

RELATION OF PALEOVEGETATION TO GEOMETRY AND CYCLICITY OF SOME FLUVIAL CARBONACEOUS DEPOSITS¹

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ABSTRACT: The fluvial lower Eocene Willwood Formation (Bighorn Basin, Wyoming) is composed largely of red, oxidized, overbank sediment that has been extensively altered by soil formation. Within this matrix are two different types of dominantly fine grained, drab- to dark-colored deposits that contain abundant plant remains. The first are areally restricted, lenticular bodies that truncate underlying mudstone layers. These are interpreted as having formed in abandoned sections of channels. Deposits of the second type are tabular, as much as 10 km in lateral extent, and rest conformably on other floodplain sediment. These units show a cyclic arrangement of sedimentary subunits. Sedimentologic and paleobotanic evidence suggests that these tabular deposits accumulated under a sequence of vegetational types including, in succession, a floodplain marsh, a swamp forest, and a drier-ground floodplain forest. These interpretations stress the interaction of vegetational succession, soil characteristics, and fluvial morphology in creating the chemical conditions that led to the preservation of organic matter. The stratigraphic distribution of the two types of deposits within the Willwood Formation suggests that in the Bighorn Basin, tectonism exerted a greater influence on the geometry of carbonaceous deposits than did climate.

INTRODUCTION

In many of the intermontane basins of the Northern Rocky Mountains, drab lignite-bearing strata of the Paleocene Fort Union Formation are overlain by brightly red-banded lower Eocene rocks. In the Bighorn Basin of northern Wyoming (Fig. 1), these red-banded rocks are placed in the Willwood Formation (Van Houten 1944).

The Willwood Formation is a fluvial deposit about 780 m thick composed largely of mudstone (> 75%) and sandstone. The red and brightly variegated mudstone layers were formed by pedogenic alteration of floodplain sediment under oxidizing conditions (Neasham and Vondra 1972; Bown 1979, 1980; Bown and Kraus 1981). Sand bodies in the Willwood Formation were deposited by numerous small- to medium-size, meandering streams (Bown 1979; Kraus 1979, 1980). Some Willwood Formation rocks were not modified by oxidizing soil conditions, and these small amounts of drab shale and siltstone contain abundant plant-compression fossils (Wing 1980). These relatively carbonaceous units account for only 2% of exposed thickness for the total formation, but in the

bottom and top 100 m of the section may compose up to 20% of stratal thickness (Fig. 2).

In this paper I describe the occurrence of these isolated plant fossil-bearing units, and then consider their origin within the overall context of an oxidized floodplain environment. Field studies of the plant-bearing deposits showed that they comprise two distinct categories, each category recognized by a variety of features, and each with a different genesis.

METHODS

Badland topography in the study area provides exceptional exposure of the Willwood Formation. Many of the observations on the geometry of the plant-bearing deposits were made by inspection of outcrops, although cross-sections showing sedimentary subunits were constructed from observations made in trenches. Over 40 plant-bearing units were examined and placed in a composite stratigraphic section of the Willwood Formation (Fig. 2). Efforts were concentrated on five of them, designated WCS7, WCS15, LB, H, and Pn. Plant megafossils were collected at these sites, and the relative abundances of the taxa were counted. Pollen samples were also taken.

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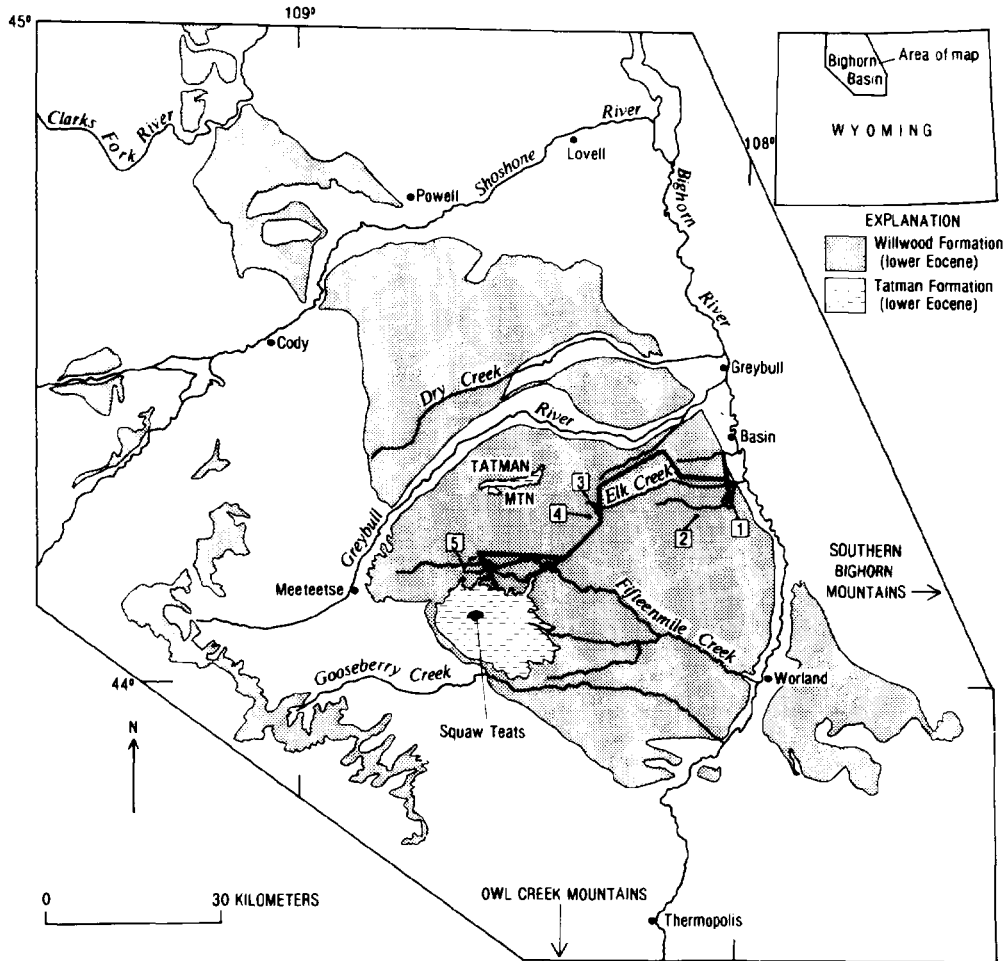


FIG. 1.—Map of the Bighorn Basin, Wyoming, showing outcrop area of the Willwood Formation and the locations of the five carbonaceous units mentioned in the text: 1, Type II unit WCS7; 2, Type I unit LB; 3, Type I unit H; 4, Type I unit Pn; 5, Type II unit WCS15. Stratigraphic section indicated by heavy black line.

OBSERVATIONS

Plant compressions are abundant in various lithologies of the Willwood Formation, including mudstone, siltstone, and, less commonly, sandstone. The finer-grained rocks may acquire a dark brown or black color because of disseminated organic matter. These carbonaceous clastic rocks (there is no coal in the Willwood Formation) are usually enclosed within a sequence of dark to drab beds that contain fewer plant fragments. I have called these sequences of drab, brown or black plant-bearing beds "carbonaceous units." The term *carbonaceous unit* is not meant to imply

that the contained beds possess a uniform amount of plant matter, or that the sediment is composed entirely of plant matter. However, this name does distinguish the beds from variegated sediment, and also from other drab (light gray or yellow) units in the Willwood Formation, without referring to sediment with a specific grain size or characteristic bedding (for example, carbonaceous shale). Because the Willwood Formation is composed overwhelmingly of reddish, oxidized sediment, carbonaceous units containing even a relatively small amount of macroscopic organic matter are easily recognized. Two types of

carbonaceous units are recognized on the basis of geometry, contact with underlying rocks, primary bedding features, and fossil plant content (Table 1).

Type I Carbonaceous Units

Type I carbonaceous units are lenticular in cross-section, less than 3 m thick and 300 m long, and weakly arcuate in plan view. The basal contact of Type I units is always sharp and erosional, and in many cases truncates underlying mudstone beds diagonally. Poorly consolidated, fine-grained sandstone bearing small plant fragments usually lies upon the erosional base. Above the sandstone are the dominant lithologies of the Type I unit: weakly fissile, brown to gray siltstone and mudstone, often displaying thin, unlaminated clay layers, and multiple small-scale, fining-upward sequences (Fig. 3). Leaves and other plant remains are found throughout the fine-grained lithologies, but are rare in the unlaminated clay layers. Dense mats of relatively complete leaves may occur at the tops of fining-upward sequences. Above these layers the rock lacks bedding and becomes coarser, blockier, and lighter in color. This light gray siltstone contains only small and widely dispersed plant fragments, and also tends to be heavily root-marked. Still higher, the sequence returns to the mottled, red mudstone typical of the Willwood Formation (Fig. 4).

The identifiable megafloora of Type I units is generally recovered from the bedded siltstone and mudstone. These assemblages include abundant (15–20% of specimens) floating aquatic plants, for example the fern *Salvinia preauriculata* (Fig. 5), and the duckweed *Spirodela magna*, whose close living relatives inhabit still water. Herbaceous marshland forms (for example, sedges, cat-tails, and ginger relatives) make up 5–20% of the megafloora, and leaf fragments of riparian trees like *Platanus* (sycamore) and *Salix* (willow) are often 20–60%. At locality H the megafloora shows an upward transition over a few decimeters from domination by floating aquatic plants to a monospecific assemblage of *Zingiberopsis isonervosa*, an herbaceous ginger relative (Fig. 4). There are no identifiable megafossils in the drab siltstone above the *Z. isonervosa* zone.

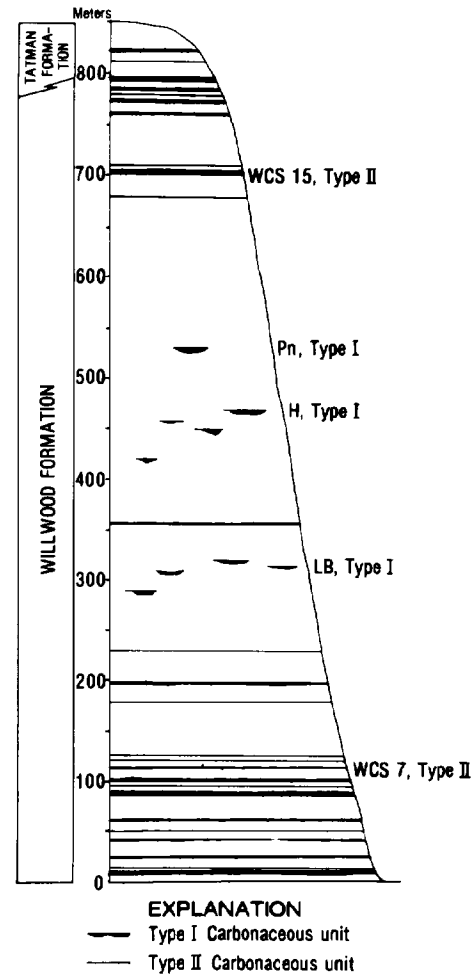


FIG. 2.—Composite section of the Willwood and Tatum Formations showing the stratigraphic distribution of carbonaceous units and the stratigraphic levels of Type I units LB, H, and Pn and Type II units WCS7 and WCS15.

The palynoflora of some of the Type I units contains large amounts of *Pistillipollenites mcgregorii*, which are derived from a member of the gentian family (Crepet and Daghljan 1981). Other common palynomorphs are those of *Pinus* and of the bald cypress family.

Type II Carbonaceous Units

Type II carbonaceous units account for the majority of carbonaceous rock seen in the field area. These units are 2–5 m thick, main-

TABLE 1.—Characteristic features of Type I and Type II carbonaceous units

	Type I	Type II
Geometry	Lenticular, <300 m lateral extent, weakly arcuate in plan view.	Tabular, up to 10 km lateral extent.
Contact with underlying rock	Downcut and erosional.	Conformable.
Lithology	Dominantly siltstone and mudstone, some fine sandstone near bottom.	Clayey mudstone, siltstone, interlaminated siltstone and sandstone, very fine to medium sandstone.
Primary bedding	Multiple fining-upward sequences, rarely with small-scale ripple crossbedding.	Ripple bedding, climbing ripple sequences, larger scale cross-beds in downcut sand bodies.
Flora	Dominantly floating aquatic and wetland forms with some leaves of woody plants.	Leaves, seeds, and stems of woody plants; roots and rhizomes of wetland plants.

tain a relatively uniform thickness over distances up to 10 km, are not channeled into underlying rock, and show great internal variation in lithology. In general they are coarser than Type I units. Ripple cross-stratification is present in interlaminated siltstone and sandstone. Channel sandstone bodies displaying larger-scale tabular and trough crossbedding commonly downcut into Type II units. The megafloora of Type II units is quite variable, but trees, shrubs, and ferns are dominant, whereas floating aquatic plants are always absent or extremely rare.

All of the Type II layers are composed of four distinct subunits: in ascending order, a clayey blue-gray mudstone, a carbonaceous shale, an interlaminated siltstone and fine sandstone, and a drab mudstone. Each Type II unit is separated from the next by a variably thick interval of variegated and drab mudstone and sandstone. The vertical sequence of these lithologies defines an aperiodic, one-sided cycle. The sequence of the subunits is consistent, but the thickness of each subunit varies both between layers and at different locations in the same layer (Fig. 6). Each of the subunits is discussed in the following sections.

Clayey Subunit.—This lowest subunit of Type II deposits rests conformably on reddish brown or gray noncarbonaceous mudstone and is composed of roughly equal amounts of clay and silt, with a small amount of sand, whose proportion varies laterally. The clayey

subunit is unconsolidated, plastic, wet, and has a steely blue-gray color. No internal stratification was observed. This subunit contains very abundant organic matter in the form of small (1 mm–1 cm diameter) roots (Fig. 7), but has no identifiable plant fossils. Irregular, vertical weathering joints are common, and they are usually lined by zones of yellow or red-orange iron oxyhydrate. Gypsum is also present in small granules. X-ray diffraction of clay from this subunit shows that both mixed illite/smectite and kaolinite are present, but that kaolin is probably more abundant than in red Willwood Formation mudstones described by Neasham and Vondra (1972).

Small-scale undulations present at the lower contact of the clayey subunit may result from irregularities in the topography of the ancient floodplain. However, a broad-scale northward thinning of this subunit is seen in WCS7 (Fig. 6A). Over approximately 1 km, the clayey subunit thins from 55 cm to 15 cm, and over the same transect the admixture of sand increases.

At its upper contact the clayey subunit grades into carbonaceous shale. In this 2- to 3-cm transition, the clay first becomes darker, then develops irregular fissility (Fig. 7). *Carbonaceous Shale Subunit.*—The carbonaceous shale subunit is light brown to black, fairly well consolidated, irregularly but often finely laminated, and usually slickensided. Current features are absent, and rootmarks



FIG. 3.—Multiple fining-upward sequences at Type I unit Pn. Scale in cm.

and root casts of varying sizes are common. The carbonaceous shale contains abundant organic matter, ranging in size from pollen grains to coalified logs 1–2 m long. Small plant fragments are distributed throughout the rock; the larger organic matter, mostly leaves and leaf fragments of ferns and of coniferous and dicotyledonous trees, occurs in dense mats on bedding planes. Crystalline and granular gypsum and a yellow iron oxyhydrate are abundant in this subunit, often coating or infiltrating the larger pieces of plant debris. Like the clayey subunit, the carbonaceous shale at WCS7 thins (65–0 cm) northward over a 2 km distance (Fig. 6A).

Interlaminated Siltstone and Sandstone Subunit.—The contact between this subunit and the carbonaceous shale is sharp, but conformable. The siltstone layers of the interlaminated lithology are 0.5–3.5 mm thick, and have a dark color imparted by a high density of plant fragments. Leaves and leaf fragments of dicotyledonous trees and shrubs are common on the silty bedding planes (Fig. 8). The interlayers of very fine to fine sand-

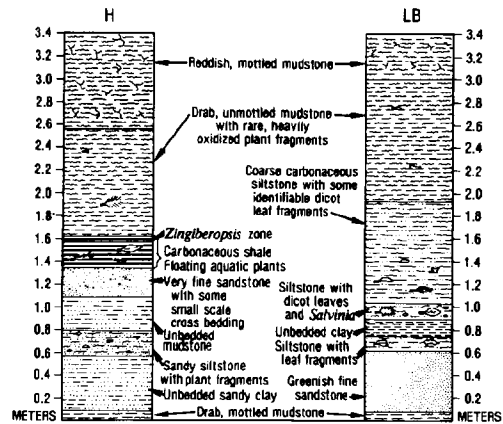


FIG. 4.—Stratigraphic sections of Type I units LB and H.

stone are 1–5 cm thick, light colored, and contain virtually no plant debris. Individual siltstone and sandstone laminae may be discontinuous and are commonly lenticular. In places the interlaminated subunit is ripple crosslaminated, and in a few places ripple-drift crosslamination is present, but generally the crosslamination is disrupted by rooting, bioturbation, and soft-sediment deformation. At a few localities, the rocks of the interlaminated subunit have a dip of 1° or 2° in relation to underlying beds. At WCS7, this subunit thickens to the north, the same direction in which the underlying clay and shale subunits thin.

At some locations the interlaminated subunit is replaced by sandstone or mudstone. The sand bodies are usually fine-grained,



FIG. 5.—Pinnules and roots of the floating fern *Salvinia*. Magnification $\times 2.3$.

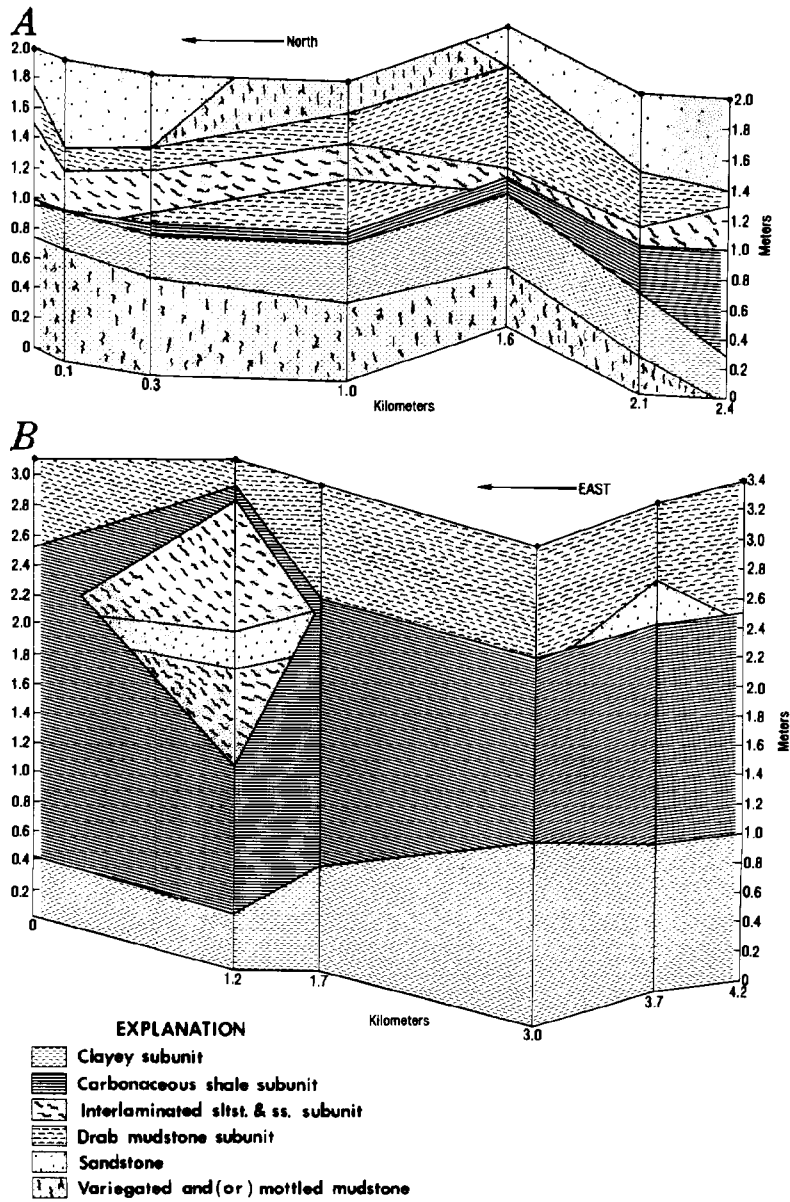


FIG. 6.—Fence diagrams of Type II units: A) WCS7, B) WCS15. The greater uniformity and thickness of WCS15 is typical of Type II units in the upper part of the Willwood Formation.

clean, trough or tabular crossbedded, and 1 to 3 m thick. Their geometry is variable. The contact with the underlying carbonaceous shale is sharp and erosional. The lower part of the sand body commonly contains ripped-up pieces of carbonaceous siltstone, and the

upper surface of the shale may have small tongues projecting into the sand. Where mudstone occurs directly above the carbonaceous shale, the contact is gradational and the mudstone is like that of the drab mudstone subunit described below.



FIG. 7.—Sharp, conformable contact of the clayey and shale subunits of a Type II unit. Note dark rootmarks in the clayey subunit (arrow).



FIG. 8.—Leaf fragments on a silty bedding plane of the interlaminated siltstone and sandstone lithology. Type II unit.

Drab Mudstone Subunit.—The uppermost subunit of Type II deposits is a drab, silty, rooted and bioturbated mudstone. This lithology is similar to the typical bright-colored mudstone of the Willwood Formation, differing only in its drab color, lack of mottling, and presence of faded plant impressions. The basal contact with carbonaceous shale is gradational, as its upper contact is, with variegated mudstone.

Flora of Type II Units.—The composition of megafloreal assemblages from these units is strongly dependent on the lithology from which the sample is drawn. Two of the sedimentary subunits, the interlaminated siltstone and sandstone and the carbonaceous shale, produced the bulk of the megaflorea.

Carbonaceous shale assemblages in the lower part of the Willwood Formation are

strongly dominated (70–80%) by the bald cypress relative, *Glyptostrobus*. Common associates are *Zingiberopsis* (15–30%), the tree fern *Cnemidaria* (0–40%), the alder *Alnus* (5–10%), and the horsetail *Equisetum* (20–30%). In the upper part of the Willwood Formation, carbonaceous shale floras are dominated by a shrubby walnut relative, *Platycarya* (30–60%), and *Alnus* (2–20%) and *Equisetum* (20–30%) are the common associates. *Glyptostrobus* was dominant (50%) at one quarry site in the upper part of the formation. In both the lower and upper parts of the Willwood Formation, 5–10 relatively rare species of shrubs, ferns, and herbaceous plants compose the remainder of the carbonaceous shale assemblage. At any one level this flora has about 7–14 species.

The flora of the interlaminated subunit is best known from the lower part of the Willwood Formation. Unlike carbonaceous shale

assemblages, these are not usually dominated by a single form. A variety of woody plants are common, including the sycamore *Platanus*, the cottonwood *Populus*, *Cercidiphyllum*, and relatives of the birches, witch-hazels and walnuts. Additionally, most of the species typical of the carbonaceous shale assemblage also occur rarely in the interlaminated siltstone and sandstone assemblage. In WCS7 the assemblage from the interlaminated sub-unit contains 30 species.

The palynoflora of Type II units was recovered primarily from the carbonaceous shale lithology. In the lower Willwood Formation this flora is dominated by pollen of the bald cypress family (presumably derived from *Glyptostrobus*) and by alder pollen. In the upper Willwood Formation, where carbonaceous shale is once again abundant, *Platycarya* and tilioid (linden family) pollen replace that of the bald cypress family as shale assemblage dominants, but alder pollen remains common.

INTERPRETATION

A Depositional Model for Type I Units

All of the sedimentologic and paleobotanical evidence for Type I units suggests that most of their sediments accumulated in floodplain ponds, probably in abandoned portions of channels. The lenticular cross section, arcuate map plan, downcut relationship to underlying sediment, and the position of the coarsest sediment at the bottom of the lens are all characteristic of abandoned channel deposits (Allen 1965). The middle portions of Type I units are fine grained and have multiple fining-upward sequences without current bedding. These features are typical of sediment deposited in standing water (Reineck and Singh 1980).

The abundance of floating aquatic species in the megaflores of Type I units confirms the presence of standing water. At locality Pn, *Salvinia preauriculata* was found with the delicate pinnae and rootlets still attached to one another (Fig. 5), further evidence of a very quiet environment of deposition. The abundant occurrence of pollen of herbaceous plants (for example, *Pistillipollenites* and *Typha*) in some Type I units implies that relatively open habitat was available along the

margins of the ponds. The dominance of riparian forms in the leaf remains of woody plants (for example, *Platanus* and *Salix*) also suggests that the ponds in which these sediments accumulated had once been active reaches of channels.

A combination of paleobotanical and sedimentologic data can be used to reconstruct the probable sequence of events represented by a Type I unit (Fig. 9). Deposition of each unit started with the abandonment of a reach of channel, after which fine, organic-rich sediment accumulated under standing water. During this phase the surface of the water was colonized by floating aquatic plants, and the margins were occupied by marsh vegetation, shrubs, and trees. As the abandoned channel filled in (eutrophied) the wetland vegetation grew outward into the shallowing water; this kind of vegetational change is recorded by the vertical replacement of floating aquatic species by *Zingiberopsis* at locality H. Above the siltstone and clay layers is slightly coarser, poorly bedded, root-marked, drab sediment. Root marking and absence of bedding features are evidence that this sediment served as the substrate for terrestrial vegetation, but the drab color and presence of some organic plant material indicate that it was not a well-drained, oxidized soil. Red mudstone above this level indicates that the former pond surface was finally occupied by a typical Willwood Formation floodplain soil.

Vegetation plays an important role in eutrophication; studies of hydrosere vegetational change like that hypothesized for Type I units have shown that aquatic and marsh plants effectively trap sediment and also contribute material to pond filling (Kenoyer 1929; Jewell and Brown 1929). Jewell and Brown (1929) reported that a small pond in Michigan that was 3 m deep circa 1900 was an incipient mudflat-sedgefield less than 30 years later. The rate of eutrophication of lakes is increased by small size, shallow water, soft bottom, and high water temperature (Whittaker 1975). Because the Willwood Formation was deposited under a warm temperate to subtropical climate (Bown and Kraus 1981; Wing 1981) and Type I units formed on an aggrading floodplain, it is likely that the hydroseres these units represent were completed in as little as 100 years.

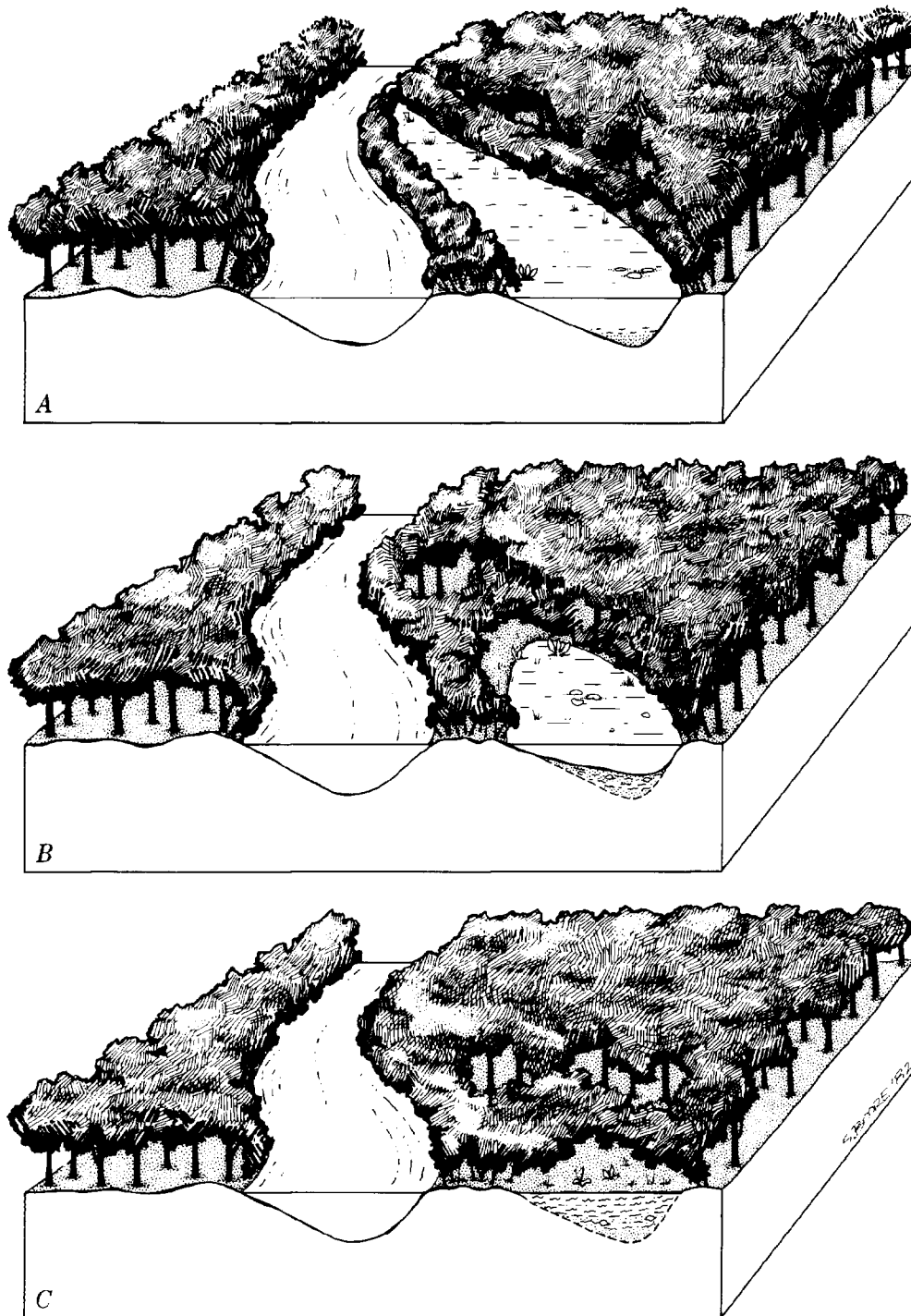


FIG. 9.—Sequence of events in deposition of Type I unit. A) Soon after channel abandonment, margin of pond is colonized by wetland vegetation. B) Encroachment of pond margins by wetland vegetation, shrubs and trees, and filling of the pond with fine, organic sediment. C) Complete filling of the pond with sediment, drying of fill material, and colonization of the old pond by forest.

*Depositional Environments in
Type II Units*

The Willwood Formation is about 75% mudstone, almost all of which has been subjected to pedogenic alteration in a generally oxidizing soil environment (Bown 1979; Bown and Kraus 1981). Sediment containing macroscopic plant matter is exceptional. Therefore, any model of the genesis of Type II units must account for conditions that led to the preservation and accumulation of plant matter on a floodplain where it was usually decomposed. The model must also explain the cyclic occurrence of the same sedimentary subunits in all of the Type II units. Before advancing an overall model for Type II unit deposition, it is necessary to consider the environment of deposition of each of the subunits.

Environment of the Clayey Subunit.—The blue-gray color of the clayey subunit indicates an absence of the ferric iron compounds that give red, orange, or purple color to many of the mudstone units in the Willwood Formation. In this respect, the clay subunit is similar to the eluviated A horizons of floodplain soils described by Bown and Kraus (1981), but the clayey subunit is unlike those horizons because of its finer grain size, its higher kaolin content, and the abundance of carbonized root compressions. The texture of the clayey subunit is similar to that of the middle portions of Type I units, but the clayey subunit differs by being laterally extensive and by lacking internal stratification and megafossil remains of the aerial portions of plants.

A modern analogue for the clayey subunit is seen in sediment deposited under marsh vegetation. Marsh substrates are frequently fine textured, rooted, have little internal stratification, and do not contain macroscopic organic matter (Coleman 1966; Gallagher and Plumley 1979). The absence of organic material in the sediment underlying these modern marshes results from high rates of decomposition on the soil surface and intense recycling of organics by the shallow roots of marsh plants (Gaudet 1977; White et al. 1978).

The clay subunits of the Willwood Formation also share many features with the un-

derclays of Pennsylvanian coals, which are laterally extensive, unbedded, rootmarked, and kaolinitic (Huddle and Patterson 1961; O'Brien 1964; Keller 1975). The high kaolin content of the Pennsylvanian underclays has been attributed to leaching by acid swamp water (O'Brien 1964), an interpretation that has been bolstered by the observation that acid water in modern peat swamps can cause flocculation and rapid deposition of suspended clay, as well as enriching it in kaolin (Staub and Cohen 1978, 1979).

The following characteristics suggest that the clayey subunits of the Willwood Formation formed as marsh soils in which reworking by roots rather than chemical oxidation was responsible for the destruction of plant material: absence of oxidized iron minerals, primary bedding, plant megafossils except for roots preserved as carbon films, and an elevated kaolin content compared to other clay in the Willwood Formation.

Environment of the Carbonaceous Shale Subunit.—Most of the differences between the clayey subunit and the carbonaceous shale reflect the much greater amount of plant matter in the shale. The presence of coalified logs, stem fragments, leaves, fruits, seeds, and root casts in a low-energy depositional setting strongly indicates that the carbonaceous shale accumulated under a forest. The great abundance of *Glyptostrobus* in carbonaceous shale megaflores and palynoflores from the lower portion of the Willwood Formation is evidence that the substrate was wet and probably at least seasonally flooded. Like its relative *Taxodium* (bald cypress), living *Glyptostrobus* favors soils that are wet and frequently flooded (Henry and McIntyre 1926). *Alnus* and *Equisetum*, two subdominants in the carbonaceous shale floras, also favor wet soils. The presence of *Alnus* is of particular interest; this genus has symbiotic nitrogen-fixing bacteria that enable it to colonize acidic, nutrient-poor substrates (Fowells 1965). The floral assemblages from carbonaceous shales in the upper Willwood Formation are generally similar to those lower in the formation, except that *Glyptostrobus* is replaced by *Platycarya*, perhaps indicating somewhat drier substrates.

The *Taxodium* swamps of the southern United States are a modern environment

comparable to those in which the carbonaceous shales of the Willwood Formation accumulated. Rates of organic litter accumulation are very high in contemporary *Taxodium* swamps (Conner and Day 1976; Day 1979), and the litter is dominated by remains of *Taxodium* (Schlesinger 1978).

Environment of the Interlaminated Siltstone and Sandstone Subunit.—The alternation of siltstone and sandstone layers and lenses, the presence of ripple cross stratification and rarer climbing ripple stratification, and the inclination of bedding planes are all characteristics of near-channel settings like levees and crevasse splays (Allen 1965; Reineck and Singh 1980). In addition, both the composition of the megafloora and the presence of numerous broken and abraded leaf fragments in this subunit (Fig. 8) support the interpretation that the sediment was deposited in a near-channel environment rather than in a distal floodplain backswamp. Trees such as *Platanus*, *Populus*, and *Cercidiphyllum* commonly occur along levees and streambanks in moist but drained soils, but they are very rare or absent from swamps. Megafloral diversity is greater in this subunit than in the carbonaceous shale subunit. A similar pattern is observed on modern floodplains, where near-channel vegetation is more diverse than that of lower, flooded areas (Nixon et al. 1977; Bell 1980). Fossils of many partly decayed leaves, and the generally disturbed and rooted condition of the interlaminated subunit indicate that the substrate was better aerated and more actively burrowed and rooted than that of the carbonaceous shale subunit.

Environment of the Drab Mudstone Subunit.—Presumably, this subunit accumulated on distal floodplains where drainage was too poor to allow oxidation of iron compounds, but good enough to allow oxidation and/or decay of plant matter. No identifiable megafloreal remains have been recovered from this subunit.

A Depositional Model for Type II Units

A model for the development of a typical Type II unit is summarized in Figure 10. The first stage in the deposition of a Type II unit is the accumulation of the clayey subunit un-

der marsh vegetation. Standing stems of marsh plants may have contributed to slowing the flow of sluggish overbank flood water, thus favoring the deposition of very fine sediment. Such deposition could have been accelerated by flocculation of clay in the acidic marsh water, as described by Staub and Cohen (1978, 1979). The most important effect of the clay was to inhibit drainage on the flood basin, thus creating a perched water table that influenced the soil environment of sediment deposited above the clay.

As the marsh filled in with clastic sediment, the soil surface would tend to be raised above the average water table level. Longer periods of exposure would allow colonization by woody trees and shrubs that can invade seasonally flooded areas but not those that are continuously immersed: for example, *Alnus* and *Glyptostrobus*. The invasion of the marsh by large, woody plants would have greatly increased the amount of organic matter contributed to the sediment. This is inferred to have created the rapid transition from clay to carbonaceous shale. The nonoxidizing conditions that allowed the accumulation of this plant matter resulted from the impeded drainage caused by the underlying clay.

As the carbonaceous shale built up, the top stratum would have had improved drainage because it was being raised farther above the water table. In areas closer to the channel, carbonaceous shale deposition was often succeeded directly by interlaminated siltstone and sandstone. The coarser grain size of this subunit would have increased drainage and hence oxidation and decay of plant matter. This better-aerated substrate supported a more diverse flora than did the backswamp. Over time, the wedges of interlaminated silt and sand built out on to the floodplain, halting deposition of carbonaceous shale.

The drab mudstone subunit formed in the distal flood basin when organic and clastic sediment had built up enough to allow degradation of plant debris. But the absence of red mudstone directly above the carbonaceous shale indicates that drainage of this sediment was still too poor to allow thorough oxidation.

In sum, the deposition of relatively impermeable clay set the stage for preservation of plant matter on the usually oxidized flood-

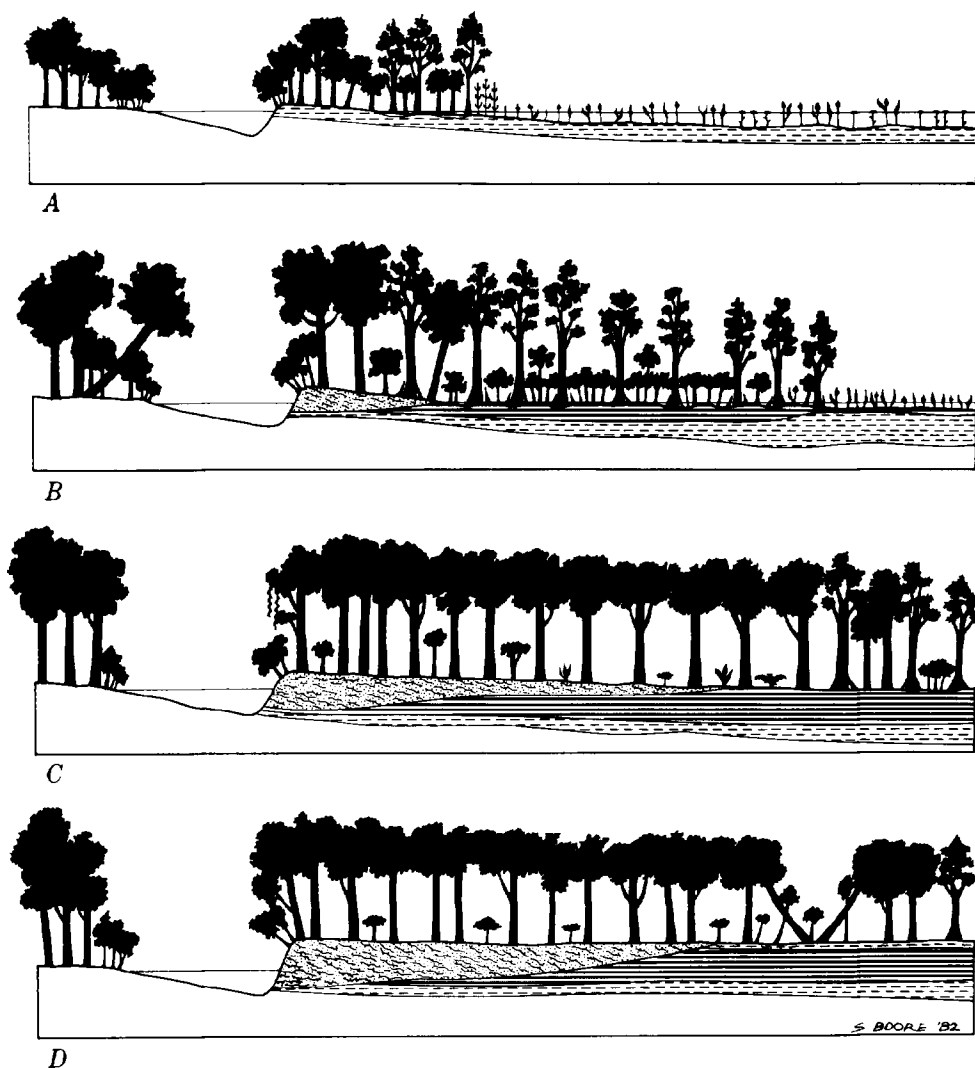


FIG. 10.—Sequence of events in deposition of Type II unit. A) The clayey subunit accumulates in a low-lying floodplain marsh. B) The carbonaceous shale subunit accumulates after colonization of the marsh by swamp forest trees such as *Glyptostrobus* and *Alnus*. C) A wedge of interlaminated silt and sand builds out onto the flood plain. Because it is better drained, this substrate supports a diverse woody vegetation. D) The drab mudstone subunit is deposited when the substrate becomes better drained and aerated, allowing decay and oxidation of plant remains.

plains of the Willwood Formation. The interaction of vegetational succession and continued aggradation of the floodplain caused the sequential recurrence of the same lithologies and the return to oxidized conditions following deposition of each Type II unit.

On floodplains that are not rapidly aggrading, vegetation might have an even more profound effect on deposition of carbonaceous sediment. Some types of vegetation, for example, *Taxodium* swamps, can greatly reduce the amount of evaporation that occurs under their canopy (Brown 1981). The effect of this reduced evaporation is the maintenance of an unusually high water table (Crawford 1978). This prevents other plant species from colonizing the substrate. Thus, in the absence of clastic sedimentation, certain kinds of vegetation may stabilize environments favorable to the preservation and accumulation of plant matter.

CONCLUSIONS

Type I and Type II units have a nearly inverse stratigraphic distribution in the Willwood Formation, the former being concentrated in the middle of the formation and the latter being abundant only at the bottom and the top (Fig. 1). This pattern suggests that conditions favorable to the deposition of one type of unit were unfavorable to the deposition of the other.

A fluvial system characterized by unstable channels and high rates of floodplain accretion should produce more Type I units. Frequent channel abandonment creates more opportunities for channel-fill deposition, and rapid accretion on the floodplain would bury the channel-fill deposits, thus preventing them from being reworked during subsequent sweeps of the channel. Such an unstable system is less compatible with the deposition of Type II units. The wedges of interlaminated siltstone and sandstone seen in Type II units suggest multiple overbank floods from the same channel, and the clayey and shale subunits show that the distal flood basin received only fine sediment during the deposition of each Type II unit.

This inferred association of Type II units with lower rates of sedimentation is further

supported by observations that they occur in sections of the Willwood Formation having relatively large numbers of sheet sand bodies and a low mudstone/sandstone ratio. These are characteristic of lower rates of sediment accumulation (Allen 1978; Kraus 1980; Bown and Kraus 1981).

It is unclear what factors controlled the characteristics of the fluvial system, which in turn influenced the geometry of carbonaceous deposits in the Willwood Formation. However, the shift during middle Willwood time from Type II to Type I units occurs at about the same time (mid-Wasatchian) as the rapid structural elevation of the Owl Creek and southern Bighorn Mountains and the shift of southern Bighorn Basin drainage to the north (Bown 1980). These events may well have caused changes in fluvial regimes that affected the geometry of carbonaceous deposits. For instance, an increase in stream gradient at the headwaters might increase sediment load and decrease channel stability in the basin bottom. This would favor deposition of Type I rather than Type II units.

The effect of climate on the geometry of the deposits is less apparent. A drying trend is recorded for the northern Rocky Mountains during the later early and middle Eocene (MacGinitie 1969; Leopold and MacGinitie 1972; MacGinitie 1974). In the Bighorn Basin, drying is indicated during middle and later Willwood time (Bown and Kraus 1981). The return to Type II units during this same interval implies that geometry was not strongly influenced by climate.

SUMMARY

There are two types of carbonaceous deposits in the lower Eocene Willwood Formation of northern Wyoming. Type I units are lenticular and formed by the infilling of abandoned channels. Type II units are tabular, composed of cyclically recurring sedimentary subunits, and formed on broad, poorly drained floodplains.

The deposition of both types of units is influenced by vegetation. In type I units, floating and emergent aquatic vegetation accelerated eutrophication of the ponds. In Type II units, marsh vegetation contributed to conditions that favored the deposition of an im-

permeable clay layer, which in turn created a perched water table and an environment favorable to the preservation of plant matter. The eventual return to an oxidized and bioturbated floodplain soil occurred when clastic and organic sediment had accumulated high enough to escape the drainage-blocking effects of the clay. The remains of swamp vegetation made an important contribution to this accumulation and thus to the return to oxidizing conditions. The two types of carbonaceous units apparently formed under different fluvial regimes. Type I units being favored by relatively unstable channels and rapid floodplain accretion and Type II units by more stable channels.

Preliminary observations in lower Eocene rocks of the Great Divide and Powder River Basins of Wyoming have shown that Type II units are present, and are composed of the same sedimentary subunits. This suggests that the interactions between sedimentation and vegetational succession discussed here may apply generally to other fluvial basin-fill deposits.

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