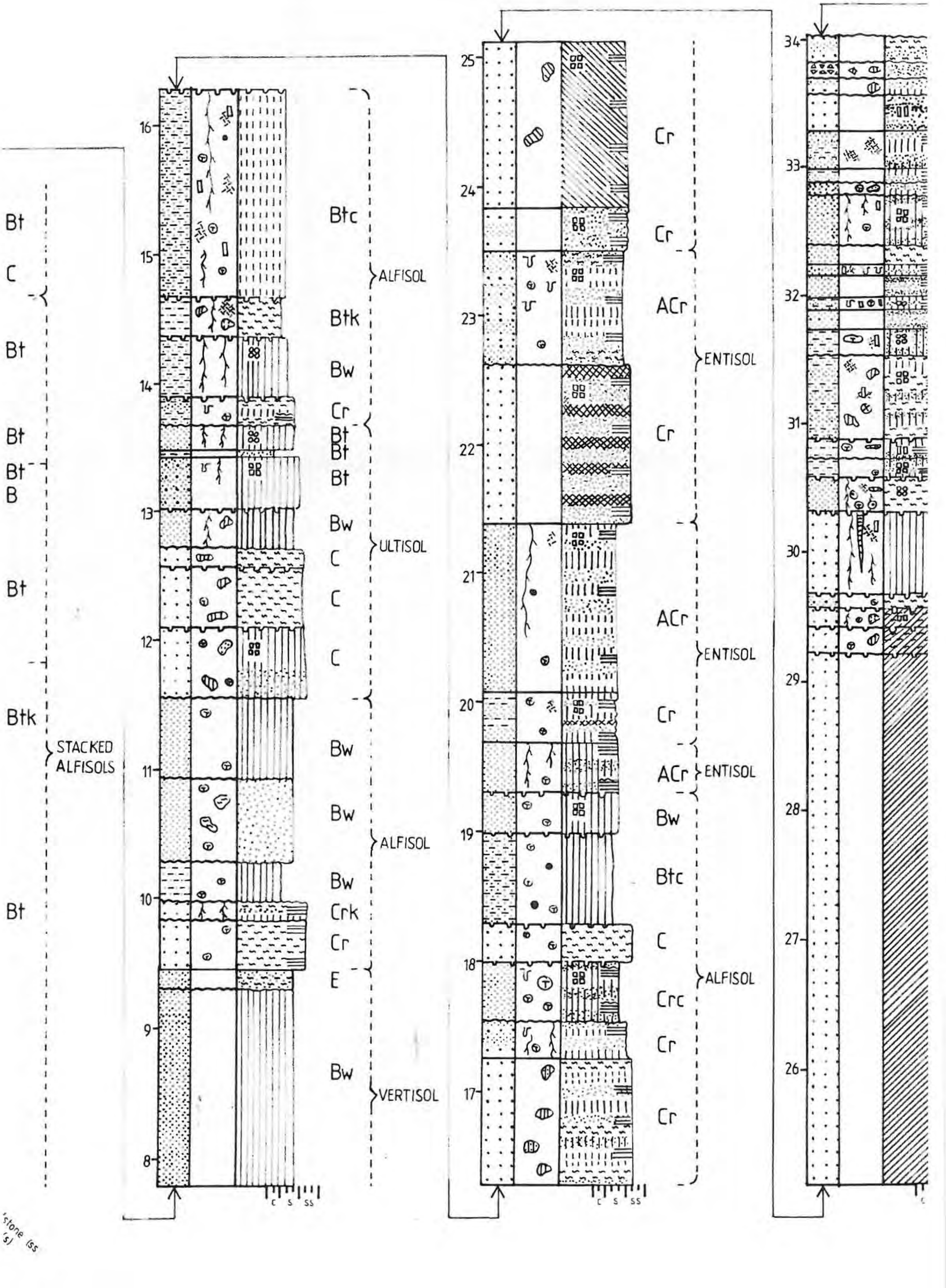
Cr
ALFISOL
38
C
Bt
Bt
37
Bw
ALFISOL
c s ss

APPENDIX 3.3: DETAILED LOG OF THE UPPER MUDROCK SEQUENCE PALAEOSOLS





Bt
C
Bt
Bt
Bt
B
Bt
Btk
STACKED ALFISOLS
Bt
Btc
Btk
Bw
Cr
Bt
Bt
Bt
Bw
C
C
C
Bw
Bw
Bw
Crk
Cr
E
Bw
ALFISOL
ULTISOL
ALFISOL
VERTISOL
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ACr
Cr
ACr
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ACr
Bw
Btc
C
Crc
Cr
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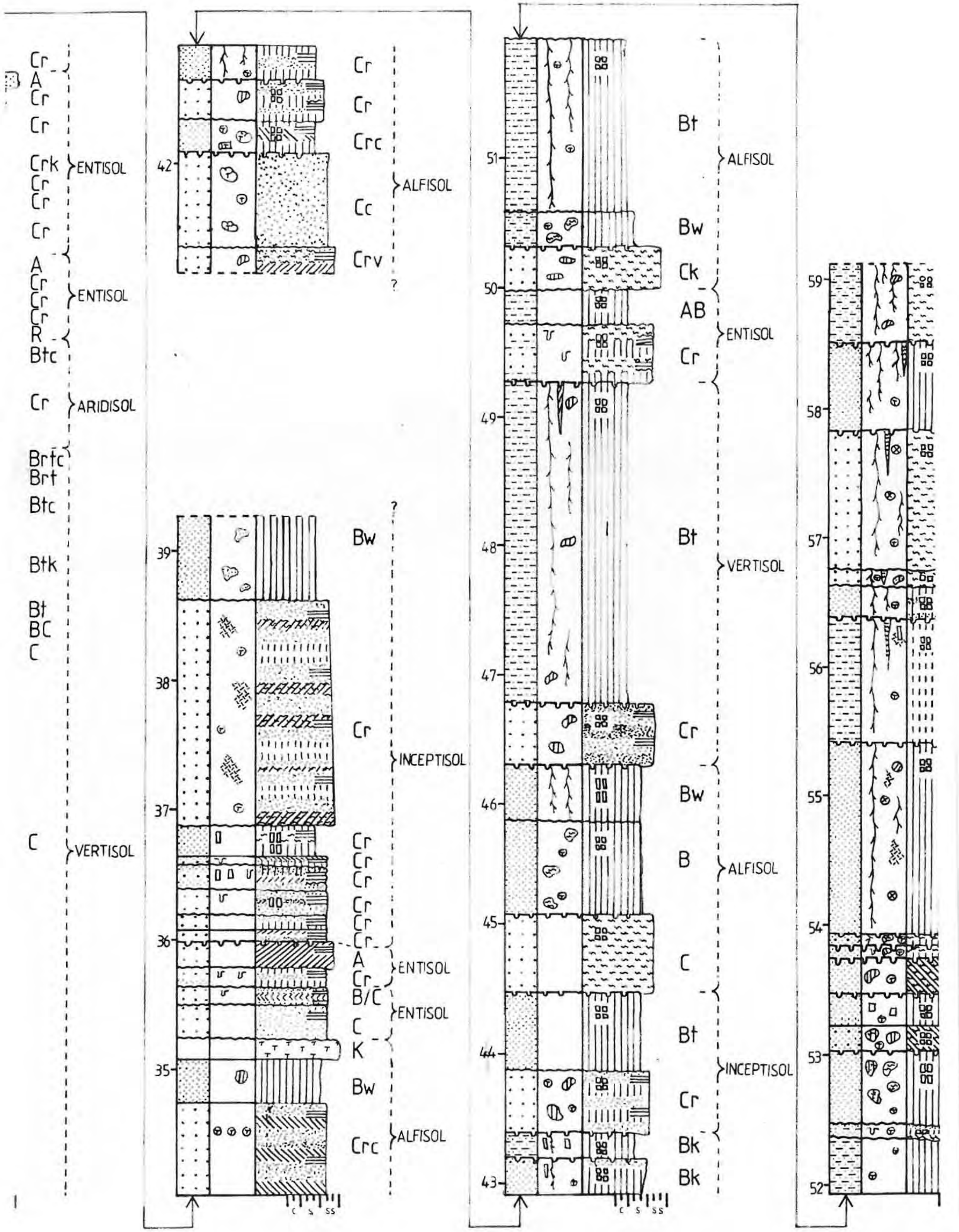
ENTISOL
ENTISOL
ENTISOL
ALFISOL
c s ss



Cr
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Cr
Cr
Crk
ENTISOL
Cr
Cr
Cr
A
Cr
Cr
Cr
ENTISOL
R
Btc
Cr
ARIDISOL
Brtc
Brt
Btc
Btk
Bt
BC
C
C
VERTISOL
42
Cr
Cr
Crc
Cc
ALFISOL
Crv
?
39
38
37
36
35
Bw
?
Cr
INCEPTISOL
Cr
Cr
Cr
Cr
Cr
Cr
A
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ENTISOL
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ENTISOL
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Bw
Crc
ALFISOL
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ALFISOL
Bw
Ck
AB
ENTISOL
Cr
Bt
VERTISOL
Cr
Bw
B
ALFISOL
C
Bt
INCEPTISOL
Cr
Bk
Bk
c s ss
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58
57
56
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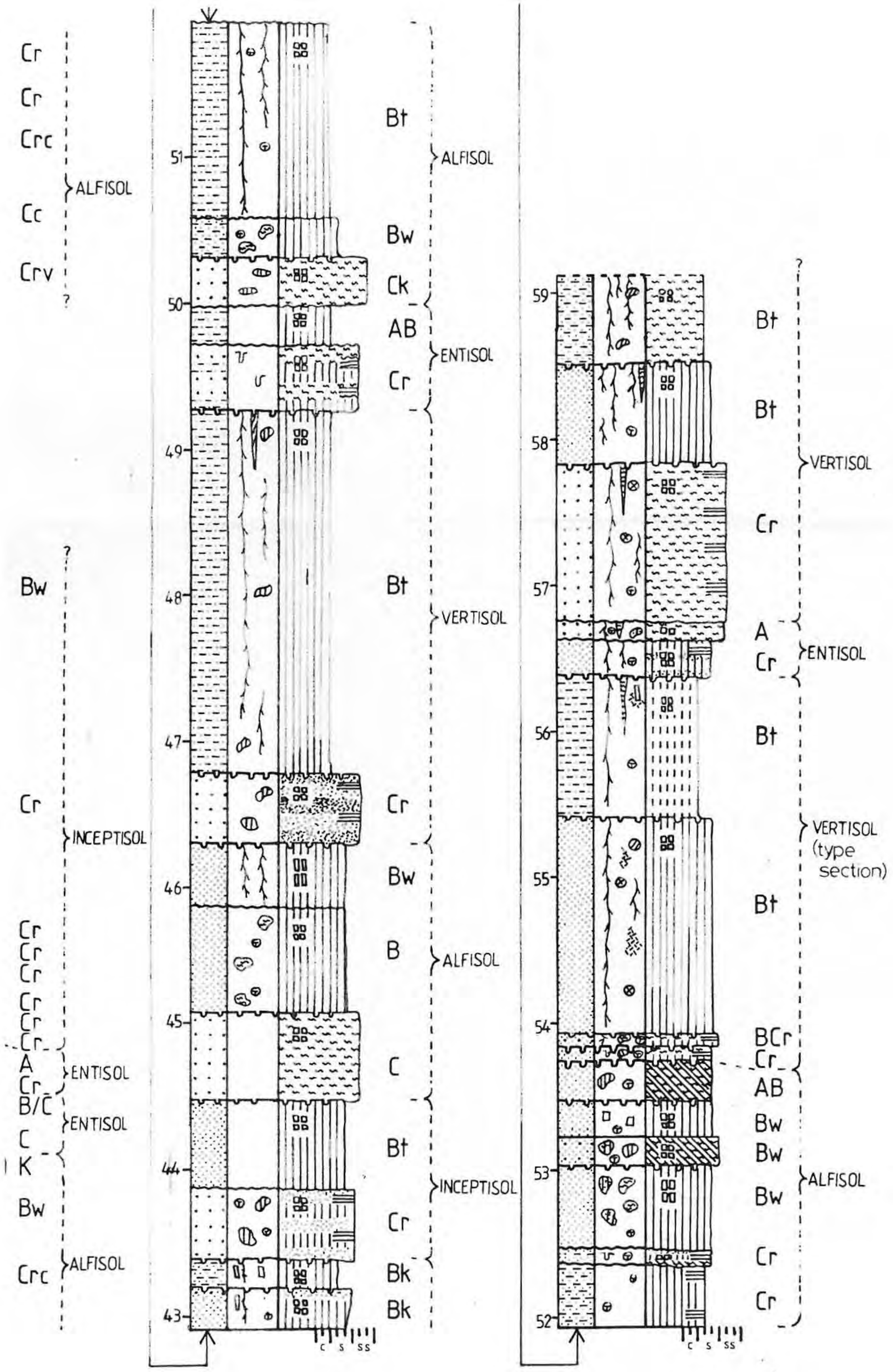
54
53
52


Cr
Cr
Crc
ALFISOL
Cc
Crv
?
Bw
?
Cr
INCEPTISOL
Cr
Cr
Cr
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Cr
B/C
ENTISOL
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Bw
Crc
ALFISOL
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ALFISOL
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Ck
AB
ENTISOL
Cr
Bt
VERTISOL
Cr
Bw
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ALFISOL
C
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INCEPTISOL
Cr
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Cr
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Cr
ENTISOL
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VERTISOL
(type
section)
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BCr
Cr
AB
Bw
Bw
Bw
ALFISOL
Cr
Cr
c s ss