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Sequence Stratigraphy of the Glenshaw Formation (Middle–Late Pennsylvanian) in the Central Appalachian Basin

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ABSTRACT

The Glenshaw Formation consists predominantly of sandstones and mudrocks with thin limestones and coals, which are thought to have accumulated in alluvial, deltaic, and shallow-marine environments. Analysis of 87 Glenshaw outcrops from southern Ohio, eastern Kentucky, and southern West Virginia has revealed widespread, well-developed paleosols. These paleosols are used, along with marine units and erosional disconformities, to develop a high-resolution sequence-statigraphic framework. The tops of the paleosols constitute boundaries for nine allocycles, which are interpreted as fifth-order depositional sequences. Allocycles in this framework correlate with similar allocycles described from the northern Appalachian basin.

A sequence-stratigraphic model is proposed that provides a framework for interpreting facies architecture in terms of base-level dynamics linked to relative sea level changes. Lowered base level caused valley incision along drainage lines and sediment bypassing of interfluves, which led to development of well-drained paleosols. Rising base level produced valley filling by fluvioestuarine systems (lowstand systems tract/transgressive systems tract), whereas pedogenesis continued on interfluves. As drainage systems aggraded, the coastal plain water table rose, and interfluvial paleosols were onlapped by paludal and lacustrine deposits. Histosols succeeded and partially overprinted paleosols with vertic and calcic features. Highstand systems tract (HST) facies in the coastal plain consist of widely separated, high-sinuosity fluvial channel and estuarine channel sandstones encased in overbank mudstones, whereas within marine units, HST facies with coarsening-upward regressive deltaic and interdeltaic facies are developed.

The sequence-stratigraphic framework provides the basis for a better understanding of the depositional systems, base-level dynamics, and climatic changes that influenced the infilling of the central Appalachian basin. The paleoenvironmental and sequence-stratigraphic context of channel and valley fills may benefit future petroleum exploration in the Appalachian basin and other analogous settings.

INTRODUCTION

Glenshaw Stratigraphy

The Glenshaw Formation constitutes the lower 66–80 m (217–262 ft) of the Conemaugh Group in the central Appalachian basin (Martino et al., 1996). The current stratigraphic framework is based on key beds, including laterally persistent coal seams and marine units (Figures 1, 2). In West Virginia, four widespread marine units have been distinguished, including, in ascending order, the lower Brush Creek, upper Brush Creek (Pine Creek), Cambridge, and Ames (Arkle et al., 1979; Merrill, 1986; Martino et al., 1996).

Paleogeographic Setting

The Dunkard basin (Figure 3) is a synclinorium containing strata from the cratonward portion of the central Appalachian foreland basin. These features were formed by warping and thrust loading and, during continental collision, associated with the Alleghanian orogeny (Quinlan and Beaumont, 1984). During the late Pennsylvanian (Stephanian), the center of what is now the Dunkard basin was positioned approximately 0–6° south of the equator (Opdyke and Divenere, 1994). The beginning of the Stephanian was marked by a long-term climate change toward increased aridity in the Appalachian basin attributable to orogenesis and associated rainshadow effects. Short- and intermediate-term (tens of thousands to hundreds of thousands of years) climate cycles may have produced the alternation of geochemically distinct stratigraphic intervals, including paleosols, coal beds, and nonmarine limestones (Cecil, 1990; Cecil et al., 1994).

Depositional Environments

The Glenshaw Formation contains channel-fill sandstones, red and olive mudrocks, and coal beds that accumulated on an alluvial coastal plain with a northwest paleoslope (Arkle, 1974; Donaldson, 1979). Nearshore and deltaic facies have been interpreted for sparsely fossiliferous olive-gray mudrocks and limestone and burrowed sandstones in the middle and uppermost portions of the Glenshaw (Donaldson, 1979; Martino et al., 1985; Merrill, 1986, 1988; Martino et al., 1996).

Shallow seas advanced at least eight times from the southwest into the Appalachian basin during Glenshaw deposition (Busch, 1984), whereas regressions were accompanied by the development of deltas that advanced northwestward across the basin (Donaldson, 1979).

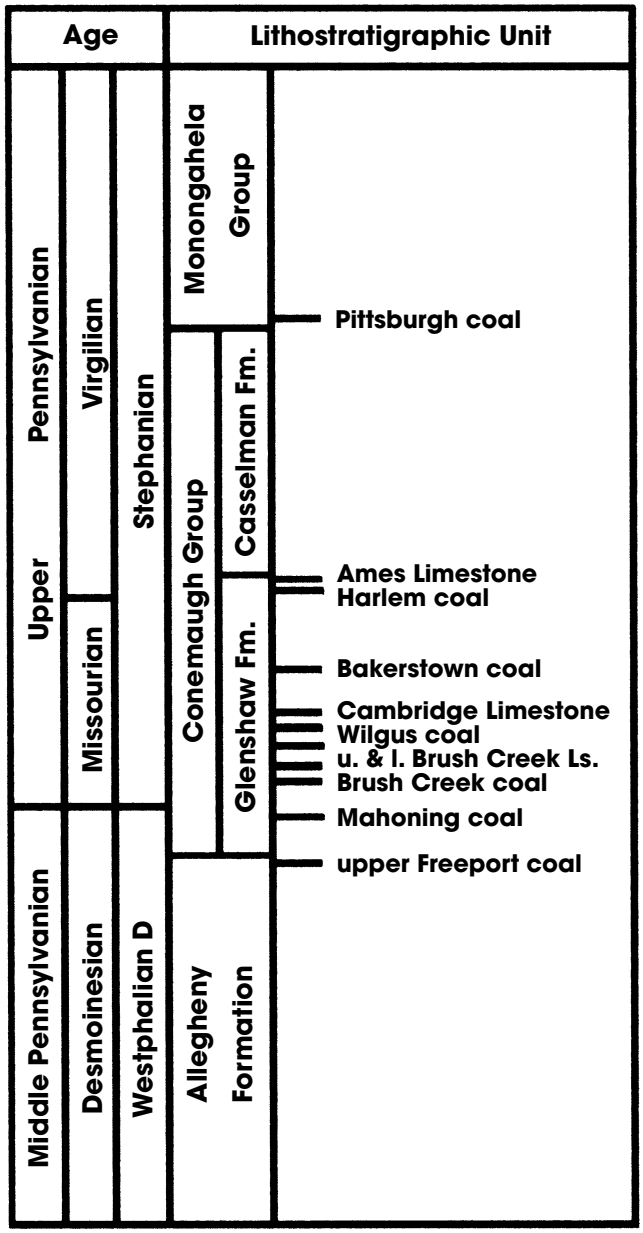


Figure 1. Stratigraphic framework for the Glenshaw Formation in the southern portion of the Dunkard basin (from Martino et al., 1996).

Economic Significance

The Glenshaw Formation contains several high-volatile bituminous coals that are generally too thin to mine, except along the northeastern edge of the Dunkard basin. These coals tend to be high in total sulfur (1–3%; Repine et al., 1993).

Two oil-producing sandstones occur in the Glenshaw Formation, including (1) the First Cow Run and (2) the Big Dunkard sands (driller's terms). These correspond to the (1) Saltsburg and Buffalo Sandstones and (2) the Mahoning Sandstone (Cardwell and Avery,

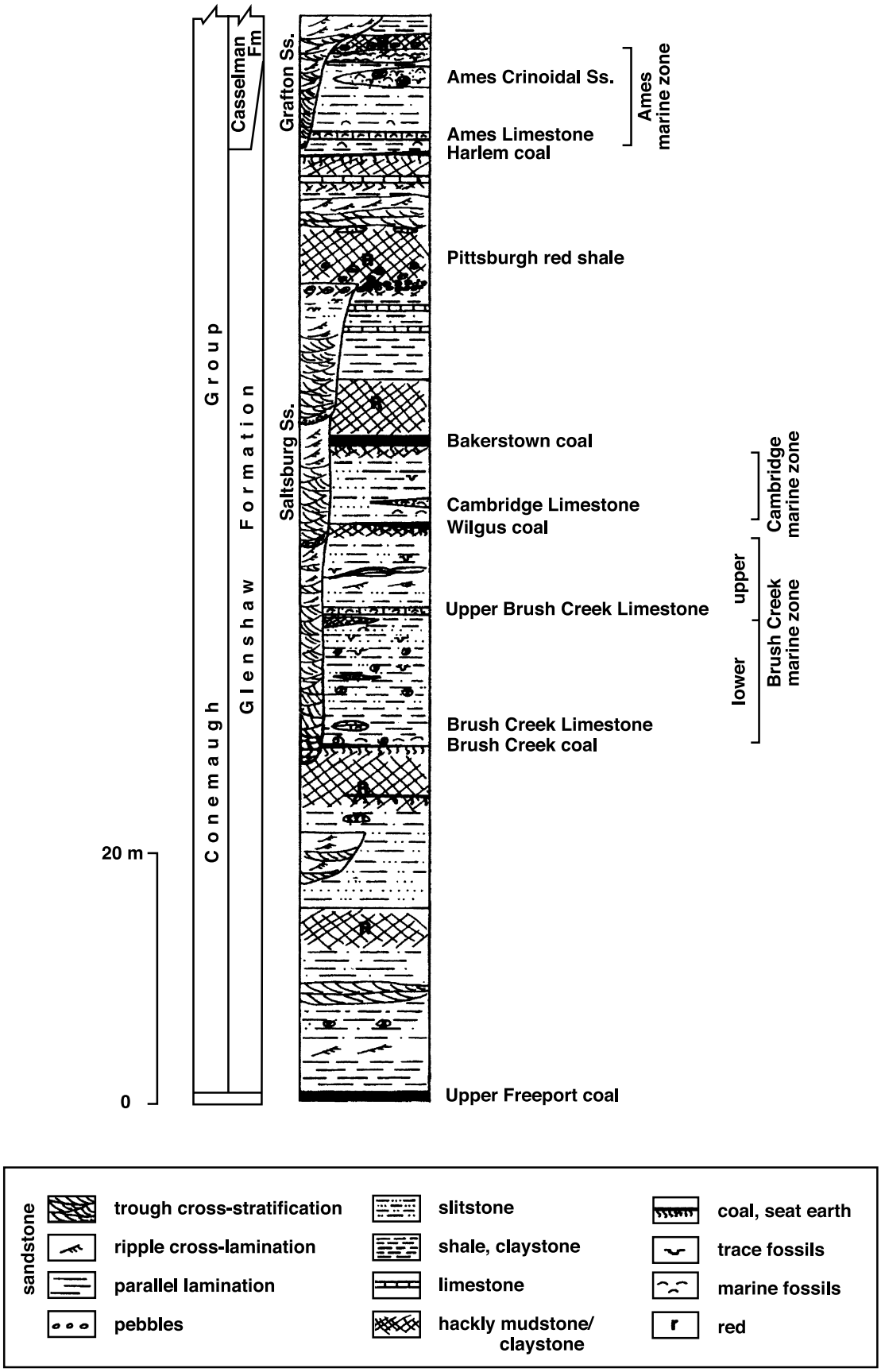


Figure 2. Composite stratigraphic section for the Glenshaw Formation in the vicinity of Huntington, West Virginia (modified from Martino et al., 1996).

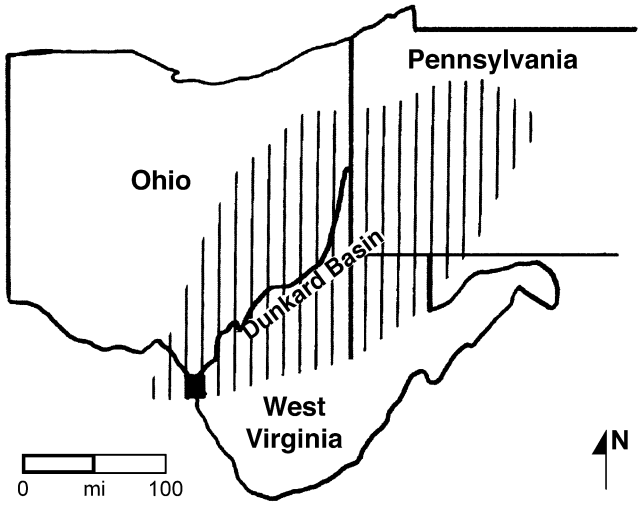


Figure 3. **Aerial extent of the Dunkard basin, with Huntington, West Virginia area, at southwest end represented by black square. Black rectangle at southern end of the basin defines the area of the present study (see Figure 4).**

1982). There is still some minor production from these reservoirs, but they are shallow targets that were of greater importance during early development in the late 1800s (Haught, 1963). Oil typically occurs in combination traps resulting from broad folds with gently dipping limbs in conjunction with a permeability barrier (Cardwell and Avary, 1982).

CYCLIC STRATIGRAPHY

Autocycles and Allocycles

Local repetitions of facies in vertical sequences are typically the product of processes that are intrinsic to a particular depositional system. Meandering rivers can produce a series of fining-upward cycles composed of alternating channel and flood-plain facies. Abandonment and reactivation of delta lobes can cause aerially restricted transgressive-regressive (T-R) cycles. Such autocycles were interpreted by many workers in the 1970s to be characteristic of Pennsylvanian strata of the central Appalachian basin (e.g., Ferm, 1970; Donaldson, 1979).

In contrast, allocycles are broader, regional or interbasinal cycles that result from factors that are extrinsic to the depositional system. External factors include tectonics, eustasy, and climate. Tectonics and eustasy control accommodation space through base-level changes, whereas tectonics and climate control sediment supply.

Allostratigraphy

Allostratigraphy is one method of describing and evaluating basinwide or interbasinal cycles. Allostratigraphic units are mappable units bounded by discontinuities that reflect extrinsic processes that "...initiate and terminate the deposition of a sedimentologically related succession of facies" (Walker, 1992, p. 9). Commonly used bounding surfaces include disconfomities and the tops of paleosols (North American Commission on Stratigraphic Nomenclature [NACSN], 1983). Allostratigraphy is distinguished from sequence stratigraphy in that it is descriptive. There are no implicit assumptions regarding which specific processes caused the stratigraphic features.

Sequence Stratigraphy

Currently, there are two conceptual frameworks for sequence stratigraphy. One developed by Exxon researchers uses unconformities as the boundaries of sequences (Vail et al., 1977; Van Wagoner et al., 1988), whereas the other uses maximum flooding surfaces as genetic sequence boundaries (Galloway, 1989). Both types of sequences include the deposits of one complete relative sea level cycle.

Sequence-stratigraphic concepts provide a powerful tool for unraveling the evolution of sedimentary basins by dividing the basin fill into genetic packages (Van Wagoner et al., 1988). Recognition of individual sequences requires identification of subaerial unconformities of regional or interregional extent and their correlative marine unconformities and conformities. The deposits of depositional systems become progressively stacked to form sequences as a result of the interplay among subsidence, sediment input, and sea level change. Sequence stratigraphy provides a chronostratigraphic framework for the correlation and mapping of sedimentary facies. It also acts as a tool for stratigraphic prediction (Emery and Myers, 1996). A potential problem in employing sequence-stratigraphic analysis is the assumption of eustatic control, particularly where other potentially overriding allocyclic factors may be involved (Walker, 1992).

Type 1 sequence boundaries are the most common type of boundary in siliciclastic basins (Van Wagoner et al., 1990). They are laterally continuous, basinwide or interbasinal surfaces that are distinguished in shelf settings by the presence of erosional truncation, subaerial exposure, and a basinward shift in facies. Incised drainage lines formed during lowstands of sea level produce erosional truncation. The erosional surface associated with incised valleys passes laterally

into a correlative paleosol formed during subaerial exposure (Van Wagoner et al., 1990). These paleosols represent ''condensed sections'' formed in terrestrial settings caused by low rate of deposition or nondeposition. Avulsion of channel systems out of an area may cause local paleosol development, but widespread, strongly developed paleosols are more likely to form from extrinsic controls on sediment input. Rejuvenation and incision of rivers would reduce or sharply eliminate sediment to interfluvial uplands and would be expected to accompany falling base level.

Valley fills are elongate cut-and-fill bodies that are larger than a single channel and may be formed by relative sea level changes, inland tectonic uplift, and climate change (Dalrymple et al., 1994). Paleovalley fills range from 8 to 100 m (26 to 328 ft) thick and from 0.5 to 64 km (0.3 to 40 mi) in maximum width (Schumm and Ethridge, 1994). In valley fills formed by relative sea level change, the valley wall and floor represent type 1 sequence boundaries, and the fills typically include some evidence for marine influence. Simple valley fills are produced by a single relative sea level cycle. In compound valley fills, more than one sea level cycle may take place during valley filling. This can produce a complex mixture of fluvial facies of varying styles, estuarine facies, and possibly shallow-marine facies in the valley fill.

Channel fills may also develop during regression as coastal plain drainage systems override shoreline and shallow-marine deposits. In these cases, channel sands will represent coarse members in coarsening-upward sequences deposited during sea level highstands. This pattern of sedimentation is commonly terminated by a fall in base level and fluvial incision (Miall, 1997).

Avulsion events could introduce channel systems into flood basins producing incision. In this instance, the depth of incision probably would not exceed the channel depth if this took place in a highstand systems tract (HST). Channel deposits of this type would differ from those produced during lowstand incision and infilling during transgressive systems tract (TST), in that greater relief in the latter would be expected along the erosional sequence boundary.

Previous Work on Pennsylvanian Depositional Cycles of the Central and Northern Appalachian Basin

Depositional cycles have been recognized in the Pennsylvanian strata of the Appalachian basin since the 1930s (Weller, 1930; Stout, 1931; Wanless and Weller, 1932). Eight cycles (cyclothems) were distinguished in the Glenshaw portion of the Conemaugh Group in Ohio (Sturgeon and Hoare, 1968). Wanless and Shephard (1936) attributed these types of cycles to global sea level changes caused by fluctuations in ice volume of Gondwanan ice sheets.

Through the 1960s and 1970s, an increasing awareness of inherent behavior of alluvial and deltaic depo-systems led many workers to reinterpret cyclothems previously distinguished in the Appalachian basin as autocyclic in origin (e.g., Ferm, 1970; Donaldson, 1979). Attempts to correlate mid-continent cycles with those in the Appalachian basin were inhibited by lack of a detailed biostratigraphic framework for the Appalachian basin, and by the prevailing view that eustasy would be masked or overshadowed by tectonic and/or autocyclic processes that were not prevalent in other cratonic basins.

During the 1980s, conflicting views emerged regarding the presence and origin of Glenshaw cycles. Busch (1984) and Busch and Rollins (1984) described 11 fifth-order, allocyclic, T-R units associated with the Glenshaw Formation. Their proposed cycles closely corresponded to cyclothems that were described earlier (Flint, 1951; Sturgeon and Hoare, 1968). The T-R cycles of Busch and Rollins are 5–30 m (16–98 ft) thick and were interpreted to have resulted from glacioeustatic sea level changes. Their study was based mainly on data from Ohio and Pennsylvania in the northern portion of the Appalachian basin. Busch and West (1987) included both T-R units and climate-change surfaces in their fifth-order allocycles. Climate-change surfaces were defined as contacts between continental strata formed under arid subaerial conditions (e.g., aridosols and vertisols) and overlying coal and lacustrine limestone formed under more humid conditions. Busch and West (1987) correlated the Glenshaw allocycles with those known from the mid-continent, maintaining that they were the product of glacioeustasy.

Heckel (1995) also correlated Appalachian basin allocycles with mid-continent cycles. He used conodonts and palynomorphs and attributed both T-R cycles and climate-change cycles to a glacioeustasy. Veevers and Powell (1987) indicated that the maximum extent of glacial ice on Gondwanaland occurred during the late Pennsylvanian. Heckel (1995) maintained that moisture needed to feed the wet portions of cycles in totally nonmarine sequences was provided by the proximity of greatly expanded cratonic seas produced during glacioeustatic highstands. Heckel's work relied largely on the stratigraphic foundation of Busch (1984) and Busch and Rollins (1984),

which was developed in the northern Appalachian basin.

Cyclic variations in paleoclimate are thought by some to be reflected in late Pennsylvanian, 100,000–400,000-yr sedimentary cycles recorded in the Appalachian basin (Cecil, 1990; Cecil et al., 1994; Cecil and Dulong, 1998). The wetter portions of the cycles were interpreted as sea level lowstand phases and are represented by laterally extensive coal beds deposited in topographic lows and contemporaneous upland ultisol-like paleosols. Drier portions of the climate cycles were thought to be recorded by lacustrine limestone that grades laterally into highly calcareous paleovertisols formed during sea level highstands. This perspective sharply contrasts with those expressed by Busch and Rollins (1984), Busch and West (1987), and Heckel (1995), who maintained that wetter climate phases corresponded to highstands, whereas increased dryness was associated with lowstands.

Merrill (1986) described the lithostratigraphy of Conemaugh outcrops along the West Virginia–Kentucky border. He concluded that the cyclothem concept could not be applied to Conemaugh strata in this area because of the limited lateral extent of individual lithosomes and packages of lithosomes. He favored Ferm's (1970) view that differential rates of deltaic growth and abandonment generally caused the development of aerially limited marine units. Martino et al. (1996) argued that whereas individual beds (such as a particular marine limestone) were commonly laterally restricted, genetic packages of strata did appear to be widely developed in the southern Dunkard basin.

Donaldson and Eble (1991) interpreted the Conemaugh Group to contain (1) an intermediate allocycle 90 m (295 ft) thick and 3.5 m.y. long resulting from tectonic processes (uplift/thrust loading) and (2) minor allocycles with an average duration of 0.4 m.y., which were probably caused by glacioeustatic sea level fluctuations. These minor allocycles correspond to the fifth-order cycles of Busch and Rollins (1984). Donaldson and Eble (1991) suggested that autocycles formed by river avulsion could occur embedded in minor allocycles.

STATEMENT OF THE PROBLEM

The preceding literature review indicates not only considerable interest but also varied viewpoints concerning the presence, character, and origin of Glenshaw depositional cycles. Many workers (Wanless and Shepard, 1936; Busch and Rollins, 1984; Busch and West, 1987; Heckel, 1995) maintain the predominance of eustatic sea level changes (over tectonic and climatic factors) in causing allocycles. If correct, then Exxon's sequence-stratigraphic approach would be appropriate. However, a significant portion of the Appalachian basin (West Virginia, Kentucky, southernmost Ohio) remains understudied at the scale needed to verify the basinwide extent of these cycles and the dominance of eustasy in their origin.

Problems addressed by this study include the following:

1) Are there widely developed depositional cycles in the central Appalachian basin?
2) If present, can they be correlated with those distinguished in the northern part of the basin (Busch and Rollins, 1984)? If not, what factors differed in the central portion of the basin that could account for this? If depositional sequences are distinguishable, can they be correlated with those distinguished in other basins, strengthening the case for eustasy as the dominant controlling factor?
3) What expression (if any) do these cycles have in entirely nonmarine sections of the Conemaugh in the interior regions of West Virginia? Can sequence-stratigraphic elements be distinguished and correlated toward the southeast into entirely terrestrial facies?

RESULTS AND DISCUSSION

Genetic Facies Assemblages

Glenshaw outcrops used in this study (Figure 4) consist mainly of road cuts in the central Appalachian basin. Glenshaw sedimentary facies can be grouped into the following broad divisions: fluvioestuarine channel, coastal plain flood basin, and shallow to marginal marine. A summary of their characteristic features is given in Table 1.

Large-scale Channel-fills

Fluvial and deltaic channels consist of channel-form bodies with unimodal paleoflow as indicated by cross-bedding (Figure 5). The mean flow direction is toward the north-northwest, which is away from the Alleghanian orogen and consistent with fluviodeltaic reconstructions of earlier workers (Arkle, 1974; Donaldson, 1979; Donaldson et al. 1985). Local flow directions range from west to northeast; such variability is likely in high-sinuosity channel systems and

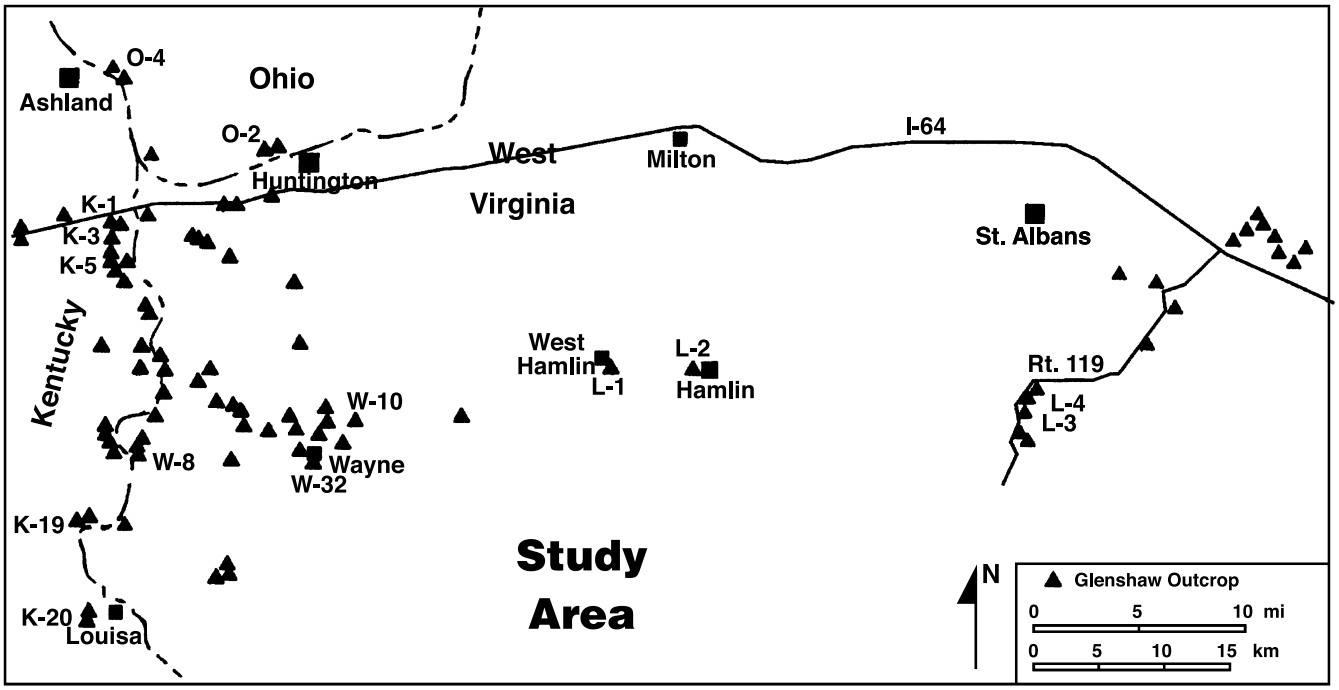


Figure 4. **Outcrop locations from Kentucky, Ohio, and West Virginia that were used in this study. Stratigraphic sections were measured and described at each location. See Figure 3 for regional perspective. Labeled locations are used in cross sections or photos.**

radiating deltaic distributaries. Channel sandstones commonly exhibit large-scale bar accretion surfaces that commonly dip at a high angle (e.g., 70–90°) with respect to the paleoflow directions indicated by internal cross-strata, a feature that is common in meandering channel systems. Mud-filled channels resulted from avulsion and channel deactivation. In meandering systems, this produces oxbow lakes. Both single-story and multistory channel fills are common (Figures 6, 7).

A deltaic origin is indicated where the channel system directly influenced the underlying or laterally equivalent marine facies. This would be evidenced by subaqueous splays or levees that thicken laterally toward the channel facies, or by mouth bar deposits that are localized in the vicinity of the channel system. A good example of this occurs in the lower Brush Creek marine zone near Wayne, West Virginia (Figure 4, W-10) (Martino et al., 1996).

Estuarine channel fills of the Glenshaw closely resemble those of fluvial channels in most respects. They are distinguished by the presence of cross-bedding with clay-draped foresets, cross-bedding with southeastward flow (up the paleoslope; Figure 5), and by parallel-laminated silt-clay couplets that exhibit thick and thin bundling (Figure 8A). These features develop in tidal settings as the result of periodic slackwater periods and varying competence associated with daily, fortnightly, monthly, and seasonal tidal cycles. Similar estuarine channel deposits have been recognized in the middle Pennsylvanian Kanawha Formation of southern West Virginia (Martino, 1996).

Flood-Basin Facies

Low-lying areas between active drainage lines consist of a mosaic of depositional environments, including lakes, splay channels and levees, and clastic and peat swamps. These facies have been modeled previously in detail for Pennsylvanian strata in the Appalachian basin in the context of fluvially dominated deltaic deposystems (e.g., Horne et al., 1978; Donaldson, 1979).

Splay and levee sandstone wedge out away from active fluvial and distributary channels. Internal textures and structures indicate waning flow and deposition of single or stacked flood deposits.

Dark gray shales that overlie and laterally intergrade with coals commonly contain plant fossils and lack root traces, and are interpreted as clastic lacustrine deposits. Nonmarine limestones, such as the Twomile Limestone of I. C. White (1885), have been

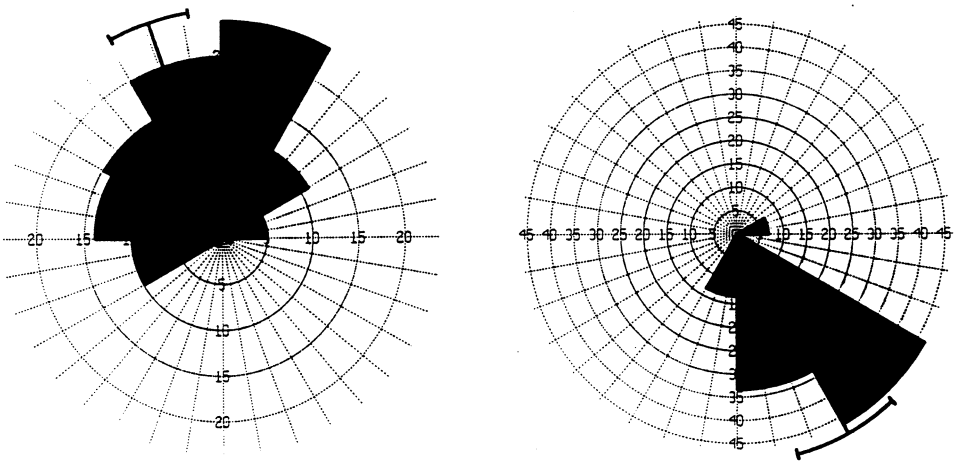
Table 1. Summary of Glenshaw facies attributes.

Facies	*Lithology*	*Sedimentary Structures*	*Geometry*	*Fossils*
Fluvial and deltaic channel	very fine to very coarse sandstone, uncommonly conglomeratic; shale/mudstone plugs	cross-stratification: trough + tabular sets; compound (epsilon) cross-beds; laminated/ hackly	channel-form ribbon; 6–10 m (20–33 ft) thick	uncommon burrows; plants
Estuarine channel	medium to very fine sandstone	cross-stratification with clay-draped foresets; southeast flow parallel lamination with thick to thin bundles	6–10 m (20–33 ft)	uncommon burrows
Flood Basin				
(1) Crevasse splay/levee	fine to very fine sandstone-shale	scour-fill trough sets, ripple cross-lamination; parallel lamination	tabular-wedge shaped; channels 1–4 m (3.3–13 ft) thick	plant fragments *Lockeia*, *Limnopus* *Sinusites*, *Diplichnites*
(2) Lakes	shale, siltstone, micritic limestone	laminated to massive	pods, sheets	ostracodes, *Spirorbis*, Conchostracans plants, coprolites, stromatolites, vertebrate fragments
(3) Mires	coal, carbonaceous shale	laminated	pods, sheets	
Offshore marine	shale, limestone, siltstone	thin-bedded, graded bedding	sheets	brachiopods, bivalves, gastropods, echinoderms, bryozoans, cephalopods, conodonts, fusilinids
Shoreface	shale, siltstone, very fine sandstone	thin-bedded, ripple bedding, parallel lamination, hummocky cross-stratification	elongate/lobate	*Wilkingea*, *Paleophycus*, *Aulichnites*, *Teichichnus*, *Rhizocorallium*
Mouth bar	shale, siltstone, very fine sandstone, siderite nodules	thin-bedded, parallel lamination, graded bedding, parting lineations, hummocky cross-stratification	lobate	*Curvolithus*, plant fossils
Sand bar/shoal	very fine sandstone	highly bioturbated; uncommon trough cross-stratification	elongate	crinoids, brachiopods, gastropods +

recognized in the study area (Henry and Gordon, 1979; Merrill, 1986). The occurrence of micritic lacustrine limestone has been attributed by previous workers to drier climates (Cecil et al., 1985; Cecil 1990). However, lacustrine carbonates can also form under more humid climatic settings (Talbot and Allen, 1996). Glenshaw facies sequences suggest both carbonate and clastic lake development took place during transgressive stages and associated rising water tables. The water table in tropical settings has been correlated with Milankovitch climate cycles (Kutzbach and Street-Perrott, 1985); lowered water table and dry conditions occur during high-latitude glaciation, whereas rising water tables and formation or deepening of lakes occurs during interglacial stages.

Marine Facies

Marginal-marine facies generally lack body fossils except for occasional burrowing bivalves like *Wilkingea* that could cope with pulses of rapid deposition. Trace fossils, such as *Paleophycus*, *Aulichnites*,



Calculation method	Frequency
Class interval	30°
Filtering	deactivated
Data type	unidirectional
Rotation amount	0°
Population	101
Maximum percentage	23.8%
Mean percentage	11.1%
Standard deviation	7.92%
Vector mean	341.12°
Confidence interval	10.3°
R-mag	0.66

Calculation method	Frequency
Class interval	30°
Filtering	deactivated
Data type	unidirectional
Rotation amount	0°
Population	15
Maximum percentage	46.7%
Mean percentage	25%
Standard deviation	18.36%
Vector mean	150.92°
Confidence interval	13.94°
R-mag	0.89

Figure 5. **Paleocurrent roses and statistical data for fluvio-estuarine channels. Unimodal flow occurs in individual channel fills, and most exhibit fluvial or ebb tide-dominated flow toward the northwest (left rose). Local occurrence of flood-dominated (southeastward) flow occurs in tidal channel and sand-flat facies in the Mahoning Sandstone (right rose).**

Teichichnus, and *Curvolithus*, are useful indicators of marine influence. Hummocky cross-stratification and symmetric ripple bedding from shoreface deposits reflect wave-generated currents, but their rarity and the generally thin nature of sandy nearshore facies probably reflect limited wave energy that would be expected for a narrow seaway located on the equator in the doldrums. Distributary mouth bar deposits, such as those in the lower Brush Creek marine zone, produce local thickening and coarsening in the marine unit that is laterally limited to 1–2 km (0.62–1.24 mi) along depositional strike (Figure 8C). Offshore marine shales and limestones contain stenohaline marine invertebrates (Table 1).

Various depth-related biofacies have been recognized in Pennsylvanian cyclothems (Boardman et al. 1984) that can be used to help delineate the maximum flooding surface. In the lower Brush Creek T-R cycle, a vertical succession of biofacies dominated by (1) *Lingula*, (2) nearshore mollusks, and (3) open-marine stenotopic organisms defines progressively deeper water in the upper portion of the TST, whereas the HST is generally barren of macrofossils because of increased rate of deposition, turbidity, and/or dilution. Locally, the base of the lower Brush Creek HST contains a return to the nearshore molluskan association.

Paleosols

Recognition of paleosols is based on the presence of soil horizons, soil structure, and/or root traces (Retallack, 1988). Glenshaw paleosols are very distinctive in outcrop because of their easily weathered, hackly, variegated appearance and horizonization (Martino, 1992) (Tables 3–5). The paleosol type and degree of development are important in assessing its paleoclimatic and sequence-stratigraphic significance.

The developmental stage that a paleosol has reached is a significant indicator of exposure time, although parent material composition and soil type also need to be considered. Glenshaw paleosols developed on mixed clayey and sandy alluvium and less commonly on sand-clay mixtures of marine facies. Thin paleosols that lack horizons, lack well-developed soil structure, and contain preserved primary stratification disturbed by root traces that represent very weak development and relatively brief periods of slow or no deposition. In weakly to moderately developed soils, peds and cutans are found, but primary stratification persists. Strong soil development results in obliteration of bedding, whereas in very strong development, the clayey (Bt) horizon is significantly thicker than 1 m (3.3 ft) and is commonly associated with major geological unconformities (Retallack, 1990) (Figure 9; Table 2).

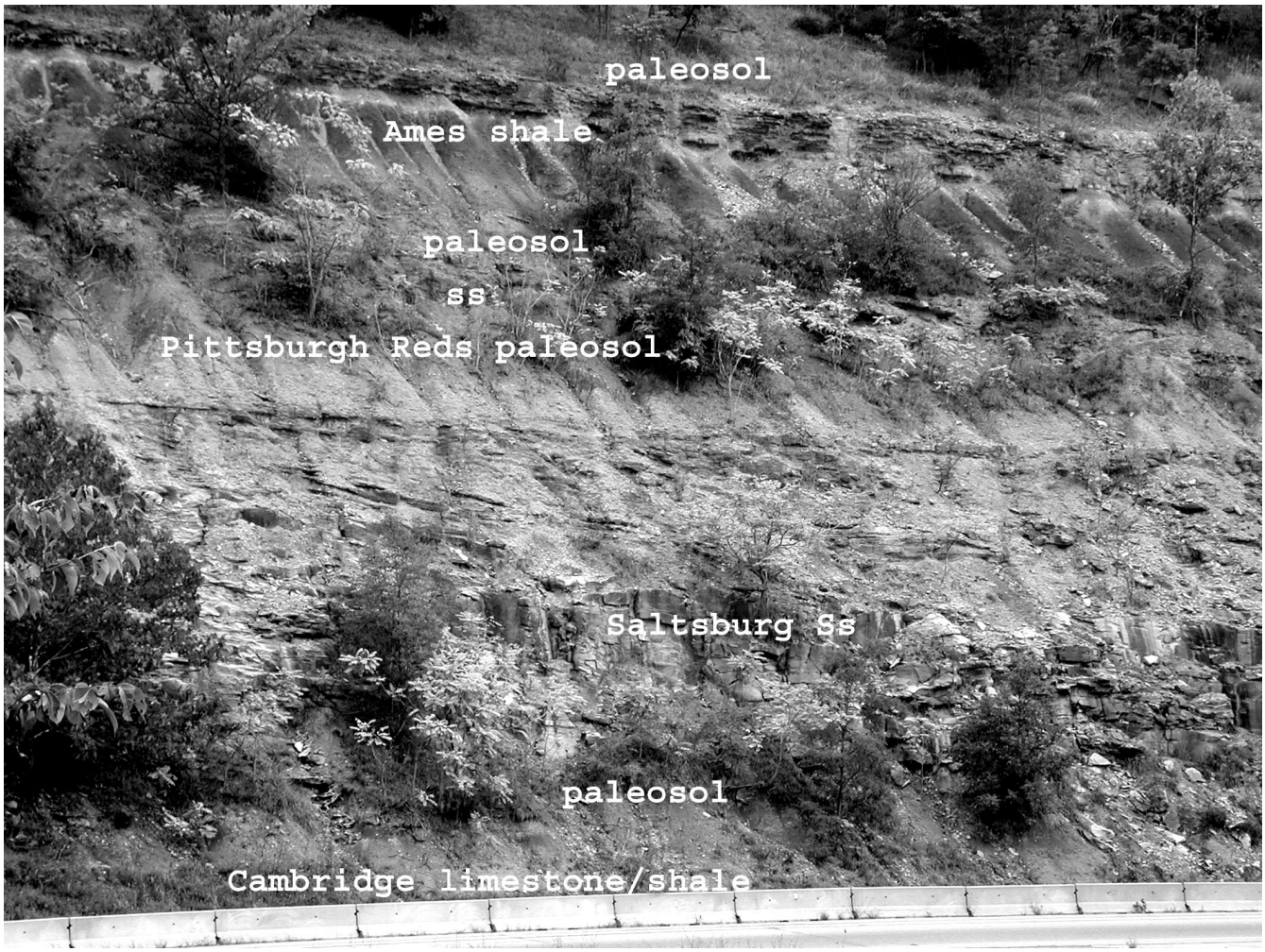


Figure 6. **Roadcut near Chesapeake, Ohio (location O-2) exposing about 30 m (98 ft) of Glenshaw strata from the Cambridge Limestone through the Ames Limestone and shale at the top of the cut. Note the large-scale accretion surfaces in the Saltsburg Sandstone, a fluvial-estuarine channel fill about 10 m (33 ft) thick.**

Entisols (very weakly developed) and inceptisols (weakly developed; Retallack, 1988) (Figure 9) are laterally discontinuous in Glenshaw flood-basin facies. Good examples occur between the upper Freeport and Brush Creek coals. These soil types typically form over brief periods of time (tens to hundreds of years; Retallack, 1990). Histosols are distinguished by thick surface organic (O) horizons and are represented by coals and carbonaceous shales where the precompaction thickness was at least 40 cm (15.7 in.). Histosols develop in low-lying, poorly drained areas where organic production exceeds decomposition. The local, pod-like geometry of many Glenshaw coals (e.g., Mahoning and Wilgus coals) suggests a rolling or undulatory topography.

Most of the strongly developed paleosols in the Glenshaw exhibit features associated with vertisols and aridosols (Tables 3–5). An excellent example has been described from above the Saltsburg Sandstone along Route 23 at Savage Branch, Kentucky (Martino, 1992) (Figure 8D; Table 3). The paleosol is 5.17 m (17 ft) thick at this location and is a widespread unit that correlates with the Pittsburgh shale of West Virginia and western Pennsylvania and the Round Knob shale of Ohio. It contains hummock-and-swale structure (mukkara), prominent slickensides and clastic dikes, and evidence of abundant swelling clay; these features are characteristic of vertisols (Retallack, 1988). The profile also contains features that develop in aridosols, including high Munsell values and extensive pedogenic carbonate (caliche). Vertisols are uniform, thick (>50 cm [>20 in.]), clay-rich paleosols with deep wide cracks for part of the year. Hummock-and-swale topography (i.e., gilgai microrelief) results from swelling and upward-buckling of the soil along hummocks with deep fissures (Retallack, 1990). The swales

Figure 7. **Outcrop along Kentucky State Route 23 about 8 mi (13 km) south of Ashland (K-3). Multistory fluvial-estuarine channel complex represents Saltsburg and possibly Buffalo Sandstones. A mud-filled, abandoned channel is exposed in the first story (right). Lateral accretion surfaces are evident in the upper story. The three stacked channels are 26 m (85 ft) thick and are capped by thick paleosol of the Pittsburgh shale at the top of the cut.**

may receive sediment eroded from adjacent hummocks, as well as chemical precipitates from ephemeral lakes. The concave-upward lenses of carbonates at the top of the paleosol appear to represent the latter. Seasonal deposition of carbonate-filled fractures as alkaline waters filled deep open fissures (Figure 8D). The carbonate lenses are spaced laterally at regular intervals of about 6–7 m (20–23 ft) along the outcrop. Conjugate systems of slickensides also developed as a result of clay heave.

Vertisols typically are associated with low-relief terrain and subhumid to semiarid climates (18–152 cm [7–60 in.] rainfall/yr) with a pronounced dry season. Aridosols develop in semiarid to arid regions and commonly have shallow calcareous horizons (Retallack, 1990). Vertisols may develop in as little as a few hundred years on smectitic claystones and shales, whereas strongly developed aridosols require tens of thousands of years to develop (Birkland, 1984; Retallack, 1990).

Compound paleosol zones occur where individual paleosol units are vertically stacked. Two kinds of paleosol zones occur in the Glenshaw Formation: (1) stacked paleosols of the same type and (2) stacked profiles representing two different types of soils. In both cases, pedogenesis was interrupted by influx of sediment. The first type is evident in multiple-bedded coal seams with rooted shale or sandstone splits. Stacking of well-drained paleosols (aridosols/vertisols) also occurs. The second type of paleosol zone is commonly represented by aridosols or vertisols that are capped by histosols. These zones represent two phases of soil development and reflect a rise in water table, which, in many cases, was associated with rising sea level (indicated by shallow-marine to estuarine roof rock). Previous workers have recognized these types of compound paleosols elsewhere in late Pennsylvanian strata of the Appalachian basin (Cecil, 1990; Fedorko, 1998).

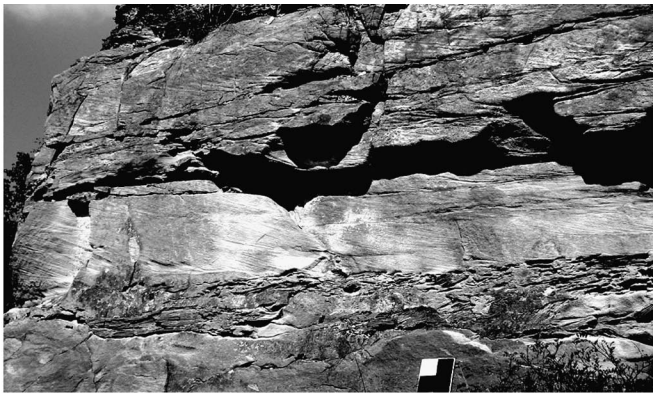
Glenshaw Sequence-stratigraphic Model

The development of a Glenshaw stratigraphic sequence can be illustrated using the model shown in Figure 10:

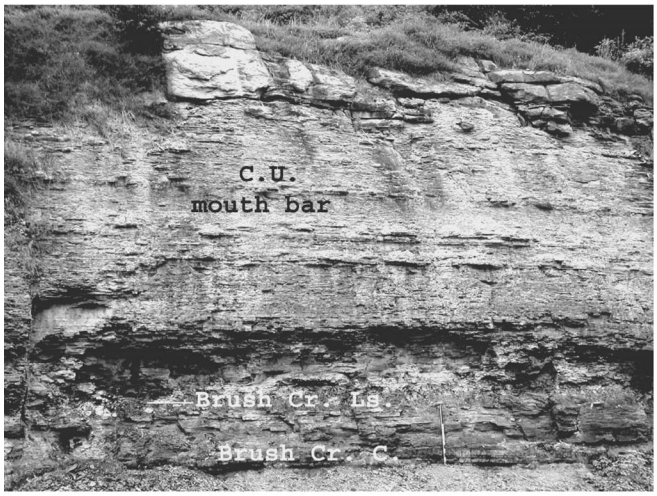
1) During lowered base level associated with sea level lowstands, coastal plain rivers downcut 20–35 m (66–115 ft), which led to valley incision. Sediment

A

B

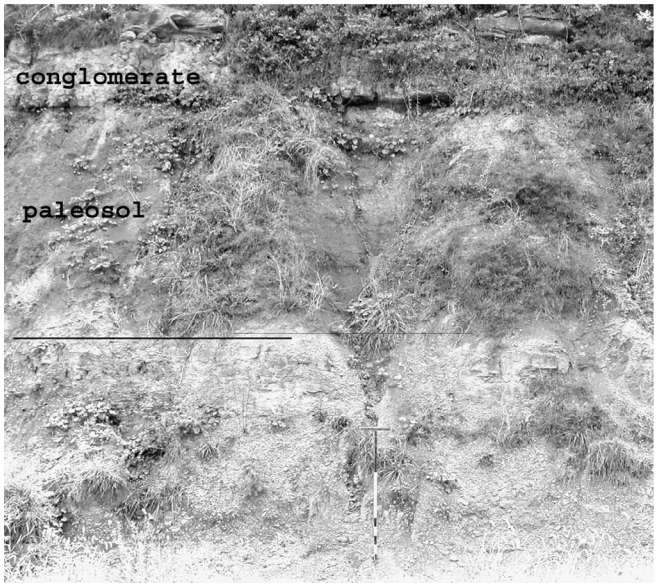


C


C.U.
mouth bar
Brush Cr. Lg.
Brush Cr. C.

D

E


conglomerate
paleosol

F


limestone cobble

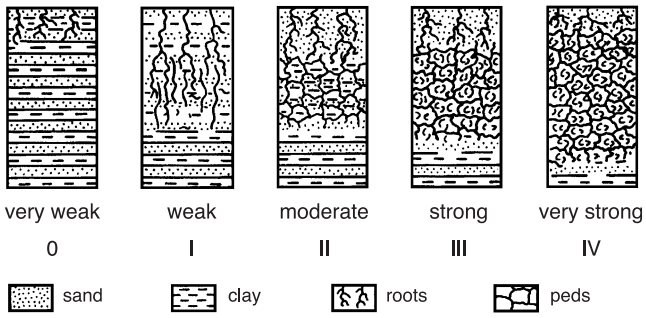


Figure 9. **Stages in the formation of clayey subsurface soil horizons (Bt) in mixed clayey and sandy alluvium (from Retallack, 1990).**

bypassing of interfluves led to pedogenesis. The lower water table (following falling river and sea level) caused well-drained conditions for soil development. A type 1 sequence boundary formed, which is marked by an erosional disconformity along paleovalley and by a nondepositional disconformity on the interfluves (top of a well-drained, mature paleosol).

2) Rising sea level and base level initiated aggradation of fluvial system in paleovalley (lowstand systems tract [LST]); pedogenesis continued on interfluves, which allowed the maturation of vertisols and aridosols.
3) Continued rise in sea level or base level led to a rising water table; standing shallow water resulted in peat accumulation where clastic influx remained low; late-stage valley-fill associated with high-sinuosity streams commonly preserves evidence of tidal influence (TST). Completion of valley filling allowed alluvium to spread out over interfluves that had been sediment starved up to that point. Clastic and carbonate lakes developed in the coastal plain where water depth became too great to support standing vegetation, whereas in downdip locations, marginal to shallow-marine environments onlapped interfluvial paleosols and valley fills (TST).
4) During sea level highstand, rapid aggradation of the coastal plain occurred in association with high accommodation space. This produced isolated, high-sinuosity fluvial channel deposits encased in overbank fines (Shanley and McCabe, 1993) (Figure 11). Regression occurred in marine units during highstand once estuarine sediment sinks became filled. Deltaic channel fills and mouth bars formed locally during late highstand.
5) Incision of fluvial drainage lines into HST coastal plain and sea-fill deposits occurred in response to falling sea level or base level. Between rivers, withdrawal of the sea led to erosion or exposure and pedogenesis of shallow-marine or flood-basin facies, which produced the next sequence boundary.

Rising base level that allowed infilling of valleys also ultimately led to peat accumulation. Coal beds that formed in this way would develop across the region, but the same seam would overlie well-drained paleosols on former interfluves interfluvial sequence boundary (ISB) and hydromorphic paleosols above the valley fills (Figure 10).

A characteristic feature of Glenshaw paleosols that mark sequence boundaries is that they exhibit evidence of well-drained conditions followed by ''drowning.'' This is illustrated by the facies sequence (1) vertisol or aridosol, (2) coal/histosol, (3a) lacustrine shale and/or limestone, or (3b) marine shale and/or limestone. In some cases, facies sequence 2 is missing, and lacustrine or marine facies directly overlie a vertisol or aridosol. This indicates an initially low water table that subsequently rose to inundate the topography. Busch (1984) described similar Glenshaw paleosols representing allocycle boundaries in the northern Dunkard basin. Rising sea level may have led to a wetter climate, which also helped to raise the water table in the coastal plain (Busch, 1984; Busch and West, 1987; Heckel, 1995).

In cases in the Glenshaw Formation where relief produced by channel incision is less than 10 m (33 ft), HST avulsion channel fill would be difficult to distinguish from LST/TST incised-valley fills (IVFs). If facies reflected rising sea level were found (braided fluvial to meandering fluvial to estuarine), a LST/TST origin

Figure 8. **(A) tidal rhythmites in Mahoning Sandstone along West Virginia State Route 52 south of Prichard (W-8). Scale divisions are 5 cm (2 in.). (B) Tabular planar cross-beds from estuarine sand-flat facies, Mahoning Sandstone. (C) Coarsening-upward distributary mouth bar sequence in lower Brush Creek cyclothem along Kentucky Route 23, about 8 mi (13 km) south of Ashland (K-4). Jacobs staff = 1.5 m (4.9 ft). (D) Paleovertisol 5.17 m (17 ft) thick (=Pittsburgh shale) along Kentucky Route 23, about 9 mi (14.5 km) south of Ashland Conjugate shears are filled with micrite (K-7). (E) Stacked paleosol zone along Kentucky State Route 3 about 6 mi (6.7 km) south of Ashland (K-1). Paleosol and overlying Brush Creek coal truncated by a 1.5-m (5-ft)-thick cobble conglomerate. (F) Conglomerate in (E). Note limestone cobble at left, probably from upper Brush Creek Limestone. Scale divisions are 5 cm (2 in.).**

Table 2. Stages of paleosol development.*

Stage	*Features*
Very weakly developed	little evidence of soil development except for root traces; abundant sedimentary textures remaining from parent material
Weakly developed	with a surface-rooted zone (A horizon) as well as incipient subsurface clayey, calcareous, sequioxidic or humic, or surface organic horizons, but not developed to the extent necessary for qualification as a U.S. Department of Agriculture (USDA) argillic, spodic, or calcic horizon or histic epipedon
Moderately developed	with surface-rooted zone and obvious subsurface clayey, sequioxidic, humic or calcareous, or surface organic horizons: qualifying as USDA argillic, spodic or calcic horizon or histic epipedon and developed to an extent at least equivalent to stage II carbonate accumulation (few to common carbonate nodules and veinlets with powdery and filamentous carbonate in places between nodules)
Strongly developed	with especially thick, red, clayey, or humic subsurface (B) horizons or surface organic horizons (coals or lignites) or especially well-developed soil structure or calcic horizons at accumulation stages III–V (III: carbonate forming continuous layer comprised of coalescing nodules with isolated nodules and powdery carbonate outside main horizon; IV: upper part of carbonate layer with weakly developed platy or lamellar structure capping less pervasively calcareous parts of the soil profile; and V: platy or lamellar cap to carbonate layer strongly expressed, brecciated in places, and with pisolites of carbonate)
Very strongly developed	uncommonly thick subsurface (B) horizons or surface organic horizons (coals or lignites) or calcic horizons of accumulation stage VI (brecciation and recementation, as well as pisoliths common in association with the lamellar upper layer): such a degree of soil development is mostly found in major geological unconformities

**Modified from Retallack, 1990.*

Table 3. Paleosol description for Pittsburgh shale along Route 23, milepost 7.9.*

Depth of Paleosol [in Centimeters]	*(Horizon)*	*Composition/features*
0–1.3	(A)	mudstone, dark greenish gray (N4 5GY 4/1), noncalcareous, sharp erosional upper contact
1.3–14	(A)	mudstone, dark greenish gray, weathers greenish gray, noncalcareous; laterally equivalent to light gray micritic limestone lenses which are concave-upward, and laterally spaced at 4.8–5.6-m (16–18-ft) intervals
14–144	(Bk)	claystone, dark greenish gray (N4 5GY 4/1), moderately to strongly calcareous; micritic carbonate present as infillings of steeply inclined fractures 3.8–5.1 cm (1.5–2 in.) in width, and as greenish gray (N6 5 GY 6/1) to light gray (N7 5Y 7/1) nodules
144–296	(Bk)	mudstone, variegated, dusky red (7.5 YR N 4/2) and dark greenish gray (N4 4GY 4/1); weakly to moderately calcareous; slickensides common to abundant; fine to medium angular blocky peds; micritic carbonate nodules (light gray to greenish gray)
296–357	(K)	micritic limestone, gray (N6 5Y 6/1) with angular fragments of greenish gray (N5 5G 5/1), calcareous mudstone; comprised of coalescing nodules
357–517	(C)	sandstone, fine grained, calcareous, sideritic; clastic dikes(?); micritic and sideritic nodules; calcite-filled fractures at top

**All Munsell colors are from fresh, unweathered surfaces (from Martino, 1992).*

Table 4. Description of paleosol directly beneath Ames Member, Route 23, Savage Branch.*

Depth of Paleosol [in Centimeters]	*(Horizon)*	*Composition/features*
0–2	(O)	coal, bright, mostly vitrain/clarain
2–17	(E)	underclay, gray (N6) with yellow-brown mottles; platy soil structure, uncommon slickensides
17–112	(Bt)	claystone, dark gray (N4) in upper part to dark greenish gray (N4 5GY 4/1) in lower part; black metallic staining [manganese(?)]; small ironstone nodules (2–3 mm [0.07–0.12 in.]); siderite nodules in lower part; generally noncalcareous except for micritic nodules up to 5 cm (2 in.) in diameter in lower 15 cm (6 in.)
112–127	(K)	micrite, dark greenish gray (N4 5GY 4/1), light greenish gray, and weak red (10R 4/3), angular fragments
127–187	(Bk)	mudstone, dark greenish gray (N4 5GY 4/1), moderately calcareous, sandy, with blocky angular peds
187–197	(K?)	micritic limestone, brecciated

**Milepost 8.1; Martino, 1992.*

would be favored. Where relief along the erosional surface is greater than 10 m (33 ft), a LST/TST IVF also would be more likely.

Sequence-stratigraphic Analysis of Glenshaw Formation

A generalized illustration of Glenshaw stratigraphy is given in Figure 12. Nine fifth-order stratigraphic sequences are identified. The tops of well-drained paleosols are sequence boundaries and correspond to allocycles previously reported by Martino (1998) (Figure 13). Sequence boundaries and systems tracts are numbered in vertical succession (SB1, LST1, TST1, HST1; SB2, LST2, etc.).

The first depositional sequence identified in this study begins in the upper Allegheny Formation and is well exposed in Ohio Route 52 roadcuts near Ashland, Kentucky (Figures 4, O-4; 14; 15). Multistory

Table 5. Paleosol directly above Ames Member, Route 23 milepost 8.4.*

Depth of Paleosol [in Centimeters]	*(Horizon)*	*Compostion/features*
0–0.5	(O)	carbonaceous shale, claystone, dark gray (N4), sharp upper contact with overlying crudely bedded, greenish gray mudstone
0.5–38	(E)	claystone, greenish gray (N5 5G 5/1), silty, with dark greenish gray peds and brownish gray cutans; slickensides common; peds 1–2 cm (0.4–0.8 in.) in diameter and subangular
38–118	(EB)	claystone, greenish gray (N5 5G 5/1) to dark greenish gray (N5 5GY 5/1), with subordinate weak and dusky red mottles (7.5 YR 4/2 and 7.5 YR 3/2); angular blocky peds, transitional top and base; weakly calcareous with 1–2 mm (0.04–0.08 in.) carbonate nodules
118–228	(Bt)	claystone, dusky red (10R 3/3) to olive (5Y 4/3), weakly to moderately calcareous; well-developed soil structure, including angular blocky peds 1–4 cm (0.4–1.6 in.) in diameter with red clay cutans; abundant slickensides
228–238	(B)	clay, light olive green, plastic
238–298	(B)	mudstone, dark greenish gray, with angular peds
298–318	(B)	clay, light olive green, weathers rust orange
Top of Ames Member, very fine sandstone.		

**Martino, 1992.*

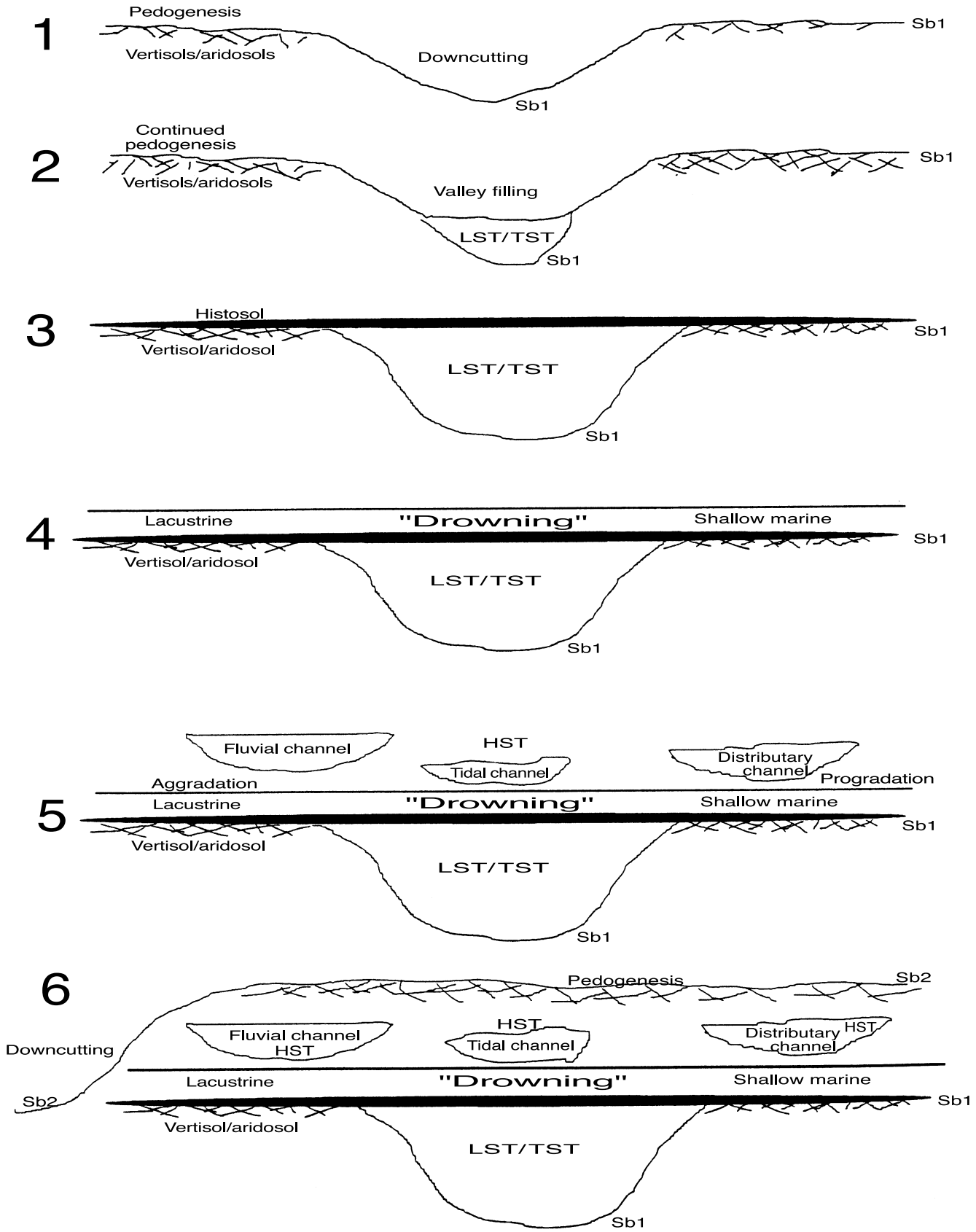


Figure 10. Sequence-stratigraphic model for Glenshaw Formation. Sequence boundaries (Sb) developed at the top of well-drained paleosols formed on interfluves during lowstands and then passed laterally into erosional disconfomities of incised valleys. LST, TST, and HST are lowstand, transgressive, and highstand systems tracts, respectively.

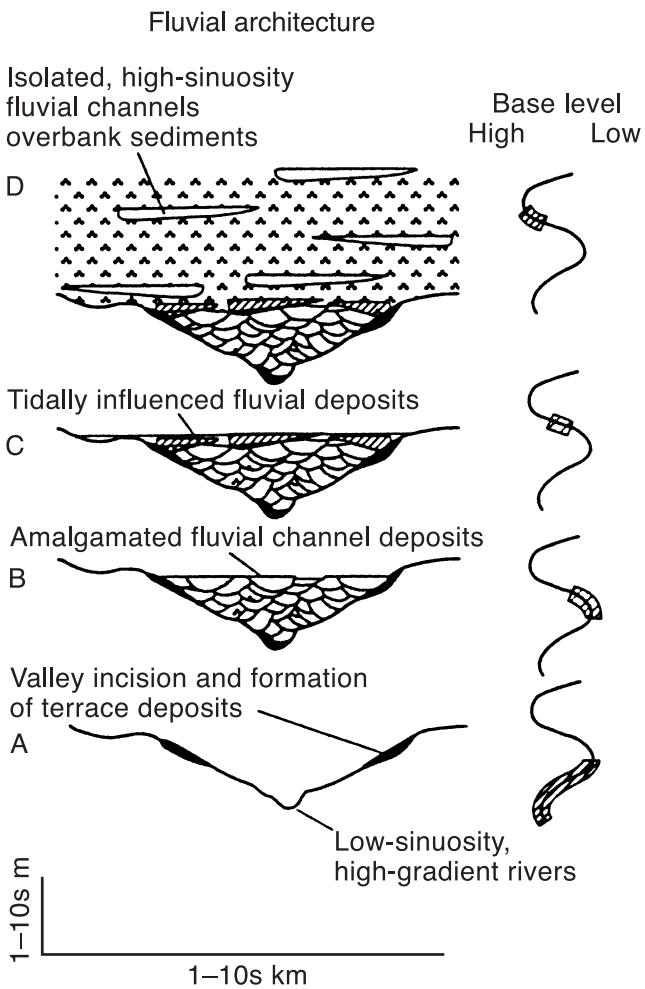


Figure 11. **Model for development of an incised-valley fill (Shanley and McCabe, 1993). Tidal influence occurs as estuaries succeed fluvial systems within valley. Once aggradation expands onto interfluves, a much lower channel/overbank ratio occurs.**

fluvial-estuarine channels beneath the upper Freeport coal comprise an IVF (LST/TST1) with a maximum thickness of about 25 m (82 ft), the base of which corresponds to SB1 in Figure 12. The upper Freeport coal is part of the TST1. McCabe (1993) noted that during rising base level, peats can form that onlap sequence boundaries. Therefore, coal beds may cap well-drained, interfluvial paleosols that represent sequence boundaries. The roof shale of the upper Freeport contains the nonmarine bivalve *Anthaconaia provosti* (E. Belt, 2000, personal communication), indicating the drowning of the swamp and the formation of lacustrine conditions during late TST. The common occurrence of isolated meandering river and tidal channel facies encased in flood-plain fines between the upper Freeport and Mahoning coal horizons is indicative of high rates of sedimentation and aggradation that accompanied increased sea and base level and high clastic sediment supply. These facies are interpreted as HST1. This fluvioestuarine package is truncated by stacked channel fills interpretable as incised valleys because of falling base level. Thus, the lower Mahoning Sandstone (i.e., sandstone between the upper Freeport and Mahoning coal horizons) includes both channel fills that are part of HST1, whereas others in the same interval are deposits of LST2/TST2 (Figure 12).

Other examples of IVFs include portions of the Buffalo Sandstone, Saltsburg Sandstone (Figure 8), and Grafton Sandstone (Figure 16). The maximum thickness of the IVFs is from 20 to 35 m (66 to 115 ft), although greater apparent thicknesses occur where IVFs incise into one another. This is illustrated by the Saltsburg-Buffalo IVF, a compound valley fill that extends from the base of the Pittsburgh shale to at least several meters below the Brush Creek coal (Figures 2, 12). One consequence of valley cutting was mass wasting of oversteepened valley walls. A spectacular example of a huge slump block of this type is well exposed near Prichard, West Virginia (Figure 17).

Intrabasinal Correlation

The nine paleosol-bounded allocycles of the Huntington area can be traced northward to the Ashland area and southward to Louisa (Figure 18). Correlations are facilitated by the presence of four marine units. These marine units pinch out eastward between Wayne and West Hamlin (Figures 4, 19). The disappearance of the lower Brush Creek, upper Brush Creek, and Cambridge marine units appears to coincide with the appearance of "probable nonmarine limestones" such as the Twomile Limestone described by Henry and Gordon (1979) in the Charleston area. These limestones commonly contain *Spirorbis*, which occur only in brackish to marine waters today (Tasch, 1980). Perhaps these were coastal lakes with intermittent connection to the sea.

Eight of the eleven allocycles interpreted for the northern Appalachian basin can be recognized in the central Appalachian basin (Busch and West, 1987) (Figure 20). Busch and West (1987) interpreted an allocycle to be represented between the upper Freeport coal and upper Freeport Rider coal, but it was only found in western Pennsylvania. The local occurrence of this cycle and its association with the upper Freeport Rider coal suggest that it may be more likely to have originated from autocyclic or local tectonic processes. Busch and West (1987) described five allocycles bounded by "transgressive" surfaces between the base of the Cambridge and the base of

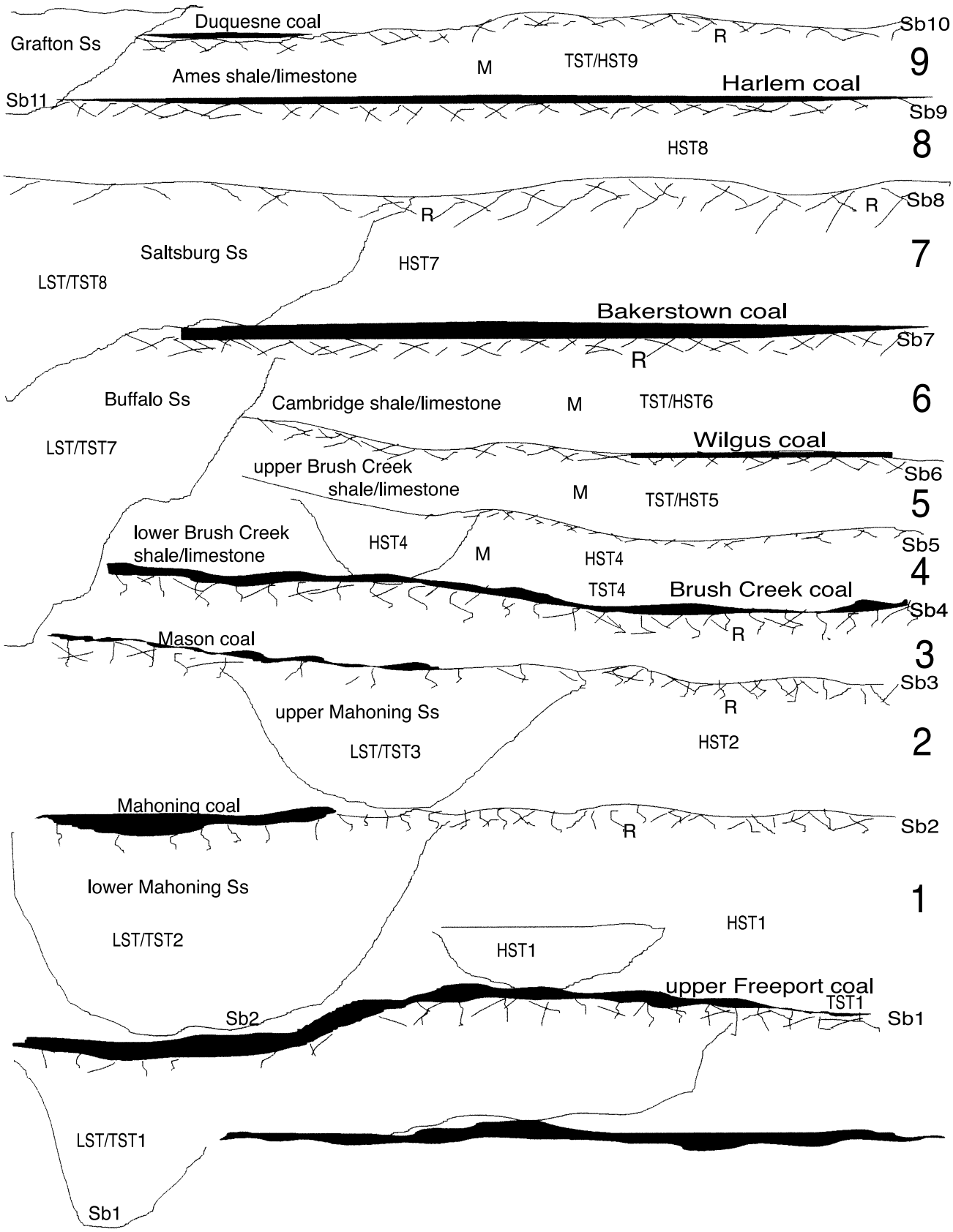


Figure 12. Sequence-stratigraphic interpretation for the Glenshaw Formation and upper Allegheny Formation at the southwestern end of the Dunkard basin. Numbers 1–9 at the right identify Glenshaw Formation sequences and correspond to paleosol-bounded allocycles reported by Martino (1998, figure 13).

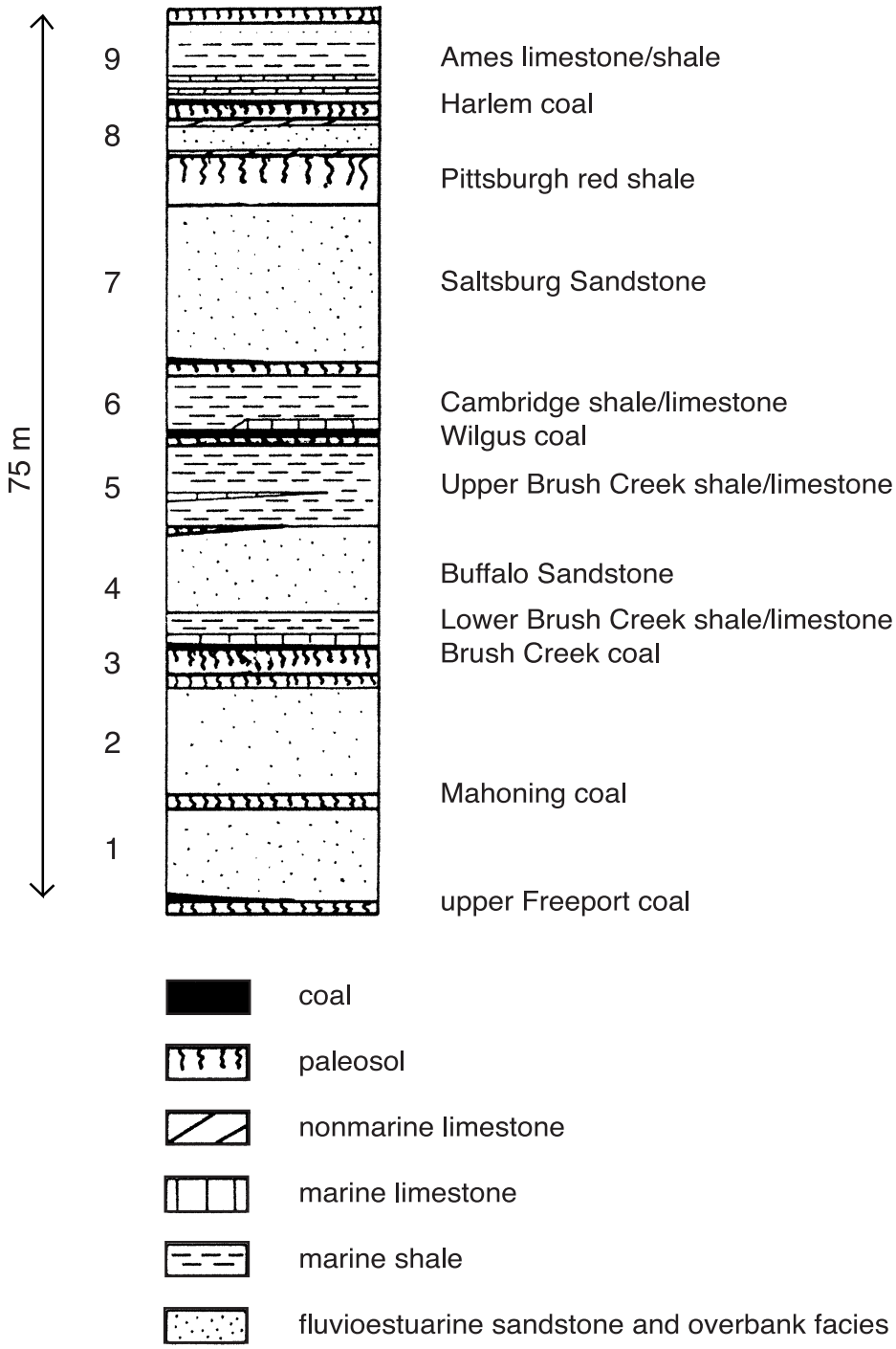


Figure 13. **Composite section of the Glenshaw Formation in the Huntington, West Virginia area, showing nine paleosol-bounded allocycles (Martino, 1998). Channel and valley fills are omitted for simplicity. Section is 75 m (246 ft) thick.**

the Ames marine units in the northern Appalachian basin, whereas only three were found in the area of this study. Decreasing accommodation space across the basin could lead to convergence of sequence boundaries, but this seems unlikely, as vertically stacked paleosols in this interval were not evident.

Interbasinal Correlation

Busch and West (1987) and Heckel (1995) proposed correlation of Glenshaw allocycles from the northern Appalachian basin with those in the Illinois basin and in Kansas (Figures 20, 21). There is a lack of agreement as to which cycles correlate. For example, more of the lower Brush Creek, upper Brush Creek, and Cambridge marine units are correlated with younger mid-continent units by Heckel (Swope, Dennis, and Dewey Limestones) than by Busch and West (Hertha, Swope, and Dennis). The Ames is correlated with the late Missourian Stanton Limestone by Busch and West, and the early Virgilian Oread Limestone by

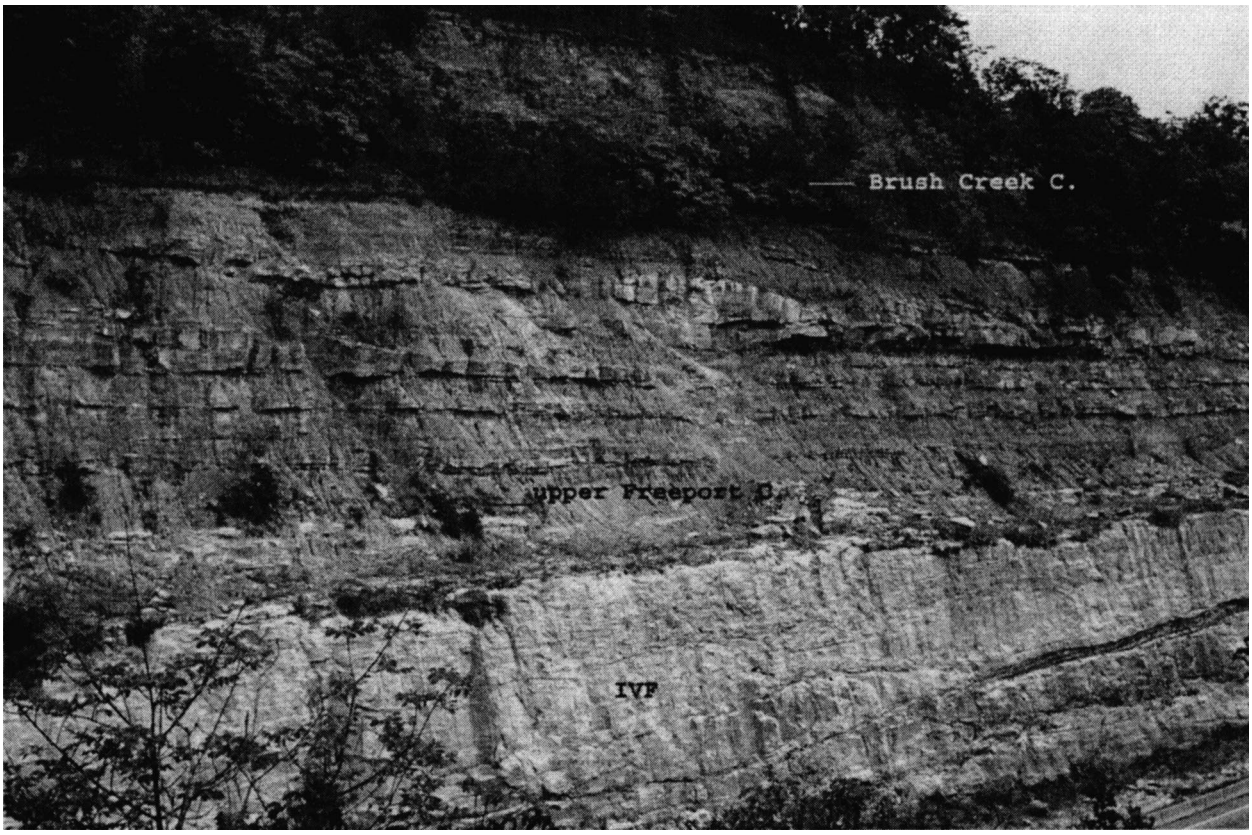


Figure 14. Roadcut along Ohio State Route 52 about 1 mi (1.6 km) northeast of Ashland, Kentucky (O-4). The lower portion of outcrop exposes a 17-m (56-ft)-thick multistory, fluvioestuarine channel complex interpreted as an incised-valley fill (LST/TST1) which locally truncates the no. 5 (lower Kittanning) coal at this location. The upper Freeport coal on bench overlies a thick paleosol with vertical features and is overlain by flood-basin lacustrine shales and splay sands. These are truncated by moderate-sized channels below the tree line. The total stratigraphic interval from the Brush Creek coal to road level is 46 m (151 ft).

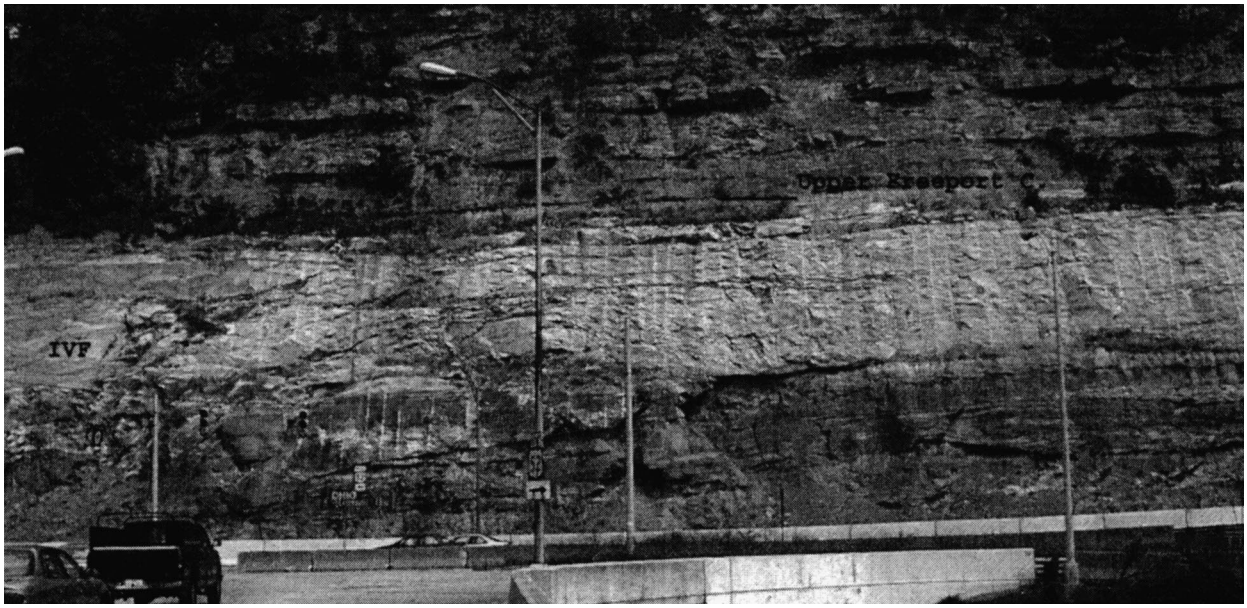


Figure 15. Outcrop along Ohio State Route 52 just north of Ashland, Kentucky. Multistory fluvioestuarine channel sandstone interpreted as IVF (LST/TST1, Figure 12) downcuts toward the left nearly to the Vanport Limestone. Upper Freeport coal (TST1) and flood-basin facies (HST1) are exposed in the upper half of the cut. Total thickness of section is about 50 m (164 ft).

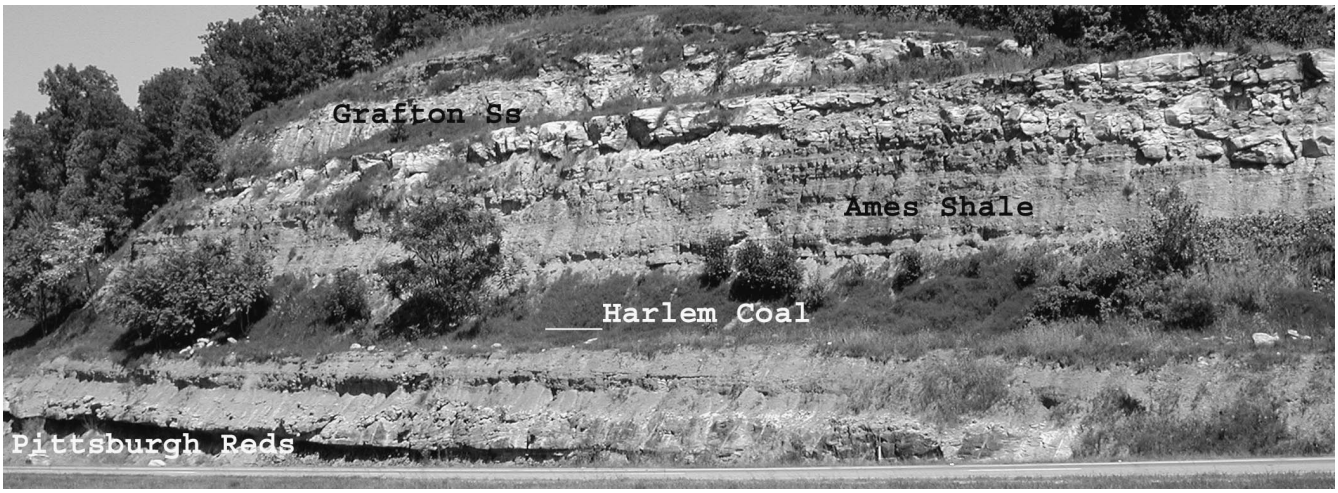


Figure 16. Upper Glenshaw Formation, Kentucky State Route 23 (K-5). Grafton Sandstone (of lower Casselman Formation) truncates Ames marine unit and down to the Harlem coal at this location. The Grafton is interpreted as an IVF. Its lower contact (SB11) truncates a mature paleosol (SB10; Figure 12) described in Table 3 that caps the Ames. These relations make it apparent that the Grafton fluvial system postdates the Ames T-R cycle. Reconnaissance suggests similar relations at most other Ames locations, calling into question the idea that the Grafton delta infilled the Ames Sea (Donaldson et al., 1985).

Heckel. An early Virgilian age for the Ames is supported by conodonts (Merrill, 1986). Heckel's (1995) correlations relied on biostratigraphy using conodonts from marine units and palynomorphs from coal beds and include data not available in Heckel (1986), which Busch and West (1987) employed in their analysis.

Ross and Ross (1988) distinguished 60 unconformity-bounded sequences of Permian–Carboniferous strata in cratonic basins on a global scale. A comparison of biostratigraphically equivalent horizons indicated in Heckel (1995) (Figure 22) for the upper Freeport coal and the Ames Limestone with the mid-continent sequence stratigraphy of Ross and Ross (1988) is shown in Figure 20. Ten unconformity-bounded sequences developed during the time interval of Glenshaw deposition in other basins. If glacioeustatic control of fifth-order Glenshaw allocycles occurred, then these depositional sequences should be developed in the Appalachian basin. Nine Glenshaw sequences are distinguished in this study. The fewer number in the Appalachian basin could be the result of the basin's high shelf position (Heckel, 1994). Discrete lowstand exposure surfaces in the mid-continent region may merge into single-exposure surfaces as accommodation space decreases up the shelf into the

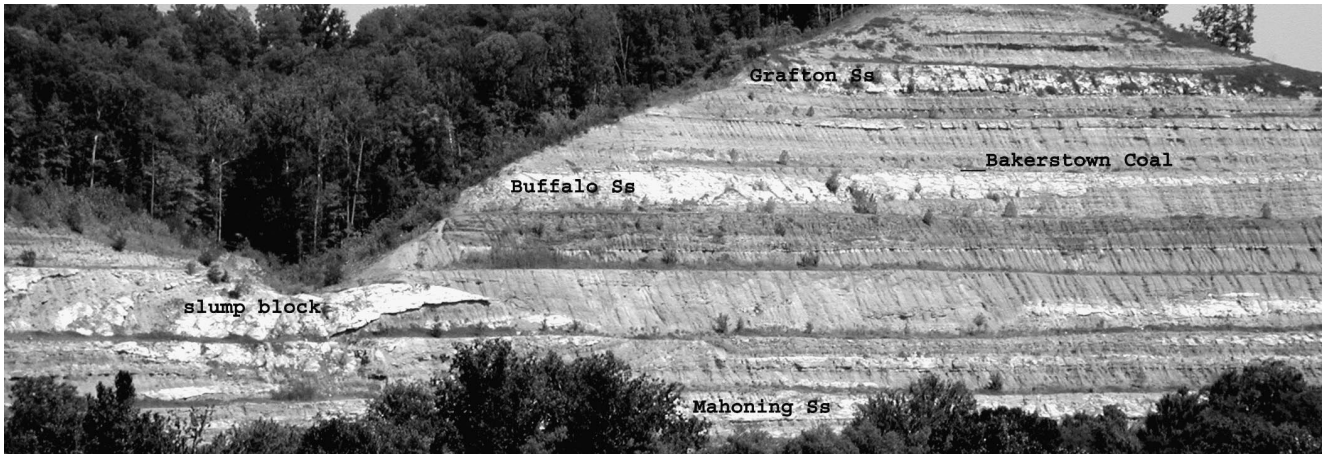


Figure 17. View of West Virginia State Route 52 roadcut 1–2 mi (1.6–3.2 km) south of Prichard as seen from Kentucky. Strata total about 100 m (328 ft) in thickness and expose the entire Glenshaw Formation and the lower 20 m (66 ft) of Casselman Formation. Note the large slump block (left) interpreted as the result of oversteepening of paleovalley wall.

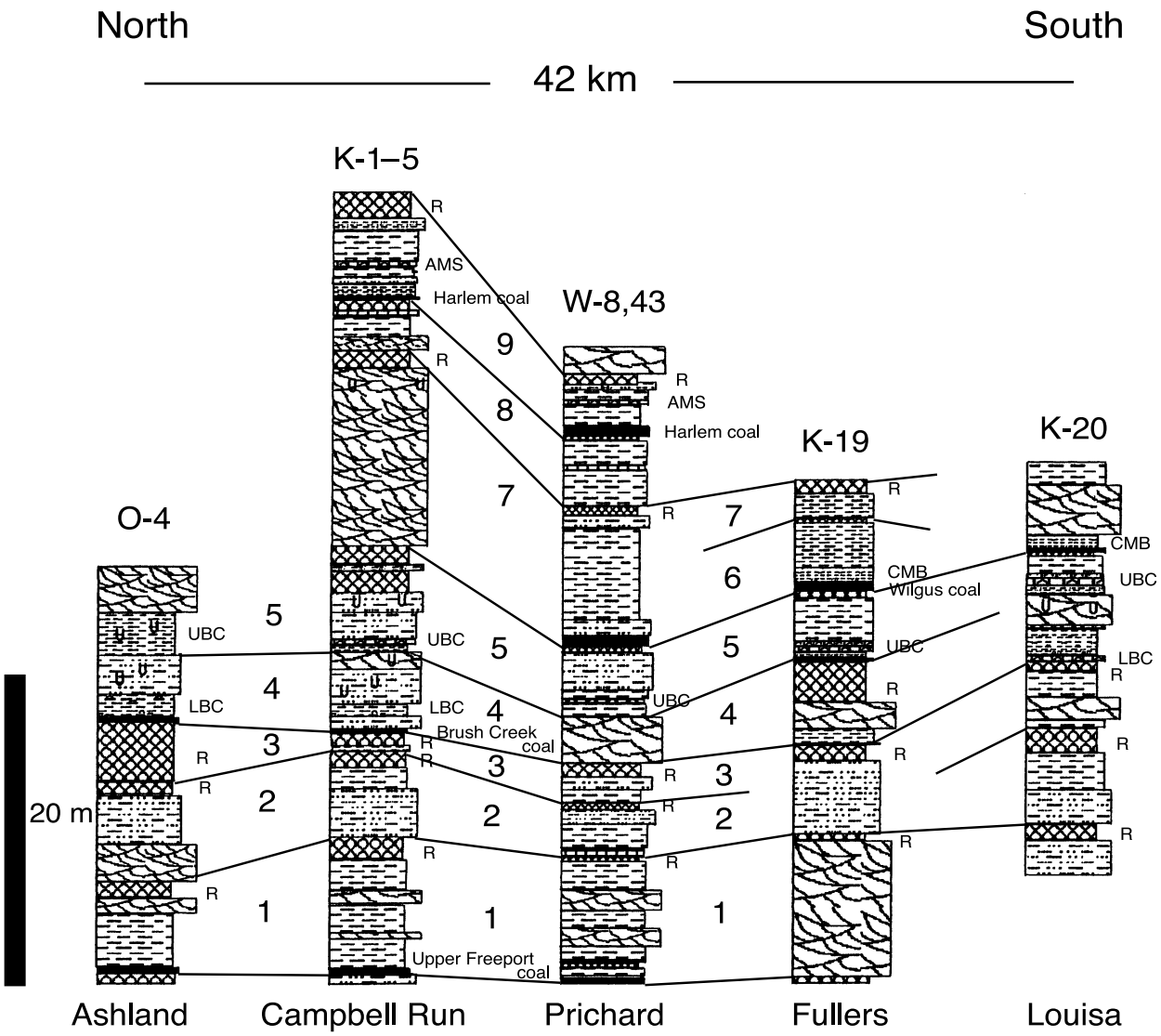


Figure 18. **Correlation of Glenshaw sections from north to south through the western portion of the study area using tops of paleosols. See Figure 4 for locations and Figure 19 for key. Marine units: LBC = lower Brush Creek, UBC = upper Brush Creek, CMB = Cambridge, AMS = Ames.**

Appalachian basin. The presence of a minor hiatus in the Appalachian basin has been suggested between the Mahoning and Mason coals at the Missourian–Stephanian boundary (Peppers, 1997). The first occurrence of lower Stepahanian taxa, including *Triticites* and *Thymospora obscura*, are in cyclothems that are closer to the stage boundary in the Appalachian basin than in the mid-continent. Despite the minor differences in number of Glenshaw allocycles, it appears probable that base-level changes inherent in these cycles were controlled by glacioeustaic sea level fluctuations.

The IVFs described in this study are similar in depth, character, and age to those reported from the Douglass Group of Kansas (Archer et al, 1994; Feldman et al., 1995). Two IVFs, including the Tonganoxie Sandstone and the Ireland Sandstone, occur in close proximity to the Missourian–Virgilian boundary and underlie the Oread Limestone (Ames equivalent of Heckel, 1995).

CONCLUSIONS

The main contributions of this study may be summarized as follows:

1) The Glenshaw Formation in the central Appalachian basin contains widespread mature paleosols with features that indicate well-drained conditions. These paleosols are interfluvial sequence

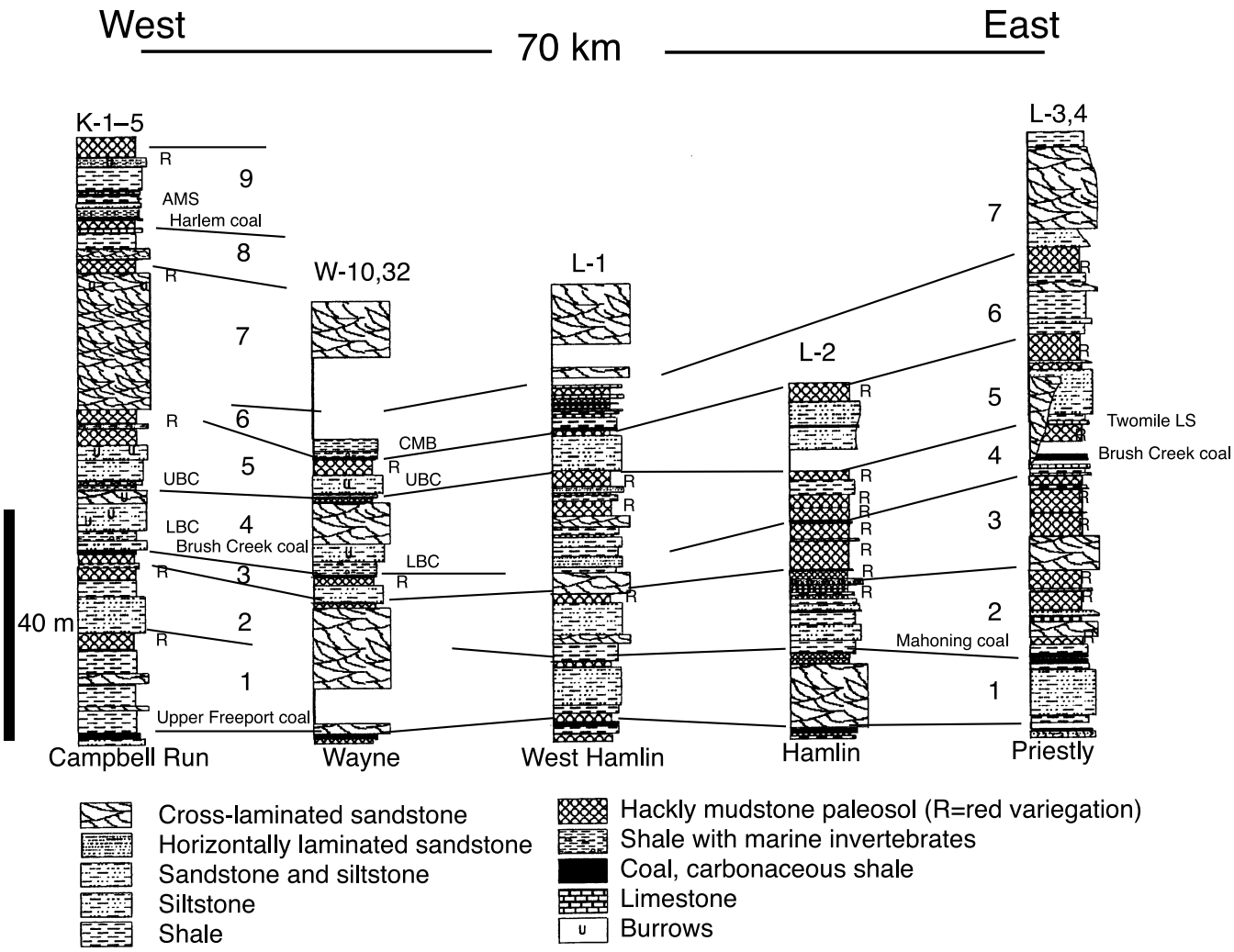


Figure 19. **Correlation of Glenshaw sections from west to east through the study area, using tops of mature paleosols as sequence boundaries.**

boundaries that divide the Glenshaw into nine allocycles. Four of these allocycles contain basin-wide marine units (lower Brush Creek, upper Brush Creek, Cambridge, and Ames), indicating a direct connection between sea level and base-level cycles. Tidally influenced strata occur in most of the other allocycles, suggesting sea level changes were instrumental in their development as well.

2) Incised valley-fills from 20 to 35 m (66 to 115 ft) thick occur in the Glenshaw Formation and adjacent strata; these valley fills contain multistory fluvioestuarine channel facies which are similar in depth, age, and character to IVFs reported from the Illinois basin.

3) The recognition of widespread, well-drained paleosols as sequence boundaries enables a more accurate interpretation of the origin of channel systems. Deltaic deposits are present, but not as widespread as indicated by previous workers. Only the lower Brush Creek cyclothem contains clear evidence for deltaic distributary systems in the area of this study. Deltas would be expected to develop during highstands after estuaries had filled. Estuarine facies are important constituents of coastal plain deposits formed during eustatic sea level cycles, yet they eluded detection by most previous workers.

4) The fewer number of allocycles recognized in this study compared to the work by Busch (1984) may be explained by less accommodation space in this study area, which might have caused thinning of allocycles toward the south and merging of bounding paleosols. The fewer number of marine units (four) in the Huntington area compared to the northern Appalachian basin (eight) may indicate higher rates of sediment influx from the

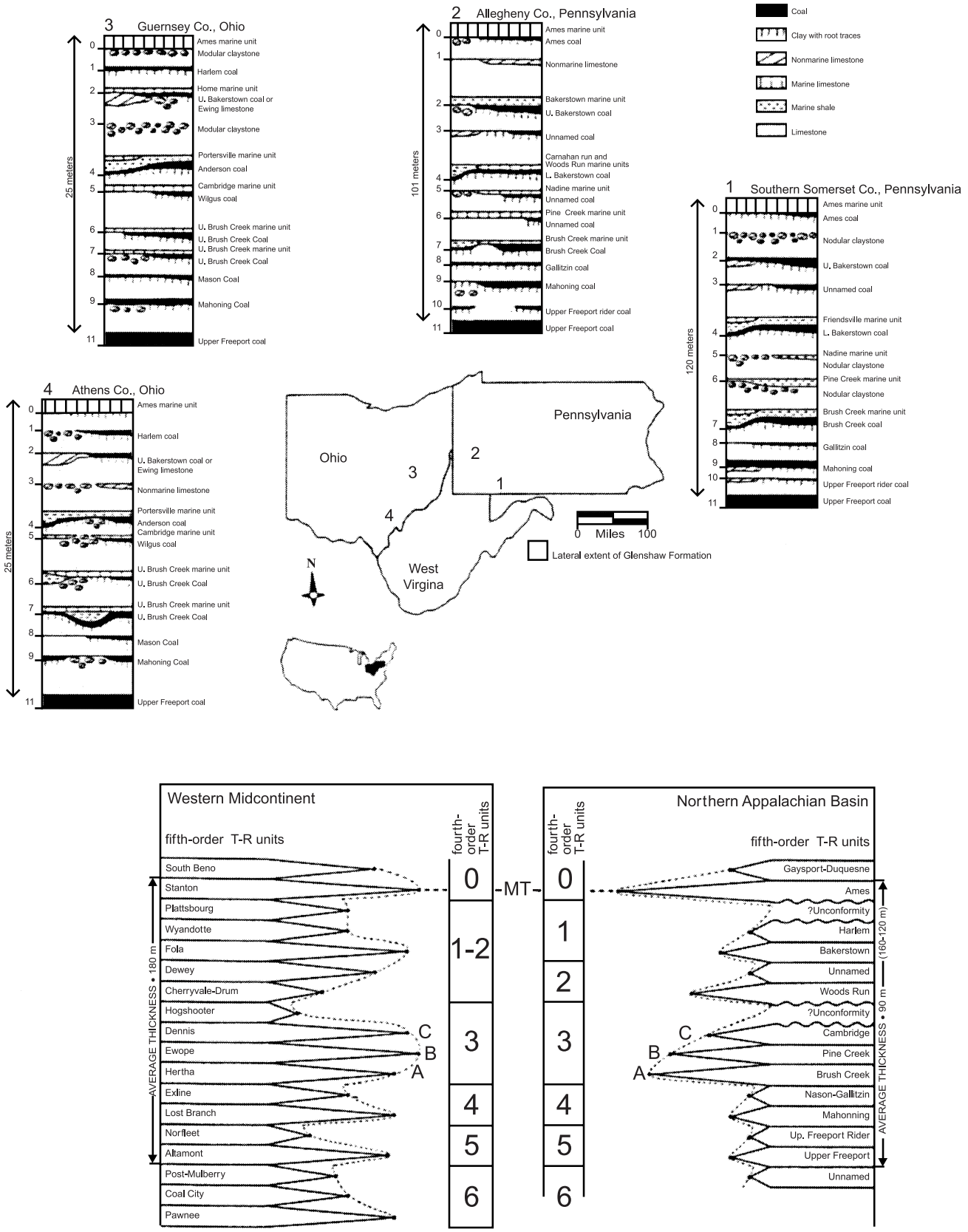


Figure 20. Eleven fifth-order T-R allocycles of Busch and West (1987) recognized in the Glenshaw Formation of Pennsylvania and Ohio.

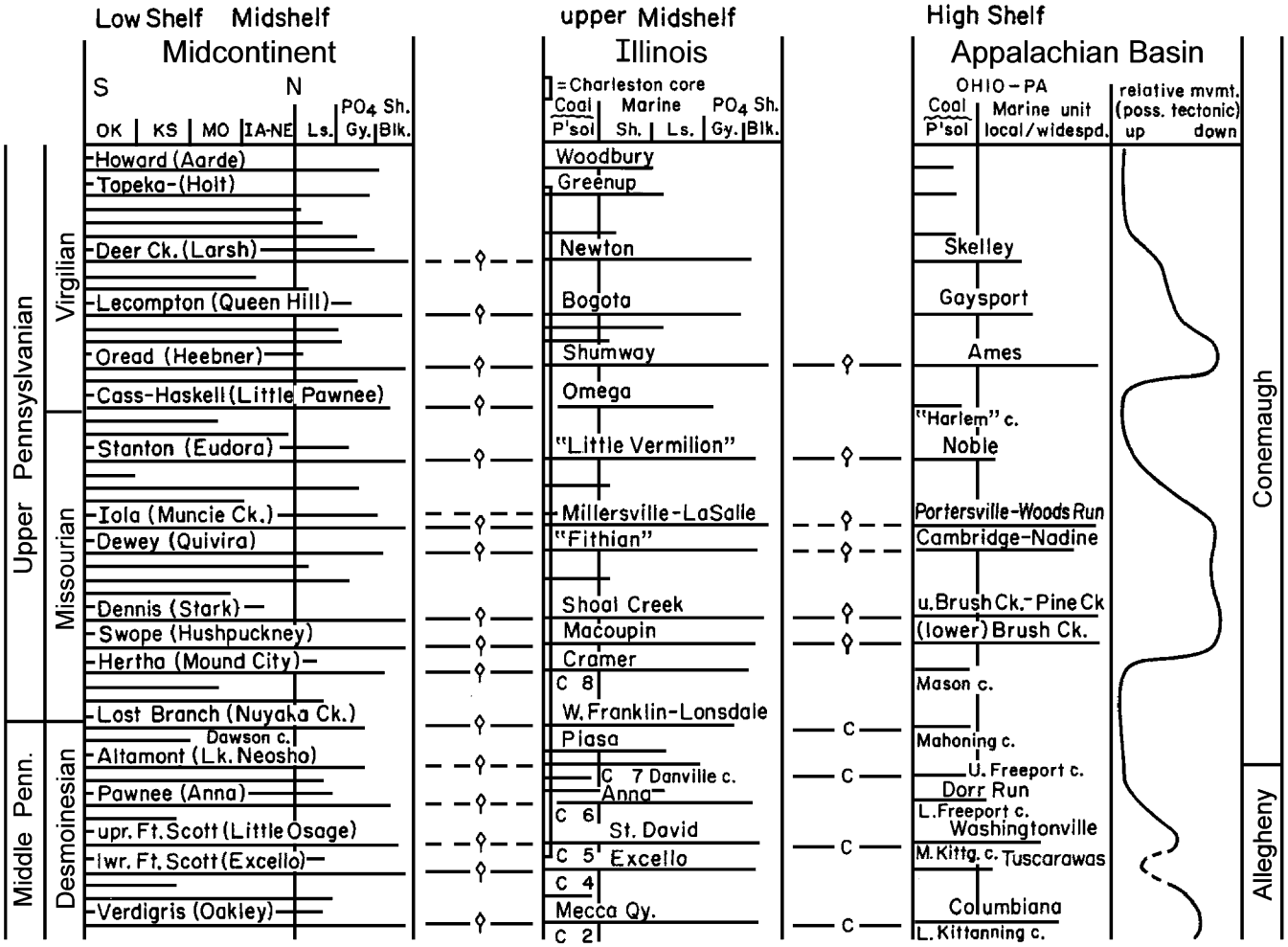


Figure 21. Interbasinal correlation of coal beds and marine units based on conodont data and palynofloras. Glenshaw Formation in Appalachian basin extends from top of upper Freeport coal to the top of the Ames Limestone. Width of horizontal lines representing marine units corresponds to the geographic extent of the transgressions. Only the more extensive transgressions in the mid-continent (low shelf) reached the Appalachian basin (high shelf; after Heckel, 1995).

southeast, which kept pace with, or outpaced rising relative sea level.

5) Changes in the Glenshaw allocycles from west to east occur across the study area. All four marine units pinch out toward the east. Lacustrine limestones, such as the Twomile Limestone, cap thick paleosols and appear to represent early highstand deposits in the coastal plain that are coeval with seas that periodically occupied the western portion of the study area.

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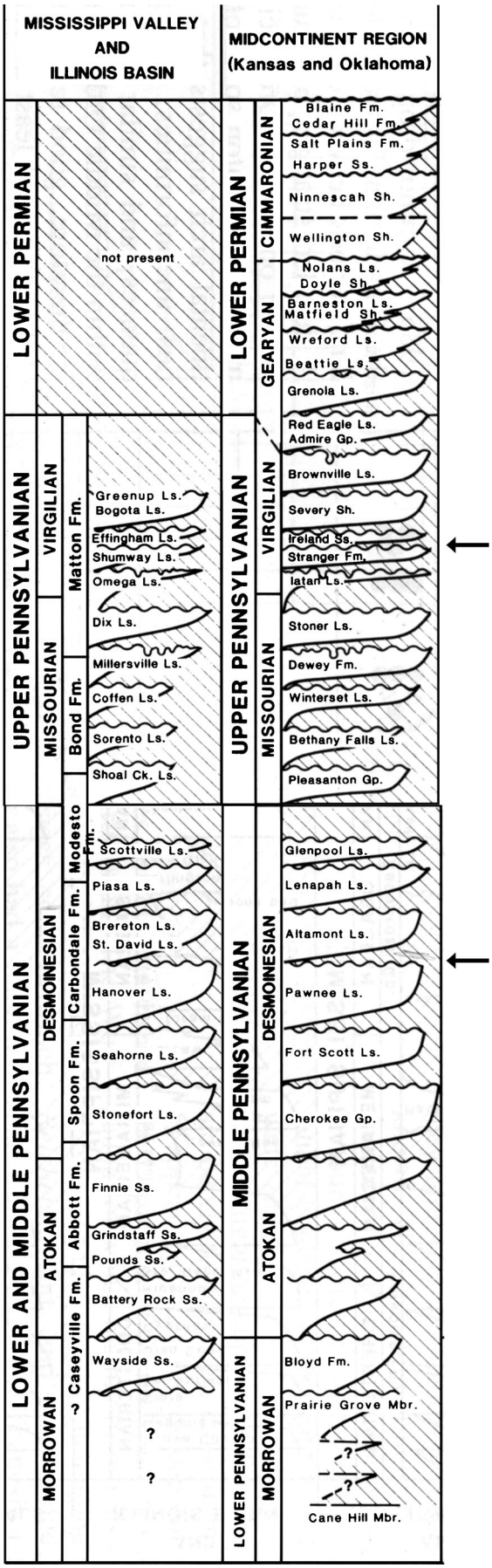

Figure 22. **Unconformity-bounded depositional sequences from the Illinois basin and mid-continent for the Pennsylvanian and Permian (modified from Ross and Ross, 1988). Sequences are interpreted as correlative with worldwide eustatic sea level changes. Arrows at right show stratigraphic interval that corresponds to the Glenshaw Formation in the Dunkard basin, using the biostratigraphic correlations of Heckel (1995) for the upper Freeport coal and Ames Limestone.**

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