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OUTCROP-SCALE ENVIRONMENTAL HETEROGENEITY AND VEGETATIONAL COMPLEXITY IN THE PERMO-CARBONIFEROUS MARKLEY FORMATION OF NORTH CENTRAL TEXAS

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Abstract—The Markley Formation of north-central Texas is composed predominantly of terrestrial rocks that span the Pennsylvanian-Permian boundary. Plant-fossil-bearing outcrops of the Markley are complex and preserve distinct environments that probably differed in position on the landscape and habitat conditions. In superpositional order, basal paleosols evidence well drained but wet conditions and supported a flora with deep rooting. The immediately superjacent kaolinite-rich, quartz mudstone beds contain a "Permian"-type flora, dominated by seed plants, particularly conifers. Above these units there are "wet" floodplain deposits including organic shales that grade into coals. Above these are floodplain mudstones coarsening upward to sandstones. The floodplain deposits contain a typically "Pennsylvanian"-type flora. The co-occurrence of these floras in different beds within the same outcrops is strong evidence of climatic fluctuations during the time of accumulation, probably in response to the glacially controlled climatic rhythmicity, still prominent during the latest Pennsylvanian and earliest Permian.

INTRODUCTION

Uppermost Carboniferous-lowermost Permian rocks of north-central Texas are broadly divided into marine- dominated strata of the Harpersville Formation to the south and terrestrial-dominated strata of the Markley Formation to the north (Hentz, 1988). The precise age of, and location of the Permo-Carboniferous boundary within, the Markley Formation is problematic due to poor biostratigraphic control as a result of limited exposures that inhibit accurate correlation with the marine-dominated Harpersville Formation to the south. The limited information available suggests that the Carboniferous-Permian boundary is in the lower Markley Formation, so a significant thickness is representive of Early Permian time.

Well logs indicate that the Markley Formation is composed dominantly of mudstones. Surface outcrops of the Markley Formation are interpreted to have been floodplain deposits that were locally modified by extensive surficial weathering and pedogenesis (Hentz, 1987; Tabor and Montañez, 2002). Coals and coaly shales are locally intercalated within the mudstones as lenticular bodies of limited areal extent, although a few coals, such as the Newcastle Coal, are widespread. Plant fossils within the Markley Formation are confined to preservation in small, widely spaced channel-form deposits that are lithologically heterogeneous but broadly consistent in pattern. Plant fossils generally occur in multiple beds, with characteristic floras restricted to specific lithotypes. If well exposed, there is a paleosol at the base, a fossiliferous kaolinite bed bearing conifers and other typically Permian plant fossils, an organic-shale bed rich in plant fossils characteristic of latest Carboniferous swamp deposits, and floodplain deposits, again characterized by typically Carboniferous plants.

Plant fossils document at least three, and possibly four vegetation types within any given outcrop. The vegetation types appear to be drawn from two nearly distinct species pools. One of these species pools is characterized by typical "Pennsylvanian" vegetation thought to have grown on substrates with high water tables for most of the year. The other species pool is typified by more xeromorphic plants generally thought to have grown in better-drained conditions with significant seasonal moisture deficits. These two floras are represented within the scale of a single outcrop and, if sampling is done carefully, appear to be preserved within stratigraphically discrete portions of the lithologic succession.

Although stratigraphic variations in these patterns are not perfectly uniform, the basic structure persists throughout the Markley Formation to the base of the overlying Archer City Formation, at which

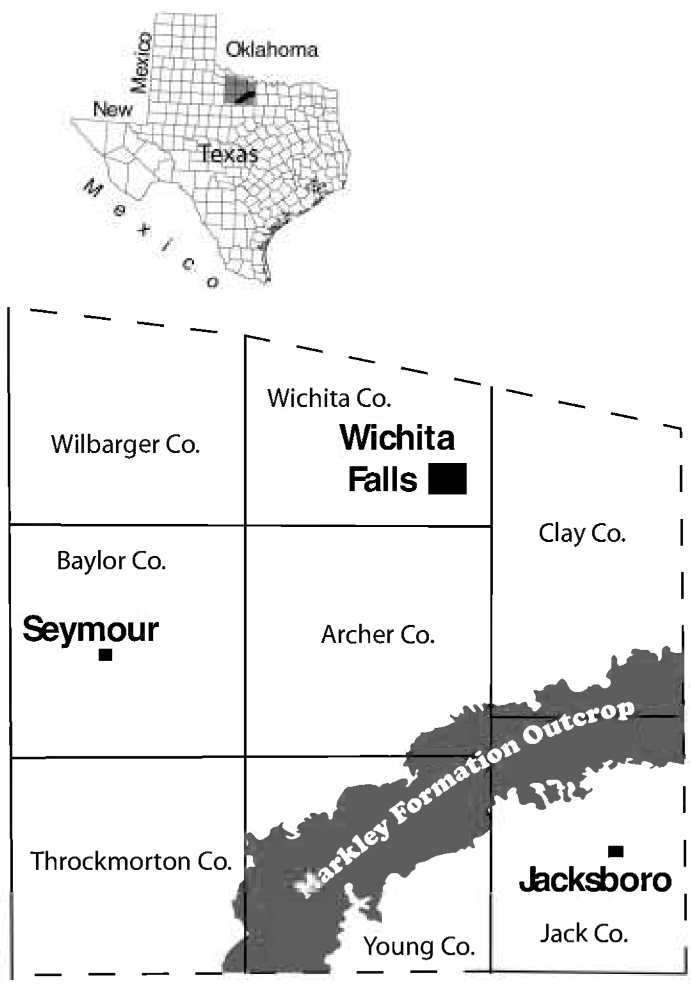

FIGURE 1. Geological map showing the location of the outcrop area and position of the Markley Formation.

FIGURE 2. "Typical" outcrop of the Markley Formation in north central Texas. Units: 1. Paleosol. 2. Kaolinitic-quartz siltstone. 3. Organic shale. 4. Floodplain mudstones. 5. Sandstone. See text for details.

point the plant fossil assemblages become significantly more "Permian" in composition, and outcrops become both lithologically and floristically homogeneous.

OUTCROP PATTERNS

The Markley Formation crops out in the area of north-central Texas in a band striking approximately NE-SW and dipping gently to the NW (Fig. 1). The Markley is composed predominantly of terrestrial rocks, including coal beds. It is overlain by the Archer City Formation.

An idealized plant-bearing outcrop in the Markley Formation contains lithologies that indicate an array of sedimentary facies including paleosols, swamp deposits, channel margin and floodplain deposits, and peculiar beds that may be lag deposits of highly weathered clays stripped from eroded soils during intervals of base level change (Fig. 2). Clay mineralogy (Tabor and Montañez, 2002) is dominated by kaolinite with subordinate illite in nearly all mudstones associated with the plant-bearing beds, indicators of humid, but relatively well-drained conditions characterized by high rainfall and chemical leaching. Smectitic clays are common only in the upper parts of the formation, associated with vertisols; indicators of seasonal moisture distribution.

The base of the section generally includes a thick, pedogenically altered, massive to angular blocky red mudstone or claystone up to 1.5-m thick with medium to coarse gray mottles. The tops of these paleosols can exhibit evidence for scour and local truncation of the profile. The paleosols are characterized by up-profile enrichment of kaolinite and Fe-oxides, whereas redoximorphic features, including "plinthite" layers, become more abundant with depth. Such characteristics indicate good surficial drainage, but a relatively shallow, seasonally fluctuating, groundwater table. These soils also contain nearly vertical root systems indicating colonization by plants adapted to free drainage. These basal paleosol profiles were deeply weathered and were probably similar to modern Ultisols (Tabor and Montañez, 2004). Ultisols are found today in upland, or well-drained, tropical to subtropical forests in warm to hot, humid areas characterized by high rates of chemical weathering (Buol et al., 1997; Soil Survey Staff, 1998).

The upper contact of the basal paleosol lithology is abrupt and overlain by a physically resistant, light gray to white quartz-silt bed that is enriched in kaolinite and varies in thickness from a few centimeters to a meter or more. These characteristics lead us to initially interpret them, incorrectly, as volcanic ash beds. Tabor and Montañez (2002) interpreted them as the B horizons of Hisotosols based upon their morphological relationships with overlying organic shales and coals. Nevertheless, the origins of their physical and chemical composition are likely attributed to events that predate pedogenic formation of the Histosol profiles. Several examples of these quartz-silt beds contain a flora consisting of xeromorphic Walchian conifers and other seed plants, including neuropterids (particularly *Neurodontopteris auriculata*), cordaites, and *Sphenopteridium*. We consider these layers to represent lag deposits, possibly derived from eroding soils upon surrounding elevated areas and subsequently deposited in the channels during initial phases of filling. The woody seed plant, xeromorphic floras contained within these deposits are most probably derived from well drained soils that occupied upland positions, such as the deeply rooted Ultisol profiles that are subjacent to these beds.

The quartz-silt, kaolinitic beds are typically overlain by an organic shale bed varying in thickness from 10 cm to more than 1 m. These units were described by Tabor and Montañez (2002, 2004), and interpreted to have been O horizons of soils similar to modern Histosols, given their high organic content and evidence for in-situ accumulation of vegetable matter (Soil Survey Staff, 1998). They consist of intermixed, densely layered plant remains, mainly *Macroneuropteris scheuchzeri* (except for *Pecopteris* in the highest known deposit of this type, Kola Switch), and paper-thin layers of mudstone with little apparent vertical disturbance by rooting, suggesting their formation in swamps with long periods of standing water and long intervals of anoxic conditions at the sediment-water interface. Thin lenses of (relatively pure) clay, generally less than 10 cm in thickness, may occur within the coaly shale layers (O-horizons), deposits that preserve a quantitatively different assemblage (tree fern and sphenopsid) than the surrounding organic shale matrix; they may represent streams that ran through the swamp environment lined by a slightly different vegetation. Alternatively, the muddier facies may represent larger scale floods into the swamp from the surrounding periswamp areas. However, the flora preserved in these clay layers is largely distinct from that of the superjacent floodplain mudstones, suggesting that the flora was not drawn from these latter settings.

Above the organic shales are a complex of small channel-fill mudstones and floodplain mudstones with weak pedogenic overprinting. Paleosols in these strata are massive and thin (only a few cm), with little or no soil reddening and very sparse evidence for rooting. Resistant, quartz-silt and kaolinite-rich beds, lithologically and floristically similar to that above the basal paleosol, may lie at the base of small scours. Other than these peculiar beds, the mudstones from this interval contain a diverse "wet" flora, typical of latest Carboniferous floodplain deposits that are dominated by ferns and pteridosperms.

Several beds of alternating sandstone and mudstone often terminate the section immediately beneath a final channel sandstone, resulting in a broadly upward coarsening sequence. Although the channel sandstone does exhibit some evidence for local scour, it does not evidence truncation of the underlying beds nor does there appear to be a long hiatus at this contact. This may represent lateral (or in part axial) facies migration across the landscape from backwater swamps (or lower coastal plain) to floodplain, to major channel environments.

FLORAS

The flora of the basal paleosol, to the extent that it can be identified, is known only from root casts. Root casts preserved in these soils are typically enriched in Fe-oxides such as goethite and hematite and can be quite large, 3-5 cm in diameter, and deeply penetrating, over a meter from the soil surface, suggesting large trees and a relatively low water table. It is possible that such roots are late stage and, in fact, are most closely associated with the flora preserved in the superjacent quartz-kaolinite beds. In this case, the flora would have been one typical of a substrate with deep water table but overall high soil moisture and periodic drying of the A horizon.

The flora of the kaolinite beds (Fig. 3) is characterized by xeromorphic plants. Such floras have been identified at 7 sites from 6

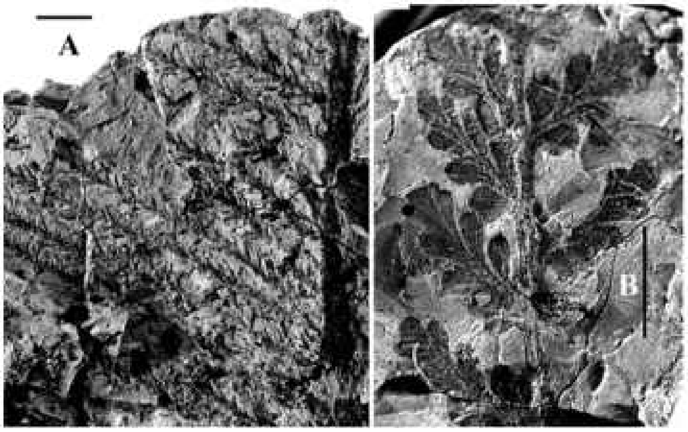

FIGURE 3. Flora of the quartz-kaolinite beds: A) *Walchia pinniformis*, USNM 528430. B) *Sphenopteridium* sp., USNM 528428. Scale bars = 1 cm.

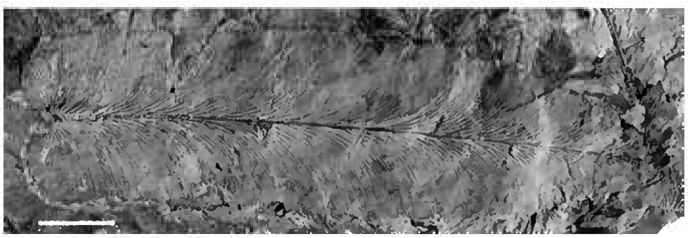

FIGURE 4. Flora of the organic-shale beds: *Macroneuropteris scheuchzeri*, USNM 528421. Scale bar = 1 cm.

different stratigraphic horizons, although quartz-kaolinite beds occur in the same intra-outcrop position at several other locations where no fossils were found. In general, few fossils are preserved and their preservation is notably poor, with exceptions, such as the Kola Switch and Squaw Mountain localities. Consequently, quantitative analyses are of limited value. The generally most common elements of these floras are walchian conifers (Fig. 3A) and the presumed pteridosperm, *Sphenopteridium* (Fig. 3B). At two localities, calamites also are abundant, either as stems or *Asterophyllities equisetiformis* foliage. *Neurodontopteris auriculata* occurs at 4 sites, in abundance at one. *Pecopteris* was abundant at one locality. Lycopsids have not been identified in the floras, although other rare elements of the "Carboniferous" flora occur. These plants may have been incorporated into samples as a consequence of the close proximity of quartz-kaolinite beds at the bottom of small channel scours and the overlying mudstone fill, which contained the more typically Carboniferous floodplain flora detailed below. In overall aspect, this flora would generally be characterized as broadly "Permian" in aspect. Although rooting structures are not common throughout the thickness of the quartz-kaolinite beds, the upper 10-15 cm of these units tends to be intensely rooted beneath contacts with overlying coal beds. Root casts are typically small (0.5-1.0 cm) diameter and preserved as Fe-oxide or jarosite minerals. However, the rooting systems preserved within these beds most likely originate from plants that were present during accumulation of the overlying coal layers.

Organic shales (Figs. 4-5) were analyzed from 7 localities from 5 stratigraphic horizons, a total of 10 sample populations. These lithologies are dominated by the pteridosperm *Macroneuropteris scheuchzeri* (Fig. 4) at all but one site, the potentially stratigraphically highest locality in the Markley Formation, Kola Switch, in which the tree-fern foliage *Pecopteris* is most abundant. The remains of plants in these deposits are so densely interlayered with thin muddy laminae that the deposit weathers to a paper-shale like consistency, grading locally to more coaly in character. In many deposits the assemblage is nearly monotypic. Small clay lenses and occasional clay rich layers contain, in addition to *M. scheuchzeri*, remains of the calamite stems (Fig. 5A) and *Asterophyllities equisetiformis* foliage (Fig. 5B); *Macrostachya* was found abundantly at one locality in a single sample, transitional between organic shales and floodplain mudstones (Fig. 8B), but without clear association with a particular sphenopsid foliage. Other elements that occur in abundance but only at one or two sampling localities include *Odontopteris lingulata*, *Alethopteris zeilleri*, *Lilpopia raciborskii*, *Sphenophyllum oblongifolium*, and several kinds of pecopterid tree ferns (Fig. 5C, E). The lycopsid *Sigillaria brardii* (Fig. 5D) was most abundant in the coalier facies of these beds, suggesting growth in habitats that were less disturbed by floods and clastic material.

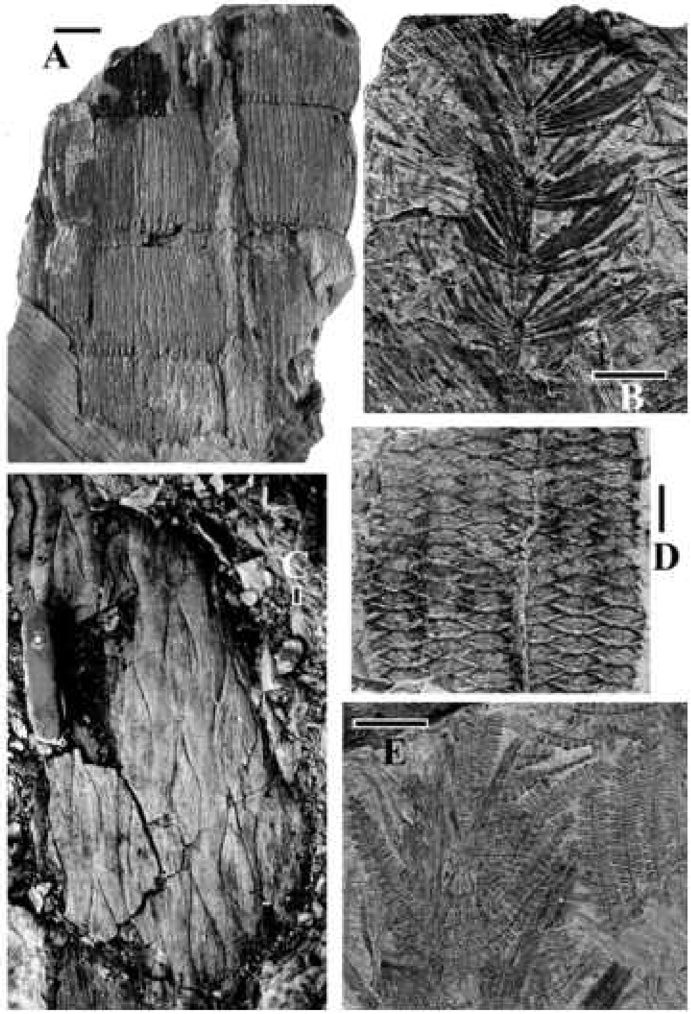

FIGURE 5. Flora of the organic-shale beds: A) *Calamites* sp., USNM 528420. B) *Asterophyllites equisetiformis*, USNM 528435. C) *Caulopteris*, stem of marattialean tree ferns with *Pecopteris* foliage, USNM 528441. D) *Sigillaria brardii*, USNM 528432. E). *Pecopteris* sp., fertile, USNM 528213. All scale bars = 1 cm.

Floodplain mudstones (Figs. 6-8) bearing plant fossils were analyzed from 8 localities, representing 7 stratigraphic horizons, a total of 10 collections. These deposits have a rich, diverse flora that may vary significantly among the collecting sites making it difficult to characterize. The most abundant and widespread elements are *Neuropteris ovata* (Fig. 6B), *Pseudomariopteris ribyronii* (= *P. cordato-ovata*) (Fig. 7A), and calamite stems (Fig. 7D). *Annularia carinata* (Figure 7E) occurs more widely and is generally more abundant than *Asterophyllities equisetiformis*; *Annularia spicata* occurs at one locality. The sphenopsid cone *Calamostachys* sp. was found occasionally in these deposits (Fig. 8A). Plants occurring more sporadically but in some abundance

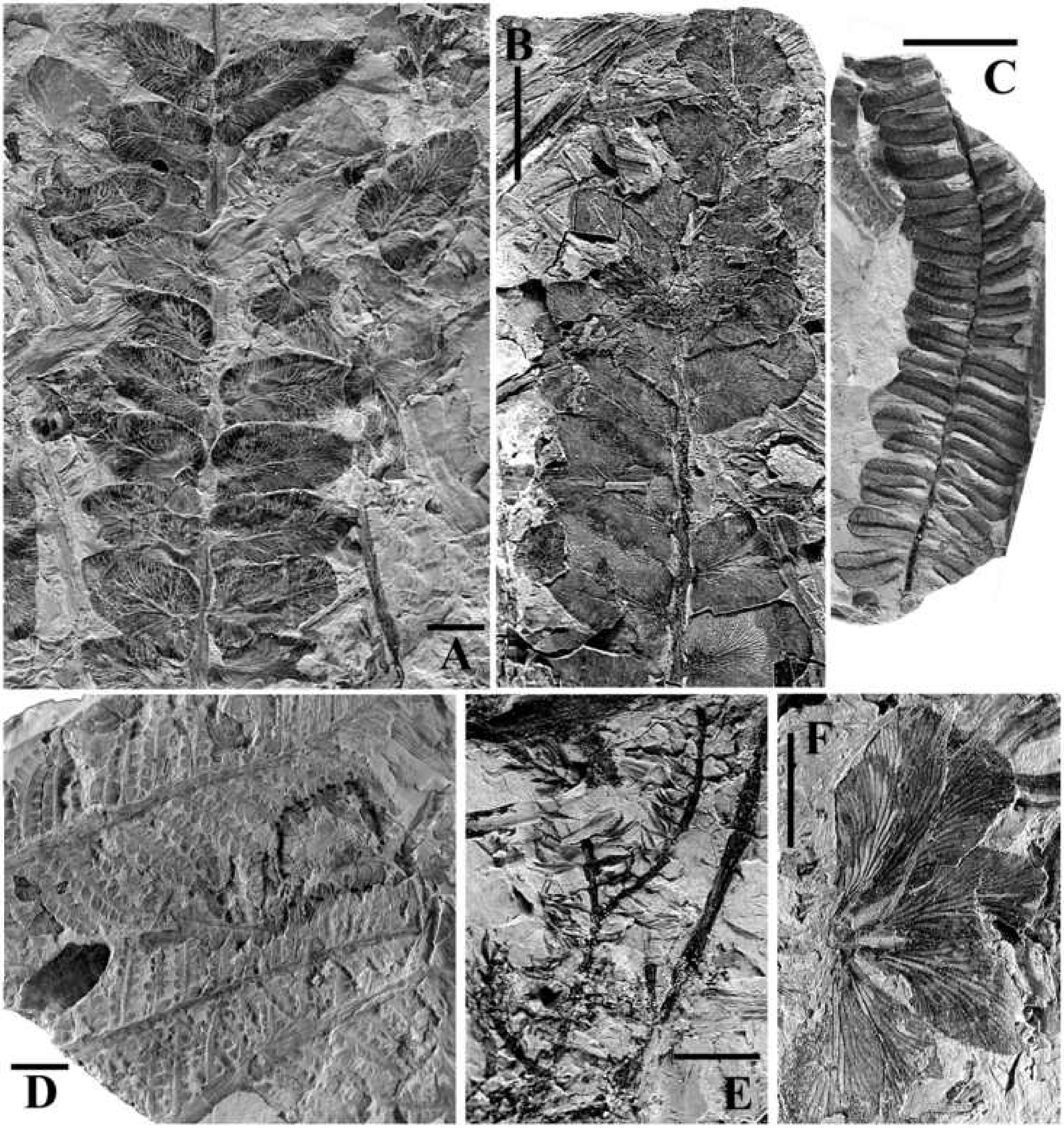

FIGURE 6. Flora of the floodplain mudstones: A) *Neurodontopteris auriculata*, USNM 528427. B) *Neuropteris ovata*, USNM 528445. C) *Pecopteris* sp., USNM 528434. D) *Lobatopteris puertollanensis*, USNM 528436. E) *Sphenophyllum* sp., USNM 528438. F) *Lilpopia raciborskii*, USNM 528439. Scale bars = 1 cm.

locally include the pteridosperms *Neurodontopteris auriculata* (Fig. 6A), *Macroneuropteris scheuchzeri*, *Odontopteris brardii* (Fig. 7B), *Alethopteris zeilleri* (Fig. 7C), and *Nemejcopteris feminaeformis*. Up to 10 different species of tree fern foliage have been identified as common to abundant, including *Lobatopteris puertollanensis* (Fig. 6D), *Pecopteris cyathea*, *Pecopteris lamuriana*, *Polymorphopteris polymorpha*, *Danaeites* sp., and many undescribed forms. The groundcover sphenopsids *Sphenophyllum oblongifolium* (Fig. 6E) and *Lilpopia raciborskii* (Fig. 6F) are widespread and occasionally abundant. Smaller ferns and pteridosperms, such as *Sphenopteris bronnii*, *Oligocarpia* spp., *Eusphenopteris* cf. *E. rotundiloba*, and *Discopteris opulenta* are widespread but individually rare and generally in low abundance. Overall, this is not a taxonomically rich flora but, together with the flora of the organic shales, it constitutes a typically "Pennsylvanian" wetlands species pool.

Sandstones bearing plant fossils were identified at a single sampling locality. Cordaitealean leaves, quite rare in general in the mudstone deposits, were the dominant element of this flora.

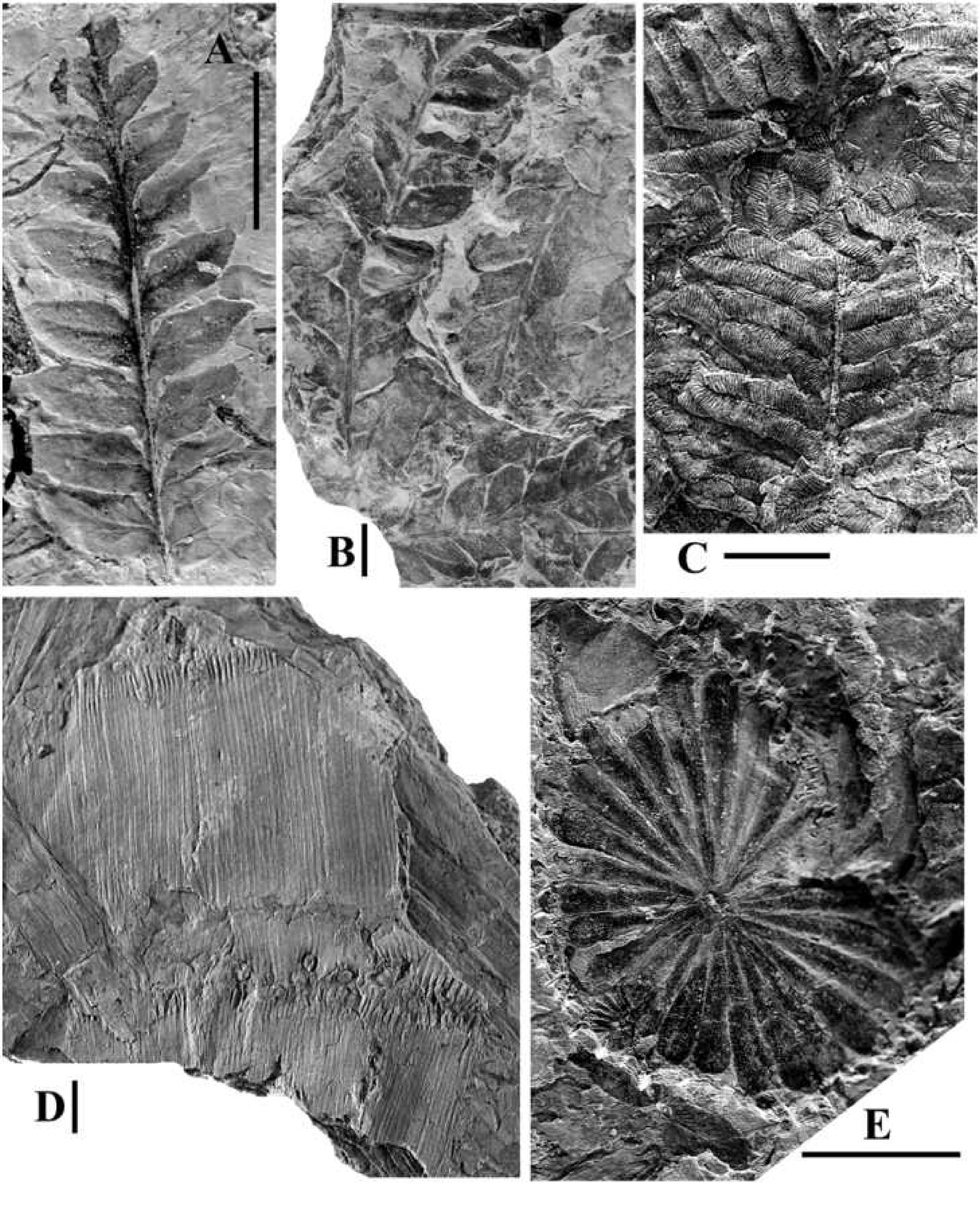

FIGURE 7. Flora of the floodplain mudstones: A) *Pseudomariopteris cordato-ovata*, X 3, USNM 528209. B) *Odontopteris brardii*, X 1, USNM 528426. C) *Alethopteris zeilleri*, also rarely prominent in organic-shale deposits, X 2, USNM 528450. D) *Calamites* sp., X 1, USNM 528424. E) *Annularia carinata*, X 3, USNM 528422. Scale bars = 1 cm.

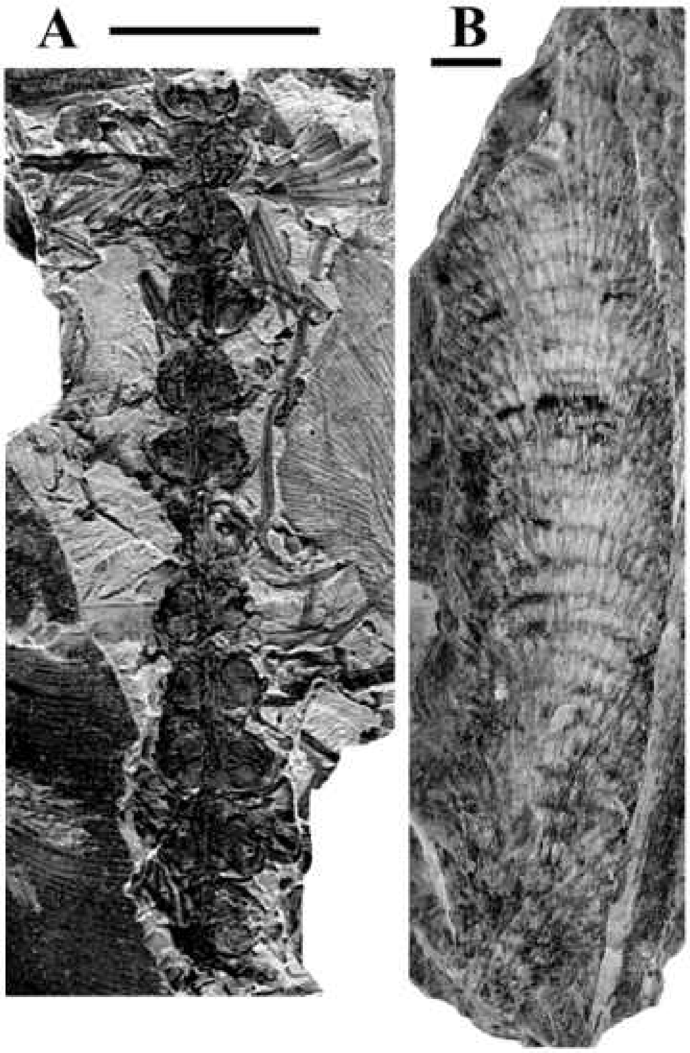

FIGURE 8. Flora of the floodplain mudstones: A) *Calamostachys* sp., USNM 528446. B) *Macrostachya* sp., USNM 528457. Scale bars = 1 cm.

INTERPRETATION

There appear to be two basic species pools represented in the floras of the Markley Formation. The more abundantly represented is that of the organic shales and overlying floodplain deposits. This flora is similar in composition to many other floras described from the later part of the Carboniferous in Europe (e.g. Laveine, 1989; Wagner, 1985 Doubinger et al., 1995) and the United States (Clendening, 1975). The second, which is represented by few, fragmentary specimens, is from the quartz mudstone-kaolinite beds, containing elements known rarely in the Carboniferous, such as conifers (Lyons and Darrah, 1989, for summary), more typical of the Permian (e.g., Kerp and Fichter, 1985).

The Carboniferous-aspect flora of the Markley Formation can be divided into three relatively distinct vegetation types that may represent subtle climatic distinctions, reflective of climatic variations arising during tropicaly climatic oscillations. The latest Carboniferous and earliest Permian were times of southern hemisphere glaciation, which should be expected to have had an attendant effect on tropical climate and patterns of lithological succession (Frakes et al, 1992 Martini, 1997). The distinctness of the floras, with some species overlaps, suggests that the strongest controls were landscape position, probably related to such processes as disturbance by local channel belts. However, the patterns of plant-by-lithotype distribution parallel those seen in areas where sequences of coals and intercoal clastic and marine deposits are better developed and tied to paleoclimatic fluctuations (Cecil, 2003; Cecil and Dulong, 2003).

The flora of organic shale beds is typically highly dominated by one taxon, in most instances *Macroneuropteris scheuchzeri*, if slightly clastic, or *Sigillaria brardii* in coalier facies where clastic input into the original swamp was limited. Other elements occur most commonly in clay lenses that may have been channels through the swamp habitats, or flood events. Nonetheless, the subdominant plants tend to be more common in this association than in the floodplain deposits. Such deposits probably represent long-periods of standing water, under humid conditions, with only slight seasonality. Clearly these environments were subject to sediment-bearing floods, although sediment loads appear to have been small. Clastic deposition in these swamps suggests a climate with seasonal rainfall, which would encourage the movement of some clastics within the local basin (Cecil, 1990).

Floodplain floras appear to have been variable, as might be expected in more ecologically disturbed areas. Paleosols are thin, only very weakly developed and small channel scours are common in these strata; collective evidence for unstable sedimentary environments characterized by relatively rapid depositional rates. The deposits are dominated by clastic sedimentation, suggesting somewhat increased climatic seasonality in the region. Foliage from small trees, represented by such forms as *Neuropteris ovata*, *Macroneuropteris scheuchzeri*, *Odontopteris brardii* and *Neurodontopteris auriculata* cooccurs with foliage of the thicket forming to climbing plant *Pseudomariopteris ribyronii* (Krings et al., 2003), suggesting a complex landscape, probably somewhat open with abundant ground cover, resulting from patchy disturbance.

Sandstone floras, unfortunately, are uncommon in these deposits. In the one occurrence, cordaitaleans are more abundant than at any other collecting site. Cecil and Dulong (2003) tie such deposits to periods of increased seasonality, associated with increased sediment transport, as vegetational rooting lessened in basinal uplands, permitting greater movement of sediment into the local streams. Falcon-Lang (2004) and Gastaldo and Degges (in press) have studied such sandstone deposits in detail from earlier in the Carboniferous of North America and also find cordaitalean-rich floras. These authors attribute this pattern of plant distribution to climatic seasonality, characterizing cordaites as extrabasinal elements that grew streamside in well drained to droughty habitats, perhaps on stream levees.

The flora of the quartz silt-kaolinitic mudstone beds bears similarities to some of the floras from the locally overlying Archer City Formation, such as the Sanzenbacher locality (see DiMichele et al., 2004), the Permo-Carboniferous boundary flora from Carrizo Arroyo in New Mexico (Tidwell et al., 1999; DiMichele et al., 2004), the precocious Permian-aspect flora of Missourian age (Late Pennsylvanian, Carboniferous) from the Kinney Brick Quarry in New Mexico (Mamay and Mapes, 1992), and numerous other floras from the late Pennsylvanian, Carboniferous (DiMichele and Aronson, 1992) and Permo-Carbonferous boundary Rotliegends of Germany (Kerp and Fichter, 1985). It is largely a distinct species pool, dominated by taxa, such as conifers and *Sphenopteridium* that do not occur in the floras typical of the swamp and wet floodplain deposits. In addition, conifers and cordaites are the only plants that are represented in this entire complex of Markley Formation deposits with growth habits likely to have produced the thick, deeply penetrating woody roots that are inferred from root casts in the basal Ultisols of the plant-bearing outcrops. It is likely that these plants and their associated flora occupied the surfaces of these paleosols, at least during some stages of their formation.

The occurrence of this flora at the base of channel scours within the floodplain mudstones that are superposed upon organic shales has significant implications. Clearly, the flora was present regionally during the time of floodplain development and growth of the Carboniferous-type flora that is most common in the Markley Formation floodplain deposits. The most likely explanation is that the plants were locally transported during times of floods into the floodplains, suggesting that they did not grow at great distances from them.

In all likelihood, the conifer-*Sphenopteridium* flora was present regionally during the deposition of all of these channel-fill components. Although speculative, it appears that most of the time in these complex deposits is represented by the thick and morphologically advanced paleosols at the bases of these depositional intervals. Consequently, the more xerophytic elements of the flora, the conifers and associated plants, actually may have periodically dominated the greater part of the regional landscape. The wetter parts of floodplains and swamps, dominated by the more typically Carboniferous elements, appear to have been significantly more ephemeral within the overall landscape, even if more abundant in terms of thickness of deposits and overall numbers of plant fossils.

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