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ARTICLES

Stratigraphic Model for Glacial-Eustatic Pennsylvanian Cyclothems in Highstand Nearshore Detrital Regimes[1]

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ABSTRACT

Lower (distal) positions on gently sloping shelves (ramps) affected by Pennsylvanian glacial-eustatic sea-level fluctuation display classic marine transgressive-regressive cyclothems, which are separated by exposure surfaces or by shallow marine to thin terrestrial beds deposited at lowstand. In contrast, higher shelf (proximal) positions display marginal marine units and coastal-plain coal beds deposited at marine highstand and separated by thicker terrestrial units. Both marine and terrestrial strata deposited in high-shelf positions underwent significant fluvial incision and valley formation during long stands of lower sea level, resulting in discontinuous erosional remnants and subsequent localized terrestrial deposition on irregular leached and eroded surfaces. Examples from the Appalachian, Illinois, and Sydney basins display features such as erosional disconformities with rotated slumps, buried hilltops preserving erosional remnants of marine units, colluvially reduced landscape relief, and buried paleovalleys filled with stacked channel sands or locally with marginal marine deposits from incursions of lesser extent. The basic cyclothem in highstand nearshore (proximal) detrital regimes consists of a widespread marginal marine-associated coal-bearing unit formed during early highstand, overlain by late highstand progradational, largely terrestrial siliciclastics. These grade upward in some places to thick paleosols and are truncated in other places by valley-fill deposits. The lower-stand weathering, erosional, and depositional features in lower areas are overlain by colluvial/alluvial to late transgressive estuarine deposits, and all lower-stand features are capped by the next major highstand coal-bearing to marginal marine unit. All features produced by sea-level fall reflect the primacy of global glacial-eustatic control over the cyclic nature of Pennsylvanian stratigraphy.

Introduction

Most systematic interpretations of cyclic Pennsylvanian successions have been made in the Midcontinent and Illinois basins, where distinctive marine transgressive-regressive cyclothems comprising diverse rock types are best developed and were first described. Although depositional cycles were recognized early in the Appalachian basin, many marine units there are discontinuous, and detrital rocks dominate the succession. Most studies there focused on the economically important coal beds formed in lowland terrestrial (but often marine-associated) environments and thereby favored autogenic delta shifting to explain the cyclic stratigraphy. Sandstone-filled channels recognized early in the Illinois basin, the north Texas succession, and the Appalachian basin were attributed respectively to allogenic tectonic uplift (Weller 1930) and autogenic fluvio-deltaic processes (Brown 1969; Ferm 1970). Allogenic glacial-eustatic fluctuation of sea level, first proposed by Wanless and Shepard (1936), but not considered seriously for a number of years, has recently become more strongly supported for the primary control over global cyclic Pennsylvanian stratigraphy, as large-scale tectonic effects have been determined to be lower frequency (though significant in providing accommodation space), and delta shifting has been relegated to more local importance (Busch and Rollins 1984; Heckel 1986, 1994; Veevers and Powell 1987; Soreghan 1994).

It is therefore appropriate to consider the effects that glacial eustasy should have had on detrital-dominated Pennsylvanian successions where its signal is obscured by lesser diversity of rock types. Accordingly, this paper examines some evidence for sea-level fall and erosional incision in detrital

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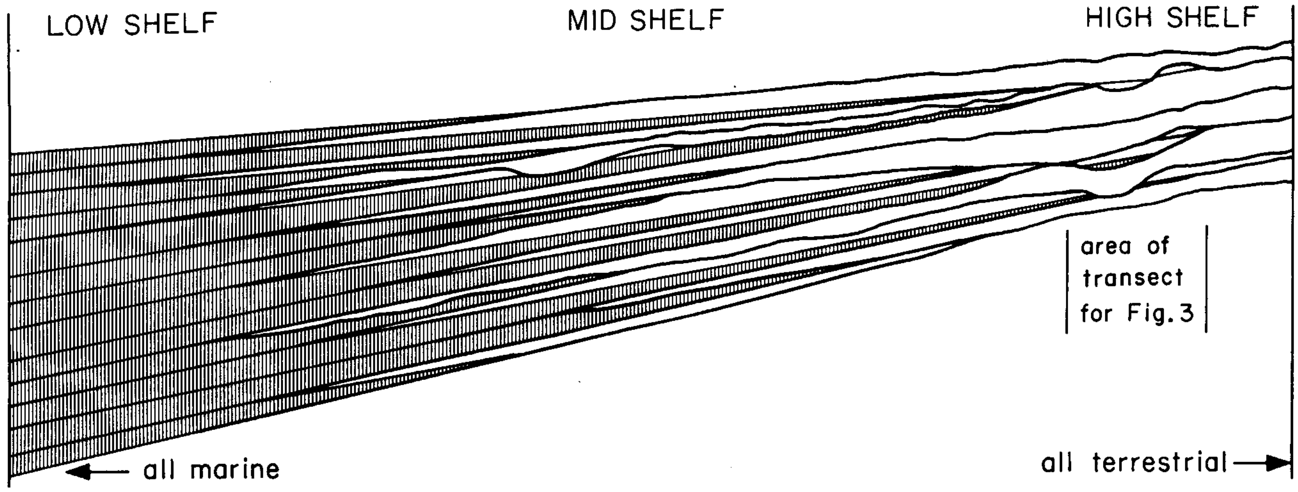


Figure 1. Dip transect showing expected relations of marine (shaded) and terrestrial (blank) strata on a gently sloping shelf (ramp) subjected to several glacial-eustatic sea-level fluctuations, with greater tectonic subsidence (hence net accommodation space) toward lower (distal) end of shelf. At lower sea-level stands, both marine and terrestrial strata deposited higher on the shelf during highstands would be subject to fluvial incision, valley formation, and pedogenesis, resulting in irregular surfaces (uneven lines) locally subdued by colluvial processes, with remaining lows filled by subsequent transgressive sedimentation.

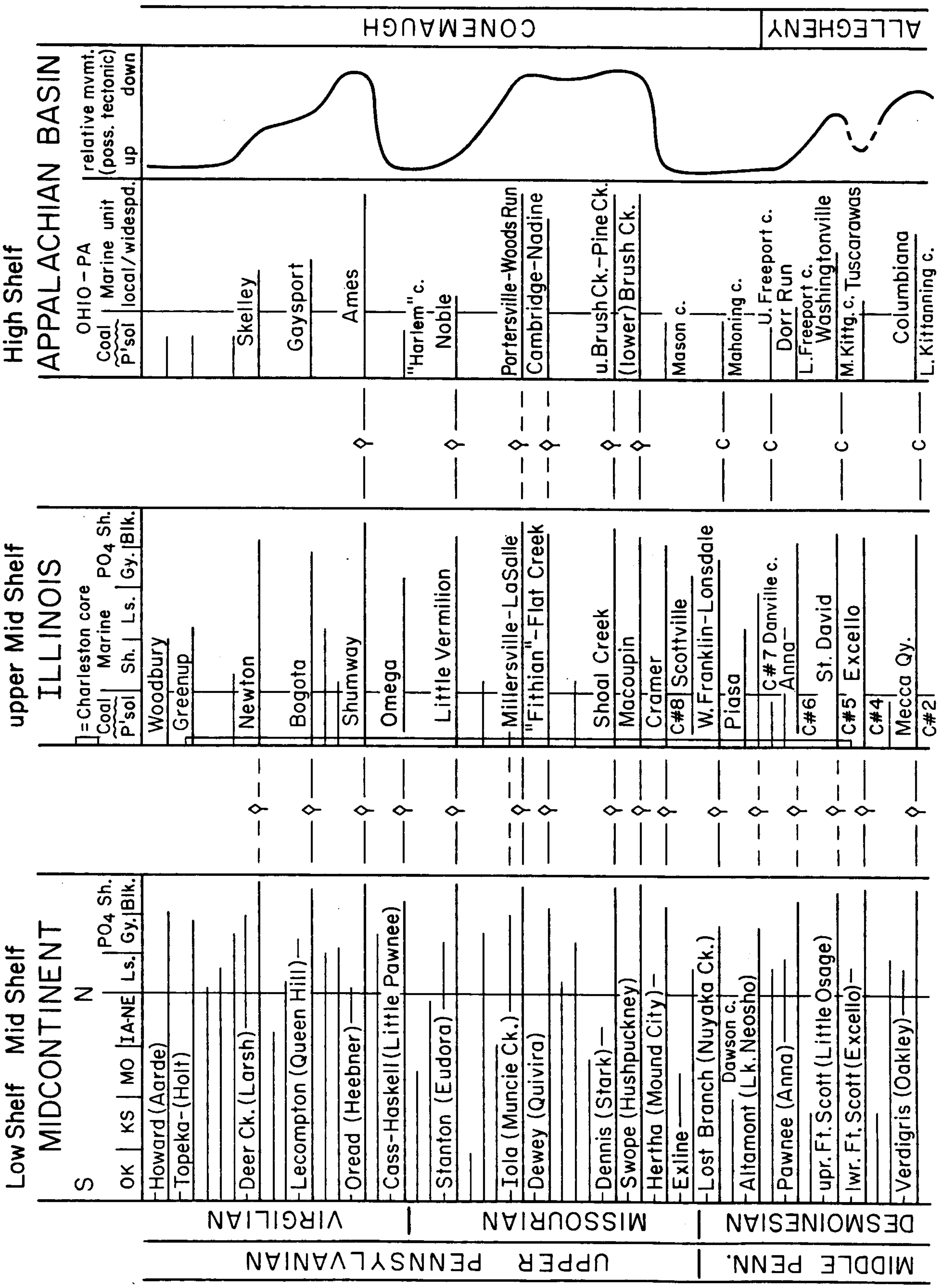
successions that formed at higher elevations and were encroached by marine shorelines only during the highest stands of sea level, because these are the effects of glacial eustasy that would be expected in such positions between times of marine transgression. These examples serve as a further test for the concept of primary glacial-eustatic control over Pennsylvanian cyclothems.

General Model

Along a basin-to-shelf (distal-proximal) transect subject to glacial-eustatic sea-level fluctuations, the stratigraphic succession would range from entirely marine in the basin (and parts of the adjacent low shelf) to entirely terrestrial high on the shelf (figure 1). At intermediate positions, the succession would comprise marine transgressive-regressive (T-R) sequences, the classic cyclothems, separated by thin terrestrial or nearshore deposits; this would grade up-shelf (proximally) to an increasingly terrestrial succession as marine units resulting from lesser highstands progressively thin and pinch out, while the bounding terrestrial units thicken, and the exposure surfaces ultimately merge.

This lateral transition is illustrated along the Midcontinent outcrop belt. In a low-shelf position at the Kansas-Oklahoma border, the Missourian–lower Virgilian (up through Deer Creek) succession consists of 35 marine T-R units (figure 2), only 14 pairs of them separated by terrestrial units or exposure surfaces. This succession grades up-shelf to 24 marine T-R units, 20 pairs separated by terrestrial units or exposure surfaces at the Iowa outcrop limit, a mid-shelf position. Over a broader region, the coeval succession in east-central Illinois contains 15 marine T-R units, 13 pairs separated by terrestrial units, suggesting a higher (upper) mid-shelf

Figure 2. Correlation of major marine cyclothems (long horizontal lines with names above) along Midcontinent outcrop belt, with those in and near Charleston core in eastern Illinois basin and with marine units of upper Allegheny and Conemaugh groups in Appalachian basin (slightly modified from Heckel 1994, 1995). Lesser marine T-R units (shorter horizontal lines) are left unlabeled to reduce clutter, but are named in Heckel (1994, p. 67). Note that total number of marine units decreases from Midcontinent basin margin (low shelf) in Oklahoma (S) to mid-shelf in Iowa (N), fewer marine units extend into eastern Illinois basin, and even fewer reach Appalachian basin, indicating progressively higher shelf (proximal) positions for those regions during this time. Correlations are based upon distinctive conodont faunas (tailed diamond symbols) collected from Charleston core and type sections of named units in Illinois (Heckel and Weibel 1991; Heckel, Weibel and J. P. Pope unpub. data) and from vertical successions of exposures at Athens, Cambridge, and Steubenville, Ohio, and Pittsburgh, Pennsylvania (J. E. Barrick and P. H. Heckel unpub. data) in conjunction with Heckel (1989), and upon coal correlations (labeled C) of Peppers (1996).


Low Shelf Mid Shelf
MIDCONTINENT
S N
OK | KS | MO | IA-NE | Ls. | PO4 Sh. Gy. | Blk.
Howard (Aarde)
Topeka-(Holt)
Deer Ck. (Larsh)
Lecompton (Queen Hill)
Oread (Heebner)
Cass-Haskell (Little Pawnee)
Stanton (Eudora)
Iola (Muncie Ck.)
Dewey (Quivira)
Dennis (Stark)
Swope (Hushpuckney)
Hertha (Mound City)
Exline
Lost Branch (Nuyaka Ck.)
Dawson c.
Altamont (Lk. Neosho)
Pawnee (Anna)
upr. Ft. Scott (Little Osage)
lwr. Ft. Scott (Excello)
Verdigris (Oakley)
upper Mid Shelf
ILLINOIS
= Charleston core
Coal | Marine | PO4 Sh.
P'sol | Sh. | Ls. | Gy. | Blk.
Woodbury
Greenup
Newton
Bogota
Shumway
Omega
Little Vermilion
Millersville-LaSalle
"Fithian"-Flat Creek
Shoal Creek
Macoupin
Cramer
C#8 Scottville
W. Franklin-Lonsdale
Piasa
C#7 Danville c.
Anna
C#6
St. David
C#5 Excello
C#4
Mecca Qy.
C#2
High Shelf
APPALACHIAN BASIN
OHIO - PA
Coal | Marine unit
P'sol | local/widespd.
relative mvmt. (poss. tectonic)
up down
Skelley
Gaysport
Ames
"Harlem" c.
Noble
Portersville-Woods Run
Cambridge-Nadine
u. Brush Ck.-Pine Ck.
(lower) Brush Ck.
Mason c.
Mahoning c.
U. Freeport c.
Dorr Run
L. Freeport c.
Washingtonville
M. Kittg. c. Tuscarawas
Columbiana
L. Kittanning c.
CONEMAUGH
ALLEGHENY
VIRGILIAN
MISSOURIAN
DESMOINESIAN
UPPER PENNSYLVANIAN
MIDDLE PENN.

position. Finally, the coeval succession in the Ohio-western Pennsylvania part of the Appalachian basin includes only 8 marine units, all separated by terrestrial intervals, indicating that this part of the Appalachian basin lay in a high-shelf position during this time (figure 2).

Because major marine transgression was infrequent, deposition on the high shelf took place mainly within the terrestrial regime; therefore, successions in high-shelf positions were subject to subaerial processes most of the time. In semi-arid marine carbonate regimes (e.g., mid-shelf Iowa), thick regressive limestones deposited during sea-level fall underwent early marine and meteoric cementation (Heckel 1983), thus ''armoring'' the surface, so that erosional incision was minimal, and leaching, microkarstification, and thin clay-rich paleosols provide the main evidence of exposure during sea-level lowstand. In contrast, quartz sand and argillaceous mud deposited in more humid detrital regimes would have remained relatively unconsolidated and more readily subject to fluvial incision, valley formation, colluvial landscape reduction, and deep soil formation during lower stands of sea level. This would produce a surface of variable topography incised by drainage systems prior to the next marine inundation, as described in the detrital Douglas Group (Missourian-Virgilian) by Archer et al. (1994) in the mid- to low-shelf transition area of northeastern Kansas. Such effects of eustatic sea-level fluctuations should be more common in higher shelf settings but may have been overlooked because the glacial-eustatic model has received little consideration in these areas.

Two stratigraphic implications of the general model are: (1) that marine units deposited across most of the higher extent of the shelf during the highest stands of sea level could be locally removed by valley incision during the following regression and lowstand, and thus become erosionally discontinuous (figure 3*A,D*); and (2) that marine units resulting from lesser highstands might be deposited only in paleovalleys and thus be depositionally discontinuous (figure 3*B,E*). In addition, tectonic overprinting could modify these patterns in two quite different ways: (a) increased subsidence rate would inhibit valley formation during sea-level falls, as less potential relief would be available for incision, and deposition would be promoted across more of the landscape during lowstands; or (b) decreased subsidence rate would promote more erosion and deeper valley formation as rivers more readily became entrenched during sea-level fall and lowstand.

Previous estimates of at least 100 m of sea-level fluctuation based on depositional interpretation of the phosphatic black shale in Midcontinent cyclothems are further supported (Heckel 1994) by considering the ice-volume/areal relations of Gondwanan glaciation (Crowley and Baum 1991) along with the 120 m post-Wisconsinan glacial-eustatic sea-level rise (Fairbanks 1989) because the area of Pleistocene ice that melted then is comparable to the Mid- to Late Pennsylvanian ice coverage illustrated by Veevers and Powell (1987, p. 476). Therefore, a vertical dimension of at least several tens of meters was available for erosional downcutting in high-shelf positions during the lowest stands of Pennsylvanian sea level.

Examples Supporting the Model

Appalachian Basin. Even though the entire Appalachian basin has traditionally been regarded as a delta-filled depocenter throughout Pennsylvanian time, the great thickness of strata resulting from foreland subsidence there appears to be confined to the Lower and lower Middle Pennsylvanian succession, which totals about 1100 m in the Pocahontas, New River, and Kanawha groups of southern West Virginia and the Lee and Breathitt groups of eastern Kentucky. The substantially thinner (200–300 m) upper Middle to lower Upper Pennsylvanian (Allegheny-Conemaugh group) succession suggests a decrease in tectonic subsidence through time (assuming even only rough equivalence in time span). Moreover, the lower Conemaugh succession (upper Freeport coal to Ames Limestone) in Ohio and western Pennsylvania is only 60–110 m thick, or about one half to three-quarters of the coeval 130–150 m succession in Iowa (Altamont to Oread Limestone: data sources in Heckel 1994). Thus, this part of the Appalachian basin had less net accommodation space during early Late Pennsylvanian time than it did earlier, or than existed at the same time at the most shelfward erosional limit of the Midcontinent outcrop belt. As a result, this part of the Appalachian basin preserved only a thin apron of detrital sediment derived from nearby highlands during this time. A higher shelf position for this part of the Late Pennsylvanian Appalachian basin is supported also by the substantially fewer (8) marine units in the Conemaugh Group than the 24 in the coeval succession in Iowa (figure 2).

Williams et al. (1965) illustrated features resulting from fluvial incision and resultant slumping in Allegheny detrital strata between two laterally persistent coal beds in west-central Pennsylvania. Here, about 6 m of bedded siltstone strata that are no longer present in an adjacent undis-

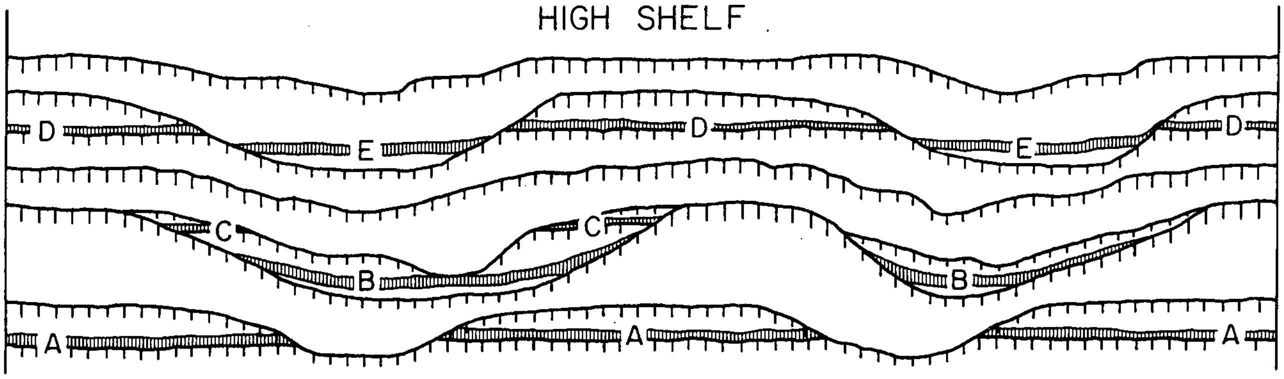


Figure 3. Strike transect showing expected relations of marine (shaded) and terrestrial (blank) strata in high-shelf (proximal) position (see figure 1) during several glacial eustatic sea-level fluctuations. Irregular erosion surfaces (hachured wavy lines) that developed during lower stands of sea level dissected originally continuous marine units (A,D) and confined marine units deposited during lesser highstands to paleovalleys (B,E) or to eroded terrace remnants (C), possibly leading to miscorrelation of age-distinct units (D,E) deposited at comparable elevations at different times.

turbed section are preserved in the top of a rotated slump block resting on a thin marine shale above the lower coal bed (figure 4). Both incised/slumped and undisturbed sections are overlain by another 6 to 9 m of non-bedded siltstone interpreted as colluvium. From this they estimated perhaps 15 m of landscape reduction on the incised disconformity to produce the gentler surface upon which the overlying coal bed formed. Residual clay units, locally with apparent soil zonation (Williams et al. 1965, p. 540), formed elsewhere on paleointerfluves. This interval was formed during lower stands of sea level by fluvial incision of late highstand progradational deltaic/paralic deposits, above the late transgressive peat and early highstand marine shale unit. Slumping reduced slopes on the weak valley sides, and colluvium accumulated in lower areas, while paleosols formed on higher areas that were more stable, until the encroaching shoreline again caused peat formation over the entire subdued landscape during the next marine transgression (see Heckel 1995).

A lenticular Conemaugh marine limestone (20 cm thick) extends along a roadcut east of Steubenville, Ohio (figure 5). Its conodont fauna allows its identification as the Pine Creek (Pennsylvania)/upper Brush Creek (Ohio) Limestone, which correlates with the Stark Shale (Dennis cyclothem) in the Midcontinent (figure 2). This limestone is truncated on the north by a thick sandstone and on the south by reddish, southward-dipping, locally rubbly shale and sandstone. The surface of truncation

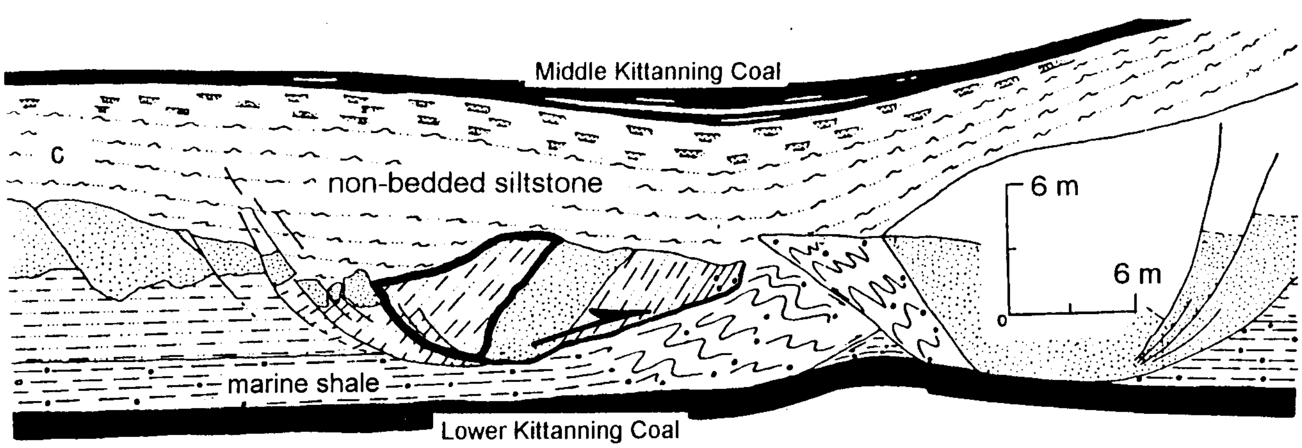


Figure 4. Rotated slumps in railroad cut 1.6 km southwest of Curwensville, Pa., showing bedded siltstone unit (heavy outline) in upper part of left slump that has no equivalent in overlying unit. Arrow shows slump direction. Bedded siltstone unit that existed prior to fluvial incision and slumping must have been removed elsewhere during landscape reduction and formation of overlying non-bedded siltstone unit, probably largely colluvium (modified from figure 3*C* of Williams et al. 1965).

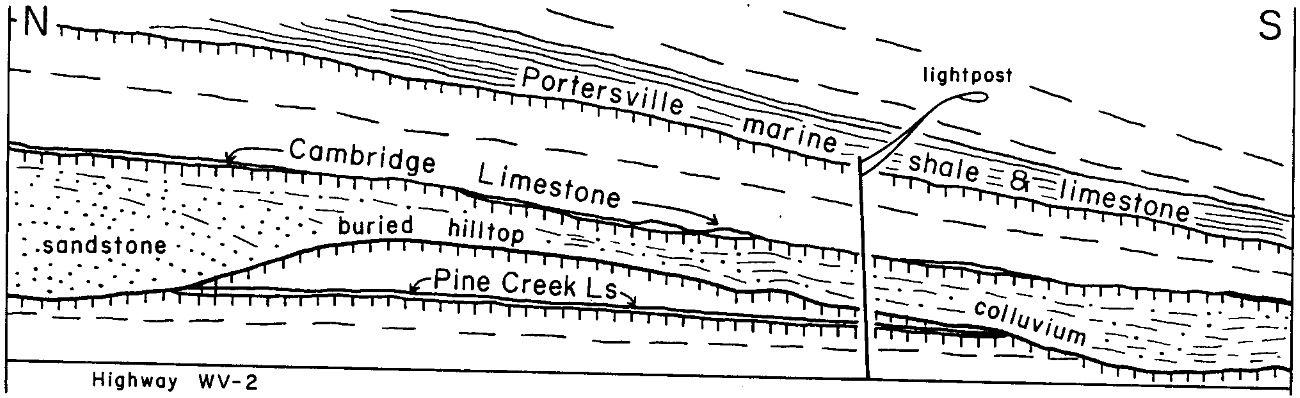


Figure 5. Buried hilltop containing erosional remnant of Pine Creek ([Pa.] = upper Brush Creek [Ohio]) Limestone exposed along W.Va. Route 2 across Ohio River from Steubenville, Ohio (drawn from photograph taken by P. H. Heckel on 1988 NC-GSA field trip led by A. T. Cross; see also Caudill 1990). Original relief was subdued by sandy (north) and muddy (south) alluvial/colluvial deposits prior to next marine incursion, when Cambridge Limestone was deposited. Vertical distance between Pine Creek and Cambridge limestones is about 4 m.

rises above the thin limestone, over a lenticular unit (up to 2 m thick) of gray shale grading upward to reddish mudstone, and delineates the local appearance of the thin limestone as an erosional outlier in an ancient "buried hilltop" with 3 m of relief in about 80 m along outcrop. This relief was subdued by sandy valley fill on the north and by muddier colluvium on the south prior to the next marine incursion, which deposited the Cambridge Limestone about 4 m above the Pine Creek outlier. The Cambridge unit correlates with the Quivira Shale (Dewey cyclothem) of the Midcontinent (figure 2), which is separated from the Stark Shale there by about 30 m of marine T-R units of lesser extent. These lesser T-R cycles are represented in this part of the Appalachian basin by a mainly erosional episode that excavated valleys and removed the Pine Creek marine unit across substantial areas; the marine highstands they record were not great enough to inundate the higher shelf present at this time in the Appalachian basin.

Even larger paleovalley fillings are recognized in the Appalachian basin. Martino (1992) noted that the mid-Conemaugh Saltsburg Sandstone in northeasternmost Kentucky comprises up to four stacked alluvial channel fills totaling 23 m in thickness. Donaldson and Mefford (1969) illustrated upper Conemaugh post-Ames sandstone units cutting out nearly 30 m of underlying strata for nearly 2 km along an exposure south of Steubenville, Ohio (figure 6); a zone with redbeds separating two of these sandstone units suggests that valley filling took place in at least two stages separated by a period of stabilization and soil formation, perhaps related to distant sea-level fluctuations. More recently, Aitken and Flint (1994, p. 355) interpreted paleovalley fills up to 60 m thick and several km wide cutting out underlying marine units in older Breathitt strata of Kentucky.

Illinois Basin. Along the southeastern margin of the Illinois basin, King (1992, 1993) delineated a subsurface dendritic paleovalley system at least 50 km long, and up to 6 km wide and 60 m deep, within upper Desmoinesian strata between the widespread Danville Coal and West Franklin Limestone (figure 2). The section in the paleointerfluve region comprises one or two coarsening-upward detrital sequences capped by a major paleosol. In contrast, the paleovalley-fill succession includes at least three more thin T-R units, each comprising a coaly zone overlain by a shelly marine bed, followed by a mudstone capped by an exposure surface (figure 7). The paleovalley system was incised into progradational sediments during a major post-Danville lowstand, and the minor coaly and marine beds were deposited only in the low area provided by the paleovalley during minor marine highstands that did not cover the paleointerfluves. Each marine bed in the paleovalley was covered by bayfill sediment that eventually became subaerially exposed during a minor lowstand. These minor T-R cycles are not recorded on the paleointerfluves but may be represented by thin coals and associated marine beds between the Danville coal and Lonsdale (=West Franklin) Limestone westward in the deeper part of the Illinois basin, and by lesser T-R cycles below the West Franklin equivalent (Lost Branch cyclothem) in the southern part of the Midcontinent basin (figure 2).

Sydney Basin. The Sydney basin of eastern Nova Scotia, within the northern Appalachian orogen, contains a succession of cyclothems of late West-

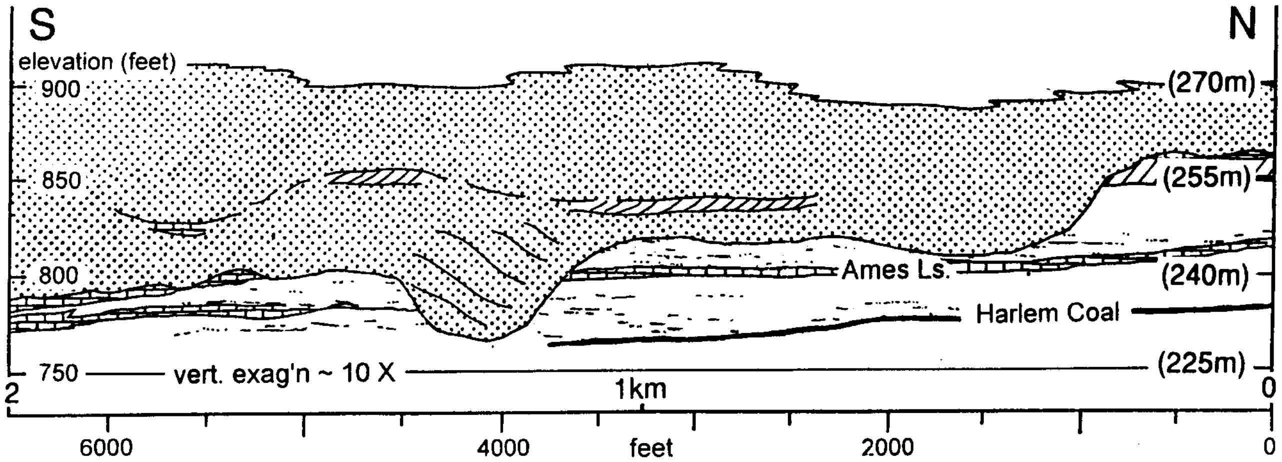


Figure 6. Paleovalley cutting down stepwise through nearly 30 m of Conemaugh strata (including Ames Limestone) along Ohio Route 7 south of Steubenville; it is filled with at least two stacked sandstone units (dots) separated by zone of redbeds (oblique lines), possibly paleosols (modified from Kovach 1979, figure 1.7, after Donaldson and Mefford 1969, p. 29).

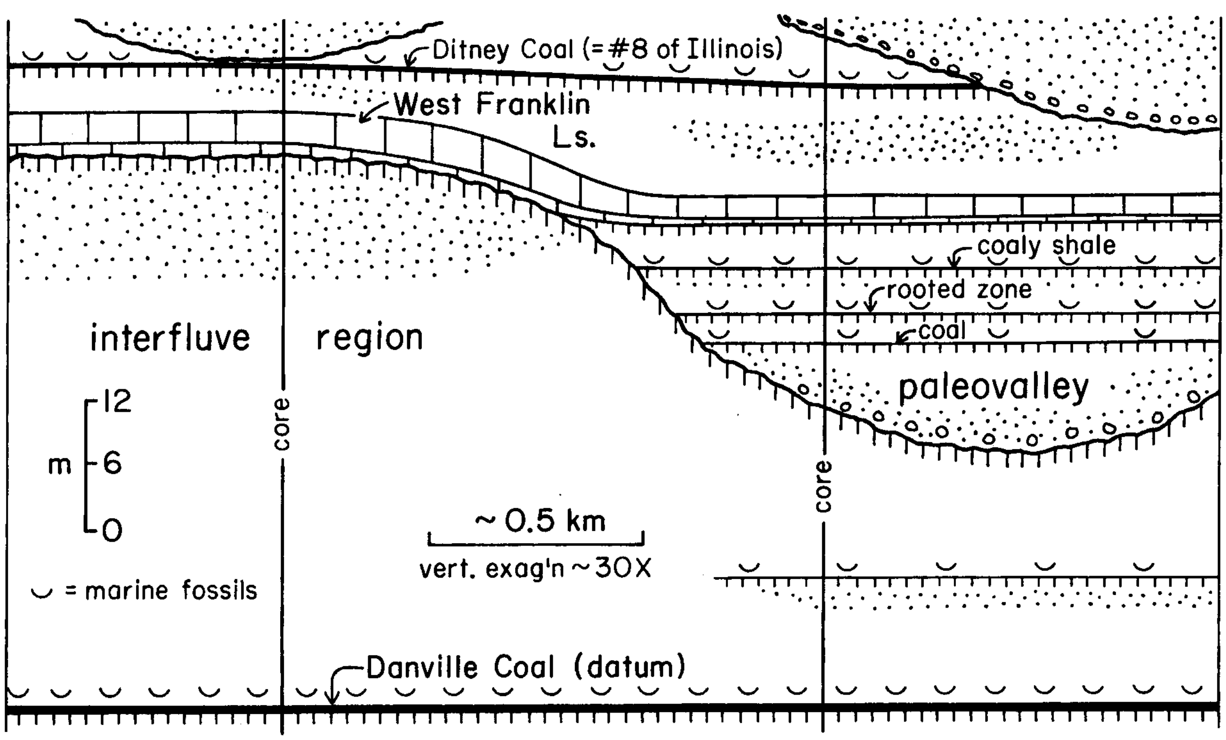


Figure 7. Inferred relations between stratigraphic successions in paleovalley (right) and interfluve region (left) between Danville Coal and West Franklin Limestone in southeastern Illinois Basin. Paleovalley contains record of minor marine T-R cycles capped by exposure surfaces (hachures) not represented in interfluves. Paleovalley system was interpreted by King (1992; in preparation) from grid of wireline well logs in southwestern Indiana; lateral relations shown here take place in 1 to 2 km in well-log grid, and lithic successions within the two areas are shown by logs of representative cores 15 km apart: Peabody Coal #3 Butler in NW-SE-NE sec. 19, T. 6 S., R. 13 W., Posey Co. Ind. (IGS file 282) in paleovalley; Bell & Zoller #2 Powell in SW-NW-SE sec. 3, T. 7 S., R. 12 W., Posey Co., Ind. (IGS file 154) in interfluve region.

phalian to early Stephanian (Allegheny-Conemaugh) age (Calder and Gibling 1994). These have laterally persistent intervals of coal beds and detrital deposits that contain marine marsh foraminifers (Wightman et al. 1993) and thus represent marginal marine highstand deposits. Above these intervals, late highstand deltaic/paralic bayfill deposits either grade up into thick paleosols (figure 8, unit C1), or are truncated by stacked channel sandstones (figure 8, unit C4) that fill paleovalleys cut when sea level stood much lower (Gibling and Bird 1994). The paleosol/paleovalley interval is overlain by reddish alluvial sediments (figure 8, unit D) that reflect renewed deposition during the subsequent sea-level rise (Gibling and Wightman 1994) that culminated in deposition of the next marginal marine to coastal-plain coal-bearing interval (figure 8, unit A). This glacial-eustatic signal persists at least 50 km from subbasin to subbasin, in spite of complex facies variation and the considerably greater tectonic subsidence evident here in the greater net accommodation space (400 m compared to 100–200 m for the roughly coeval Appalachian succession).

Conclusions

1. Recognition of these various erosional features shows that the mechanism of worldwide glacial-eustatic rise and fall of sea level first proposed by Wanless and Shepard in 1936 continues to clarify many notable characteristics of Pennsylvanian stratigraphy. These range from the high-frequency (10^5 yr) long-recognized classic cyclothems that alternate between exposure surfaces and offshore marine deposits in mid- to low-shelf positions, to the more recently appreciated evidence of substantial erosional incision and paleovalley formation between successive marine highstand deposits in higher-shelf (proximal) detrital regimes, which previously were attributed solely to tectonic uplift or to fluvio-deltaic incision at constant sea level.

2. The graphic model derived for the general cyclothem (figure 8) in high-shelf (proximal) detrital regimes inundated only at major marine highstand comprises: Widespread nearshore/marginal marine to coal-bearing lower coastal-plain intervals (A) formed during late transgression and into early marine highstand (Heckel 1995) are overlain by upward-coarsening deltaic/paralic detrital sequences (B) that prograded during late highstand. These are overlain either by thick paleosols developed on interfluves (C1), or by incised paleovalleys delineated by descending erosion surfaces (C2) overlain locally by slumps (C3), stacked valley-filling sandstones (C4), and colluvial fills representing landscape reduction (C5), all formed during lower sea-level stands. Some erosion surfaces are overlain by local coal beds and marginal marine deposits (C6) of lesser highstands confined to the paleovalleys. This entire complex in lower areas is overlain by colluvial/alluvial to estuarine sediments (D) deposited mainly during mid to late transgressive phases of the following major sea-level rise, capped by coal beds and other coastal-plain to nearshore marine units (A) deposited from latest transgression into the next major marine highstand. In higher areas, the coal beds directly overlie the thick paleosols. This range of sequences could be considered to represent the ''Appalachian cyclothem'' of late Middle to Late Pennsylvanian time. It is similar to that proposed by Williams et al. (1965, their figure 6) in a remarkably insightful but long-overlooked contribution to Pennsylvanian stratigraphy. Mid to late transgression (D) and highstand, both major (A) and minor (C6), are the phases when incised valleys provided adequate accommodation space to preserve the remarkably complete records of rapidly deposited estuarine tidal-flat sediments totalling several meters of vertical section (e.g., Martino and Sanderson 1993; Archer et al. 1994).

Implications

1. Prolonged lowstands would have provided enough time for erosion to form broad paleovalleys over much of the Appalachian high shelf while the shoreline was fluctuating only across the Midcontinent low to mid-shelf. The area of disappearance of the lower Allegheny ''Vanport'' (Obryan) Limestone delineated by Webb (1963) across 30 km of northeastern Kentucky, along with concomitant appearance of several additional thin coal and marine beds in this area of no Obryan, may represent a broad post-Obryan paleovalley that removed the Obryan Limestone and became filled largely by deposits formed during later minor marine incursions of lesser extent, like the Illinois basin example described above. More such features probably await discovery in similar stratigraphic settings.

2. Among lesser marine highstand units that filled the paleovalleys, later episodes of channeling may have removed only part of the paleovalley fill, leaving lenticular remnant terraces (figure 3*C*). This is an alternative explanation to deltas for lenticular Appalachian units delineated by Webb (1963) and other students of J. C. Ferm that are defined by local coal beds and marine units (e.g., Ogan-Zaleski-Winters of southern Ohio; Strasburg-Tuscarawas of northeastern Ohio). In any case, deltaic sedimentation that did take place during late highstand and early regression would have been fo-

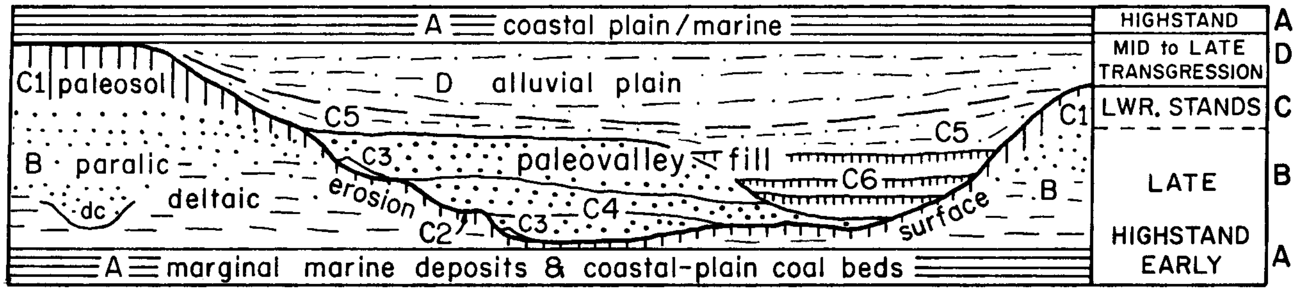


Figure 8. Model for detrital-dominated cyclothems in high-shelf (proximal) position (generalized in part from Williams et al. 1965, figure 6, for Appalachian basin; Gibling and Bird 1994, figure 10, for Sydney Basin of Nova Scotia; and modified on right side [C6] by interpretations of King 1992, 1993, in Illinois basin). Coal beds and associated transitional marine units (A) represent coastal swamp and marginal marine deposition prior to and during early sea-level highstand. These are overlain by late highstand deltaic/paralic clastics (B), with local distributary channels (dc), passing upward (on sides) to thick paleosols (C1), but cut out (in middle) by major erosion surface (C2) delineating a paleovalley formed during lower sea-level stands (C). Paleovalley fill above surface includes rotated slumps (C3), stacked sandstone bodies (C4) representing typical fill, colluvium (C5), and/or margins of cyclothemic marine incursions (hachured lines) from lesser highstands (C6). This part of cycle is overlain in lower areas by colluvial/alluvial shale and sandstone (D) deposited mostly late during next major sea-level rise, followed by next coal-bearing coastal-plain to marginal marine unit (*A*) deposited just prior to and during next major highstand. Coal beds commonly directly overlie major paleosols (C1) in higher interfluve areas (left side).

cused down the paleovalleys, resulting in lenticular units confined by the valley sides. The linear distribution and irregular outlines of Appalachian marine units mapped by Williams (1960) and Busch and West (1987) may reflect their confinement to erosional paleovalleys.

3. Recognizing the primary role of glacial eustasy in controlling the basic cyclicity of Pennsylvanian stratigraphy will allow tectonic effects on the stratigraphic pattern to be better constrained. Once glacial-eustatic cyclothems are correlated from basin to basin (e.g., figure 2), regional variations in net accommodation space can be related to large-scale tectonic control, as has been suggested above in comparing the Late Pennsylvanian Appalachian basin with the northern Midcontinent and Sydney basins. Moreover, certain local variations in thickness and facies successions can be attributed to small-scale tectonic effects (see Ferm and Weisenfluh 1989; Wise et al. 1991). Certainly, linear tectonic downwarping would provide a ready site for erosional valley formation during lowstand, and King (1992) noted possible fault control of paleovalley alignment in the Illinois basin. Also, invoking differential tectonic overprinting, the difference in the strata beneath the Ames Limestone along the northwestern Appalachian basin margin (well-drained paleosols, paleovalley fills, and lenticular coals) from those along the southeastern basin margin (less well drained paleosols capped by a widespread coal) may be related to increased rates of tectonic subsidence to the southeast (Joeckel 1995). This trend is consistent with both the thickening of the entire Conemaugh section and the generally better development of coals of this age in this same direction.

4. Lateral discontinuity of marine units in high-shelf settings can result both from erosional dissection of a once continuous unit (e.g., the Pine Creek outlier near Steubenville, figure 5) and also from confinement of marine units to a paleovalley system (e.g., the Illinois basin example, figure 7). If a depositionally discontinuous marine unit in a paleovalley lies near the elevation of an older, erosionally discontinuous marine unit now confined to the paleointerfluves (figure 3*D,E*), these temporally distinct marine units would probably be regarded as the same named unit, considering the general lack of lateral exposure. Presence of irregular erosional disconformities might help explain the complex relations of marine units such as the Putnam Hill and Vanport limestones (lower Allegheny) illustrated by Ferm (1970). Wardlaw et al. (1993) regarded the "Vanport" (Obryan) of southern Ohio as younger than the northern (type) Vanport based on conodont faunas, whereas Merrill (1968) regarded the southern "Vanport" as older; both claims hypothetically could be correct if the fossils were collected from discontinuous units of different ages. Proper biostratigraphic correlation of marine units in a high-shelf setting will require analysis of all exposures and cores within a carefully delineated lithostratigraphic framework, and avoidance of the assumption that biotic correlation of a named unit in one place applies to units given that name elsewhere.

5. Because the selection of a chronostratigraphic boundary requires a succession of continuous ma-

rine deposition, the only areas favorable for such a boundary in the glacial-eustatic Pennsylvanian System would be as basinward as possible. This means that the Middle-Late Pennsylvanian Series boundary (and any related stage boundaries) in North America should be selected in the southern Midcontinent (figure 2) rather than in any area to the north or east, where the successions were deposited higher on the shelf and are replete with significant disconformities.

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