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THE DEVELOPMENT OF UPPER CARBONIFEROUS (WESTPHALIAN A)PALAEOSOLS IN THE BIDEFORD FORMATION OF THE CULM BASIN (SOUTH-WEST ENGLAND)

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Thin rooted horizons, interpreted as palaeosols, are preserved in Late Carboniferous fining-upward sequences at the top of deltaic cycles 7, 8 and 9 of the Bideford Formation. Three root genera have been identified and their occurrences in different combinations and abundances enables differentiation of three palaeosol types. Each type is interpreted to represent an association within a plant community. The plant successions were controlled mostly allogenically, by episodical drowning (rise in the water table), and these plant associations probably inhabited a rather hydrologically and sedimentologically unstable floodplain environment, in the lower delta plain.

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INTRODUCTION

Folded Upper Carboniferous sediments of the Bideford Formation occur along the coast between Greencliff [SS 4065 2725] and Westward Ho! [SS 4175 2886], North Devon (Fig. 1). The paralic-deltaic nature of the formation was first described by Prentice (1959, 1960), who recorded a single thin coal bed, under which no real seat earth exists. The Bideford Formation, which is thought to represent the development of deltaic facies (Elliott, 1976) in the Carboniferous foreland Culm Basin (Thomas, 1988; Hartley and Warr, 1990), is underlain by turbiditic deep-basin sediments of the Crackington Formation (Namurian to Westphalian) and overlain by lacustrine rocks of the Bude Formation, which range from Westphalian A to C age (Higgs, 1991). The Bideford Formation comprises nine prograding coarsening-upward cycles that are interpreted to have accumulated in fluvially dominated elongate deltas (Elliott, 1976). A sedimentological analysis by de Raaf *et al.* (1965) divided the deltaic sediments into different facies types; logged profiles of the upper 6 cycles mentioned rootlets at the tops of cycles 4, 5, and 8. Paleobotanical workers recorded scattered plant fragments and rare appearances of either *Stigmaria sp.* or *Pinnularia sp.* in the Culm Basin, but without stating if the roots were found *in situ* or as drifted material (Hall, 1875; Arber, 1904, 1907; Rogers, 1910; Crookall, 1930). An account of the palaeobotanical and palaeontological record of the Bideford Formation was given by Rogers (1909).

This paper gives a new view on the Bideford Formation. The recently discovered palaeosols in the upper three cycles have been developed under allogenic controls suppressing the succession from pioneer- to peat-bearing vegetation. By analogy with recent plant ecology a demonstration of successive palaeosol development will contribute to the understanding of palaeosols in the Upper Carboniferous in south-west England.

STATIGRAPHY AND PALAEONTOLOGICAL RECORD

The upper Westphalian A age of the upper five cycles of the Bideford Formation can be clearly demonstrated from both goniatite (Edmonds *et al.,* 1979) and palaeobotanical data (Figure 2). The stratigraphical range (Chaloner and Collinson, 1975; Josten, 1991) of the plant fossils found in the Culm Basin and in cycles 5 to 9 (Hall, 1875; Arber, 1904, 1907; Rogers, 1909, 1910; Crookall, 1930), including new material collected by the author, indicate either a Westphalian A or Westphalian B age or both. Plants diagnostic of the Westphalian A are:

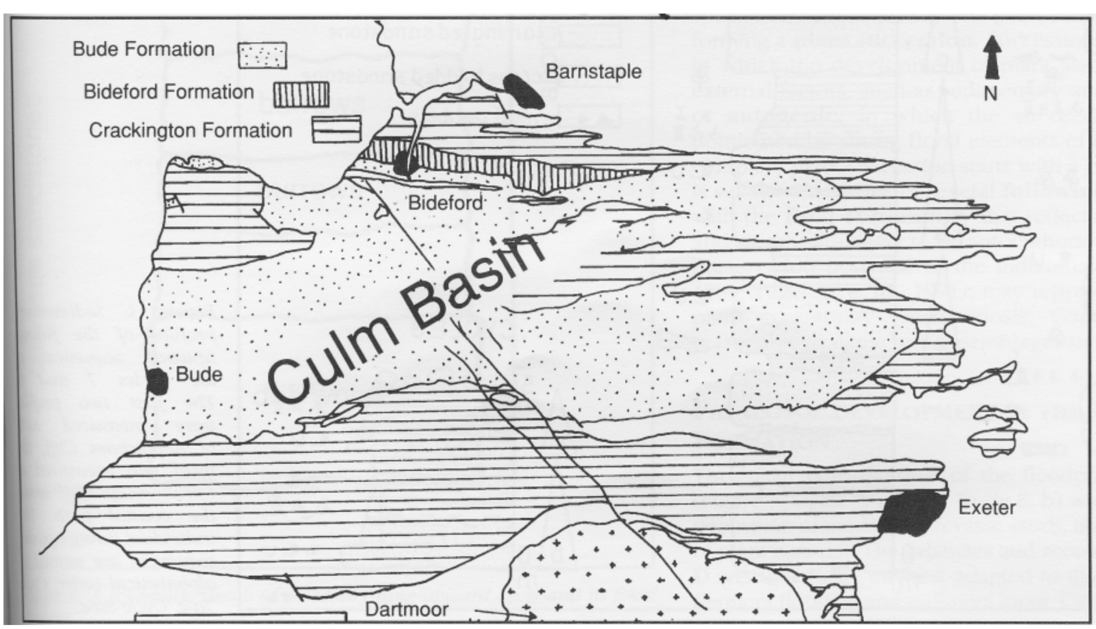

Figure 1: Distribution of Upper Carboniferous formations in the Culm Basin, modified after Thomas (1988).

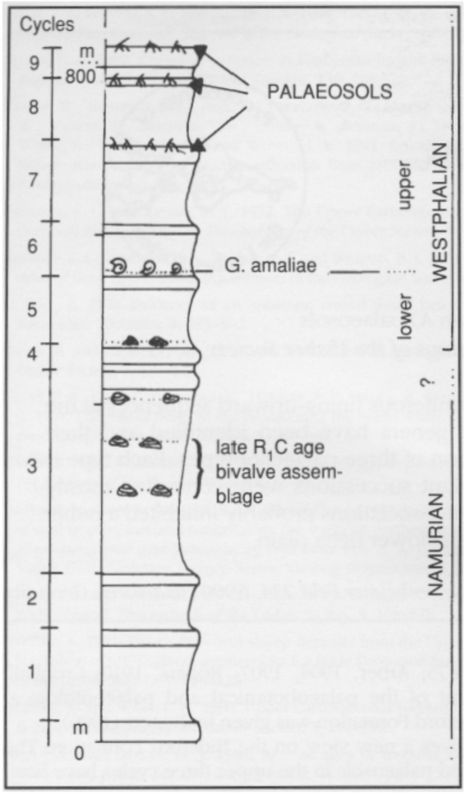

Figure 2: Stratigraphic column of the Bideford Formation after Edmonds et al. (1979), and the position of the palaeosol horizons. The marine Band with Gastrioceras amaliae indicates the boundary between Lower and Upper Westphalian. After Eagar, in Higgs (1990) the fresh-water bivalve assemblages in Cycle 3 are suggested to be middle to upper Namurian age.

Neuralethopteris schlehani and *Sphenopteris hoeninghausi.* Plant fossils representing both Westphalian A and B are: *Diplocalamites carinatus* Sternberg, *Stylocalamites undulatus, Annularia radiata, Asterophyllites equisetiformis, Alethopteris lonchitica, Mariopteris muricata* and *Asterophyllites charaeformis.* Plants indicative of the upper part of Westphalian A and of Westphalian B are: *Neuropteris obliqua, N. tenuifolia, Sigillaria scutellata.* Leggenwie (1964a, 1964b) recorded, from the Ruhr Coalfield in Germany (upper Bochumer-Schichten, upper Westphalian A), a rapid change in the flora which resulted in the development of typical Westphalian B flora. Cycles 5 to 9 of the Bideford Formation may represent the same interval; whilst retaining a Westphalian A character, the flora was evolving to a Westphalian B flora. In an investigation of the freshwater bivales, Xu Li (1990) has suggested that the Namurian/Westphalian boundary lies somewhere between cycles 3 and 6. This is supported by recent investigation by Eagar (in Higgs *et al.,* 1990).

DESCRIPTION OF THE PALAEOSOLS IN THE BIDEFORD FORMATION

Cycles 1, 3, 7, and 8 are capped by thin fining-upward sequences which are best exposed south-south-west of Abbotsham Cliff and north-north-east of Cornborough Cliff. There the tops of cycles 7 and 8 present five and three vertically stacked fining-upward cycles reaching thicknesses of 15 m and 10 m, respectively (Figure 3). Contemporaneous with the deposition of these sediments was the formation of palaeosols; four rooted horizons are present in floodplain sediments at the top of Cycle 7, three at the top of Cycle 8 (Figure 3; all except cycles 7:b and 8:a), probably two in Cycle 9 occurring only in boulders at Greencliff.

Three genera of roots are distinguishable: (1) the calamite

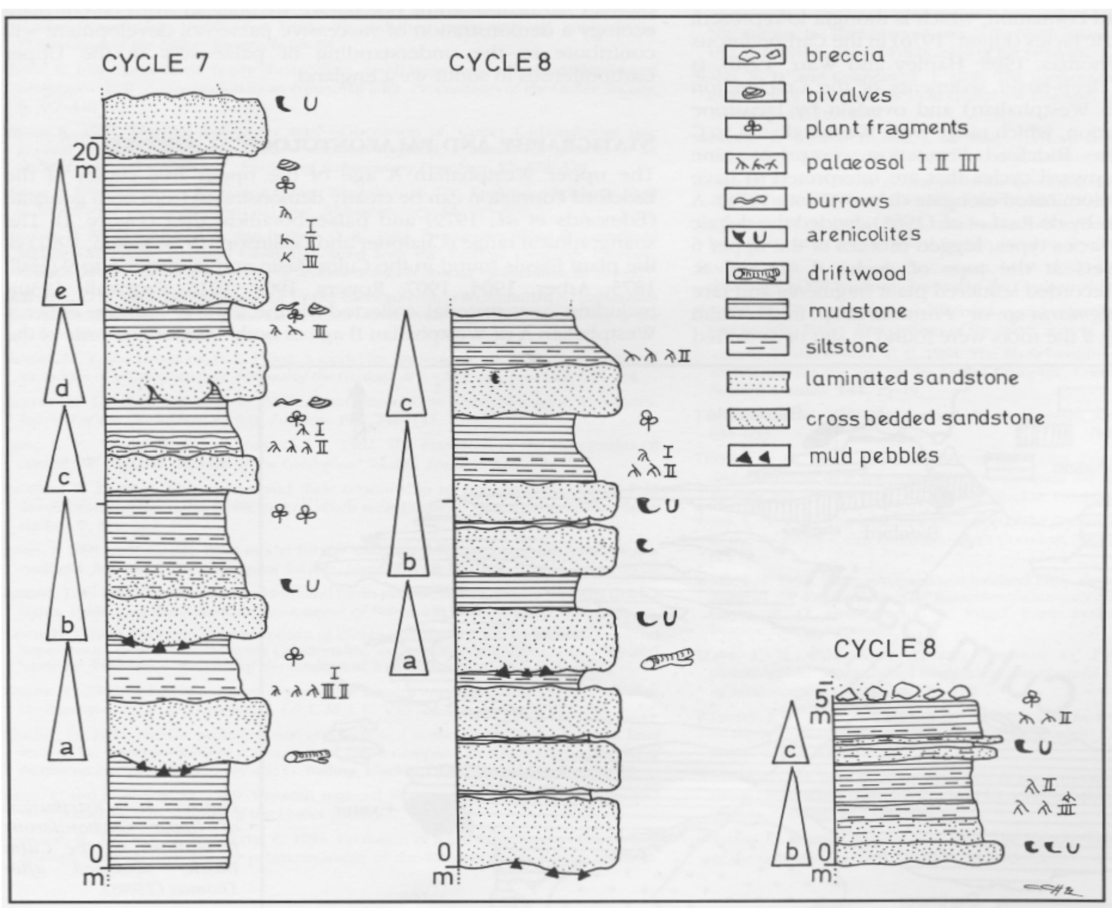

Figure 3: Sedimentary profiles of the fining-upward sequences of the cycles 7 and 8. The first two profiles were measured SSW of Abbotsham Cliff, the third was measured at Cornborough Cliff, along the coastal path. The individual fining-upward sequences are named in alphabetical order; Cycle 7a-e, Cycle 8a-c.

root *Myriophyllites gracilis; (2)* roots of calamites and ferns *Pinnularia capillacea* and *Pinnularia sp.;* (3) lycopod anchoring systems *Stigmaria ficoides* with appendages, but without stump casts. The size of *S. ficoides* specimens found in the Bideford Formation is small (ca. 8 cm width and ca. 150 cm length, appendages: 1 to 1.5 cm in width and ca. 13 cm in length) in comparison to those measured in the Ruhr Coalfield and in South Wales. *S. ficoides* is preserved as elliptically transformed casts, and its appendages as compressed coaly layers. The most common genus is *Pinnularia,* often appearing with *Myriophyllites* both are well preserved as thin coaly layers in fine-grained sediment. Different lithologies and the varied combinations and abundance of root species enables at least three palaeosol types to be distinguished:

Type I: Medium to dark grey mudstone/silty mudstone units of 8 to 12 cm thickness with a low rooting intensity. *Myriophyllites gracilis* and scattered small single rootlets of *2* to 4 mm in diameter and 9 cm length that resemble *Pinnularia sp.* are the most common root species. The sedimentary structures were not destroyed.

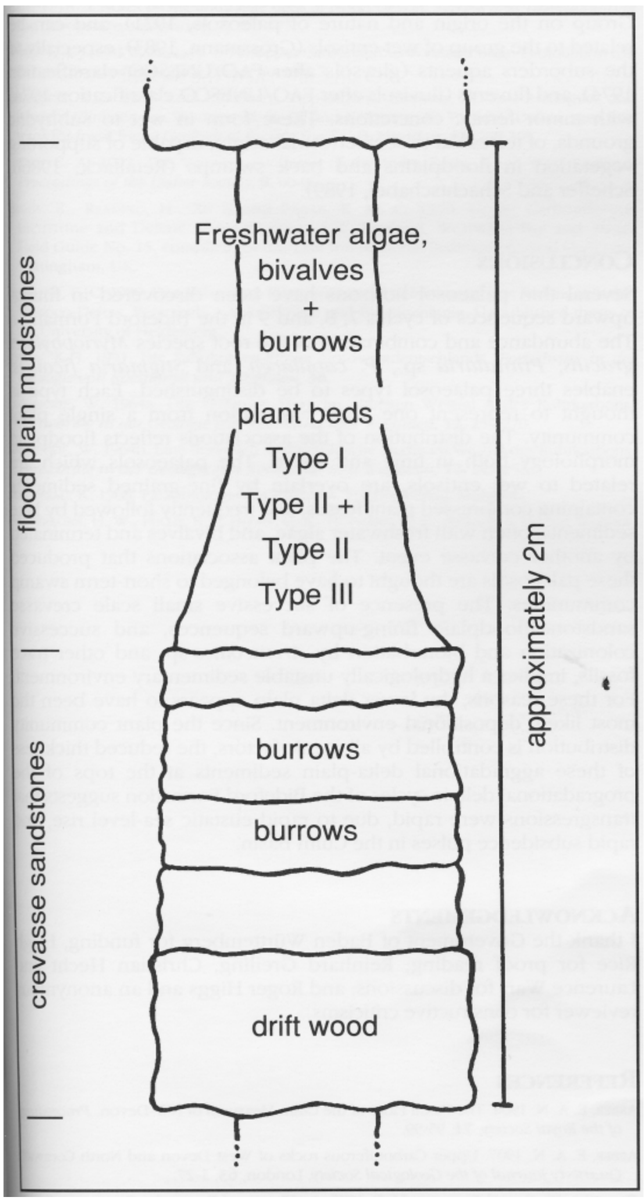

Figure 4: A schematic sketch of an ideal fining-upward cycle and its fossil content.

Type II: Medium grey, mostly muddy, siltstone units of 15 to 20 cm thickness with a moderate to locally low rooting intensity of *M. gracilis, P. capillacea* and scattered small *S. ficoides* with appendages. The sedimentary structures are bioturbated around the *Stigmaria* only. In contrast to most seat earths in the South Wales and the Ruhr coalfields, massive or disseminated sideritic or pyritic concretions precipitated around or near the roots and appendages of *Stigmaria sp.* are rare.

Type III: On the top of the crevasse sandstones small *S. ficoides,* with badly preserved appendages, are surrounded by light grey, sandy and muddy siltstones. Typical soil patterns, such as mottling structures and aggregate fabrics, are lacking in the palaeosols. In thin section they show a single grain fabric of weathered and unweathered feldspars, rounded and angular quartz grains and clay minerals.

Within a single fining-upward cycle compressed plant fragments, as listed above, are generally present above the palaeosols (Figure 3; all except Cycle 8: a). The most common plant fossils are axes and leaves of calamites, with rarer fern pinnules. In the sediments above the palaeosol of Cycle 8 an indeterminate seaweed was discovered (Figure 3; Cycle 8: c). Several impressions and casts of freshwater bivalves *(Carbonicola sp.)* were also found in dark grey to black mudstones and in fissile black shales overlying the plant beds of Cycle 7 (Figure 3; Cycle 7: c, d, e). A few centimetres above these mudstones are sandstones; those with cross-stratification commonly contain driftwood (Figure 3; Cycle 7: a, b and Cycle 8: a), whereas parallel-laminated sandstones show abundant bioturbation by *Arenicolites carbonarius* and other trace fossils (Figure 3; Cycle 7: b and Cycle 8: a, b) and are interpreted as crevasse sandstones. The ideal fining-upward depositional sequence is shown in Figure 4 and exposed sequences do not vary much in the succession, although locally any part of the sequence may be absent. Slight variations affect the combination of palaeosol types and plant horizons (Figure 3, Cycles 7: c and 8: a); all other horizons are fixed within the fining-upward cycle.

COLONISATION BY PLANTS

In the following text terminology from Recent plant ecology is used (Strasburger, 1983, Wilmanns, 1985). The development of palaeosols in floodplains is controlled by both extrinsic processes (for example, tectonic movements and sea-level and climate changes), and intrinsic factors (for example, variations in the sedimentary environment) and plant **colonisation** velocity (Retallack, 1986a). The development of a vegetation cover also needs time to produce a high number of individual specimens to form an ecologically balanced plant community. A **plant community** is formed from one or more **plant associations.** Species of a plant community react to changes in the regional environment and this is expressed by the appearance of other species and consequently one plant community alters into another, forming a **plant succession.** Successions can be either **allogenic,** in which the development of plant associations is controlled by external factors, such as sedimentary and hydrological processes; or **autogenic,** in which the succeeding plant association is dominated by strong floral elements of the former plant cover. A complete plant succession starts with a **pioneer community** that is substituted by one or several **following communities** and ends with the **final community** that reflects a living optimum. Roots and stumps are likely to be autochthonous, and depending on the preservation potential of the individual plant tissues (Hofmann, 1989; Tegelaar *et al.,* 1991), may represent the entire or a partial plant community (rhizocenosis; Gastaldo, 1986). It is thus reasonable to name root assemblages here as **plant associations.**

PALAEOSOL DEVELOPMENT IN THE BIDEFORD FORMATION

The initial **colonisation** of the floodplains in the Bideford area (Figure 3, Cycle 7: c and f, Cycle 8: b) was controlled by the rate of deposition of muds and crevasse sands, the water input, and the pool of plant material. The calamites and accessory ferns (palaeosol **Type I**) were probably the best adapted to this unstable habitat, with its frequent flooding and sediment input. Calamite roots show analogies to modern rhizomes that are able to grow new shoots from nodes and buried axes after rapid sediment accumulation (Mägdefrau, 1968, Fig. 146). Inevitably, pioneer communities growing on moving substrates are restricted in species. The **Type I** palaeosol may also represent a laterally restricted, long-residence calamite plant association which is interpreted as lowland vegetation development on limnic-brackish subhydric soils. Such an inherited colonisation stage is typical of a strongly allogen-influenced plant succession (Wilmanns, 1985). The development of **Type II** palaeosols was also controlled by allogenic factors, but the more stable environment led to a more diverse plant association, with the appearance of the first small arborescent lycopsids, such as *Stigmaria ficoides,* ferns, and rare calamites. *S. ficoides* grew mostly in coarse-grained, and well-drained sediments; their small size may reflect either dwarfing by stressful living conditions, or that the time between the individual crevasse splay events was too short to produce larger trees. The latter explanation is used to account for the thin paleosols found in the Ruhr Coalfield (Roeschmann, 1962). More stable conditions on better drained morphological highs (for example, former crevasse splays), and a lower sedimentation rate, produced an autogenic plant succession in which ecologically strong elements dominated the vegetation cover. During the transition from **Type II** to the **Type III** palaeosol environment *S. ficoides* appears to have become the dominant form.

The changes in the Bideford flora do not reflect plant successions, because no clear replacements of taxa occurred. Rather, they reflect gradual floral changes within one plant community from one plant association to another. The change from the growth of higher plants to freshwater algae which are thought to have lived in brackish or fresh water, as reported by Ramsbottom (1981), with an associated fauna can either be interpreted as an allogen-controlled succession, or the algae assemblage could have been a part of the entire plant community that covered the floodplain. More data are needed for the reconstruction of this ancient ecological environment.

All three palaeosol types could have developed both laterally to each other, depending on the floodplain morphology and the diversity of the plant community, and vertically, as the floodplain morphology varied with time; this is also demonstrated by Hazeldine (1989).

The most abundant palaeosol is Type II. Vertical transition from Type I to Type II in one root horizon is the most common and mirrors a gradual change in flora. Single appearances of Type I (Figure 3; Cycle 7: e and Cycle 8: b) are restricted to small areas with very fine-grained sediments, implying that the ground showed shallow relief, with minor depressions (ponds and channels) and mounds created by crevasse events. Observations of recent floodplains and back swamps of the Orinoco Delta (Pfefferkorn *et al.,* 1988; Hofmann, 1989) and Amazon floodplains (Furch and Junk, 1985) show relief structures of up to 200 cm scale and herbaceous swamps, dominated by a single species. It appears that the rising water table was buffered at the beginning of the fining-upward cycle by the topography of the floodplain. Variations of palaeosols and plant horizons occurred, but this ceased when lake conditions led to the establishment of freshwater organisms such as bivalves, worms and algae (Figure 3; Cycle 7: c, e).

The sedimentary environment of cycles 7 and 8 is interpreted to lie either in a lower delta plain interdistributary bay, or between it and the upper delta floodplain. Drowning associated with the fluctuating water table and the high sediment supply was not only influenced by the location and rainfall in the hinterland, but also by the compaction of underlying clayey sediments (Elliott, 1976). Probably the local situation was also overprinted by a combination of subsidence and rapid eustatic sea-level rises. Gayer *et al.* (1992) and Hecht (1992) have recognized a higher subsidence rate in the Bideford area of the Culm Basin after lower Westphalian A times. Rapid eustatic sea-level rises in north-western Europe during the Carboniferous were described by Ramsbottom (1979), who divided the Westphalian A into 5 mesothems, W1 to W5, (third order cycles: Vail *et al.,* 1977). Each of these comprises two to four rapid transgressive fluctuations (cyclothems or fourth order cycles: Vail et al. 1977) followed by relatively slow regressions. During regressive phases within the W3 and W4 mesothems, the Bideford Delta prograded basinwards, depositing thick sequences of prodelta mudstones, and coarser deltaic siltstones and sandstones, succeeded by fluvial sandstones during transgressive phases. These transgressions were too rapid, and the subsidence too fast to allow the aggradation of fining-upward sequences in cycles 1, 2, and 6, and restricted the aggradation in cycles 7 and 8. Even in fining-upward successions of cycles 7 and 8, the rising water level inhibited the growth of peat-forming plant community; only short term swamp communities, now represented by thin palaeosols, developed.

CLASSIFICATION

Thin rooted horizons in the Bideford Formation show mostly well-preserved sedimentary structures. The absence of diagnostic soil patterns, indicating a low intense bioturbation by flora and fauna, can be characteristic for weakly developed palaeosols. The thickness may reflect the length of the growth period and may be compared with the Westphalian in the Ruhr Coalfield (Germany), where Roeschmann (1962, 1971) noted that palaeosols without overlying coal seams are less rooted and thinner than seat earths. In the Bideford area the root horizons are classified as siliclastic palaeosols with more than 40% of inorganic material (Fulton, 1987; Working Group on the origin and nature of paleosols, 1971), and can be related to the group of wet entisols (Grossmann, 1983), especially to the suborders aquents (gleysols after FAO/UNESCO classification 1974), and fluvents (fluvisols after FAO/UNESCO classification 1974) with minor ferritic concretions. These form in wet to subhydric grounds, of terrestrial to semiterrestrial origin, capable of supporting vegetation in floodplains and back swamps (Retallack, 1986b; Scheffer and Schachtschabel, 1989).

CONCLUSIONS

Several thin palaeosol horizons have been discovered in fining-upward sequences of cycles 7, 8, and 9 in the Bideford Formation. The abundance and combination of the root species *Myriophyllites gracilis, Pinnularia sp., P. capillacea,* and *Stigmaria ficoides,* enables three palaeosol types to be distinguished. Each type is thought to represent one plant association from a single plant community. The distribution of the associations reflects floodplain morphology both in time and space. The palaeosols which are related to wet entisols, are overlain by fine-grained sediments containing compressed plant fossils, and frequently followed by lake sediments, often with freshwater algae, and bivalves and terminated by another crevasse event. The plant associations that produced these palaeosols are thought to have belonged to short-term swamp communities. The presence of successive small scale crevasse sandstone/floodplain fining-upward sequences, and successive colonization and bioturbation by *Arenicolites sp.* and other trace fossils, implies a hydrologically unstable sedimentary environment. For these reasons, the lower delta plain appears to have been the most likely depositional environment. Since the plant community distribution is controlled by allogenic factors, the reduced thickness of these aggradational delta-plain sediments at the tops of the progradational deltaic cycles of the Bideford Formation suggests that transgressions were rapid, due to rapid eustatic sea-level rise, and rapid subsidence pulses in the Culm Basin.

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