Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along midcontinent outcrop belt, North America

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ABSTRACT

At least 55 cycles of marine inundation and withdrawal are recognized in the mid-Desmoinesian to mid-Virgilian Midcontinent outcrop sequence in North America. They range from widespread major cycles (classic cyclothems) with deep-water facies extending across the northern shelf, through intermediate cycles persisting as marine horizons across the shelf, to minor cycles developed on the lower shelf or as parts of major cycles. Biostratigraphic differentiation of the cycles should establish interbasinal correlation on a scale fine enough to allow evaluation of differential tectonics and sedimentation. Sequential groupings of cycles are more irregular than proposed megacyclothems or mesothems, but they may be obscured by the distinctness of the major cyclothems. Estimates of cycle periods range from about 40 to 120 × 10^3 yr for the minor cycles up to about 235 to 400 × 10^3 yr for the major cyclothems. The range for all cycles corresponds well to the range of periods of Earth's orbital parameters that constitute the Milankovitch insolation theory for the Pleistocene ice ages, and it further supports Gondwanan glacial control for the Pennsylvanian cycles. Even though the dominant period of the major Pennsylvanian cyclothems is up to four times longer than the dominant 100 000-yr period in the Pleistocene, the shapes of both curves display rapid marine transgression (rapid melting of ice caps) and slow interrupted regression (slow buildup of ice caps), which suggest similar linkages between the climatic effects of the orbital parameters and ice-cap formation and melting, at the two different scales, widely separated in time.

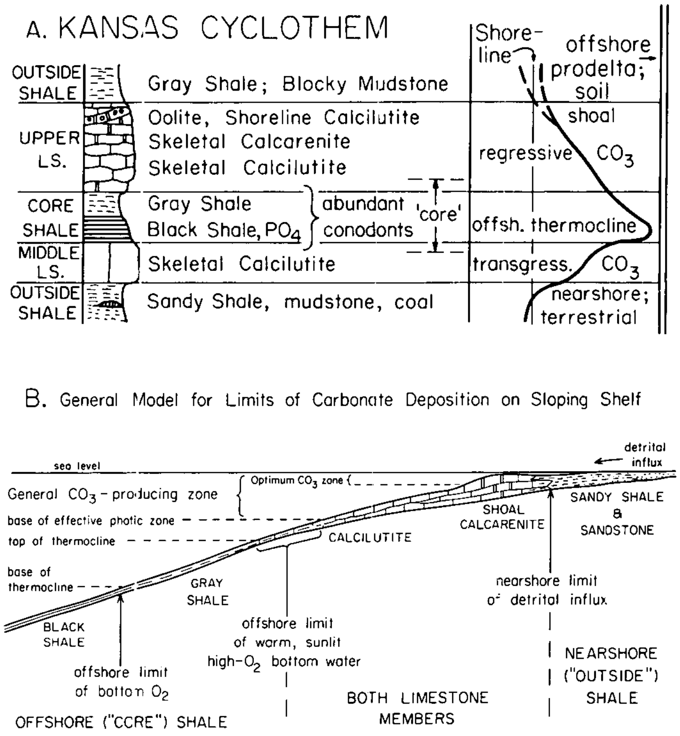


Figure 1. A: Basic four-member, trangressive-regressive, major ("Kansas") cyclothem in Midcontinent Pennsylvanian (modified from Heckel, 1984a). B: Model for deposition on sloping tropical shelf, showing positions of rock types that became superposed with transgression and regression to produce Kansas cyclothem (from Heckel, 1984b).

INTRODUCTION

Wanless and Shepard (1936) first proposed that the cyclic alternation of Pennsylvanian limestone and shale formations along the Midcontinent outcrop belt (Iowa to Oklahoma) resulted from widespread marine transgressions and regressions over the shelf, in response to eustatic rise and fall of sea level generated by waxing and waning of Gondwanan glaciation. This glacial-eustatic model recently was independently supported by Crowell's (1978) report of Gondwanan glacial deposits spanning the entire Pennsylvanian. Alternative autocyclic models of delta shifting applied to cyclic Pennsylvanian sequences in the Appalachians and Texas have been incorporated into the glacial-eustatic model by Heckel (1977, 1980). In view of the current effort to delineate eustatic sea-level changes in the Pennsylvanian (e.g., Ramsbottom, 1979; Busch, 1984; Ross and Ross, 1985; Boardman and Malinky, 1985), it is timely to present a sea-level curve for the Midcontinent outcrop belt and to examine its implications.

The basic Midcontinent cyclothem (Fig. 1A) consists upward of (1) thin, transgressive marine limestone; (2) thin, offshore, nonsandy, conodont-rich shale with black phosphatic facies; (3) thicker, shoaling-upward regressive limestone; and (4) nearshore to terrestrial noncarbonate strata. The complete sequence records (1) transgression (from the basin in Oklahoma) slow enough to form limestone over the northern Midcontinent shelf, (2) inundation far (deep) enough to establish a thermocline and thus the black shale over much of the shelf, (3) regression slow enough (and free of detrital influx) to develop limestone over the shelf, and (4) withdrawal far enough for soil to form, or for terrigenous detrital rocks to cover the limestone (Heckel, 1984b). Faster rates of transgression or regression or lesser extents of marine inundation or withdrawal produced marine horizons that lack various characteristics of the basic cyclothem. Because these less distinctive sequences, however poorly developed as cyclothems, are traceable marine horizons that represent a cycle of sea-level fluctuation, I use the term "cycle" for the general record of marine inundation and retreat.

For purposes of further analysis, I classify marine cycles into three categories that are merely subdivisions of an irregular continuum of cycle types: *Major cycles* record inundations far enough onto the shelf to form a conodont-rich shale to the northern limit of outcrop in Iowa and slow enough to develop enough of the other facies to be considered cyclothems. *Intermediate cycles* extend into Iowa and carry conodont-rich zones on the lower shelf but generally are not recognized as complete cyclothems. *Minor cycles* typically lack conodont-rich zones and extend across only the lower shelf, or represent minor reversals within more major cycles.

CRITERIA FOR CONSTRUCTING SEA-LEVEL CURVE

The extent of marine inundation is determined for the small cycles by how far onto the shelf the marine horizon is traced. Because most cycles extended beyond the northern limit of outcrop (Fig. 2), their relative extents of inundation are inferred by the direct relation of extent to amount of sea-level rise. The range of facies from deepest to shallowest in this sea (Fig. 1B) extended from black phosphatic shale, through gray shale (both rich in conodonts), through skeletal and algal calcilutite, to shoal-water and shoreline carbonates and coarser detrital facies. Thus, cycles with black phosphatic shales underwent the greatest amount of sea-level rise followed in succession by those that reached only the gray shale and various carbonates as their deepest-water facies in the northernmost exposures and cores. Supplementing this lithic progression is the offshore increase in conodont abundance and concomitant progression of appearance and disappearance of certain conodont genera shown by Heckel and Baesemann (1975) and Swade (1985).

The extent of marine withdrawal is determined by how far basinward a capping subaerial exposure surface or overlying terrestrial deposit is traced. Terrestrial deposits include (1) red to gray blocky mudstones, interpreted as paleosols (Prather, 1985; Schutter and Heckel, 1985); (2) in-place coals; and (3) alluvial shales and sandstones. Many terrestrial deposits grade basinward into thick deltaic sequences. Although small deltas may have formed locally during regression, many probably were eroded after withdrawal. Large deltaic complexes that formed at low stillstand, however, were preserved during the following transgression. Thus, even without evidence of terrestrial deposits, the position of shoreline at long-term lowstand is estimated by locating the thickest deltaic deposits between the successive marine horizons.

Because carbonate sedimentation occurred mainly during intermediate sea-level stands along the Midcontinent outcrop (Heckel, 1984b), thickness of transgressive limestones varied inversely with the rate of sea-level rise, and thickness of regressive limestones varied inversely with the rate of sea-level fall or of delta progradation. Given the inherent differences in the effect of rapid sea-level rise vs. fall on carbonate sedimentation, however, relative rates of transgression vs. regression are not estimated from comparing thicknesses of transgressive vs. regressive limestones, because transgressive limestones intrinsically should be thinner than regressive limestones (Heckel, 1984b). Because rapid transgression traps detrital influx in increasingly distant estuaries to produce a diastemic surface, the widespread presence of detrital influx within a transgressive sequence is evidence for a slight reversal of sea-level rise during a major transgression, as in the case of the Verdigris cycle (bottom of Fig. 2). Because the relative amounts of time spent at highstands and lowstands of sea level in different cycles are not readily estimated from the maximum transgressive or regressive deposits, similar times were estimated for highstand of the major cycles, and relative times at lowstand were related roughly to extent of withdrawal and abruptness of biotic changes.

IMPLICATIONS FOR CORRELATION

The sea-level curve (Fig. 2) can serve as a basis for detailed correlation of this segment of the Midcontinent Pennsylvanian sequence with other areas, inasmuch as it provides a framework for establishing biostratigraphic control. Even though these eustatic cycles ideally could be correlated by matching the patterns of extent of inundation and withdrawal (Busch and Rollins, 1984), differential tectonism and sedimentation render this practice progressively less certain the farther away it is tried. Therefore, it is imperative to establish the biostratigraphic characteristics of as many cycles as possible. Fossil groups that distinguish the major marine cycles include conodonts (Swade, 1985), which are abundant in the dark offshore shales on the shelf; ammonoids (D. R. Boardman, E. E. Chatelain, and R. H. Mapes, in prep.), which are abundant in their basinal equivalents; and fusulinids (Thompson, 1957), which are abundant in many of the limestones. Palynomorphs distinguish the terrestrial deposits between the marine cycles (Peppers, 1984). As this work progresses, the Midcontinent outcrop will become a critical area for integrating the biostratigraphic zonations based on different fossil groups. When firm correlations with more distant basins are made, then interbasinal differences in development of correlative cycles will allow assessment of differential tectonic and sedimentary events in the different basins. Watney (1984) already has assessed the relative roles of eustatic sea-level changes and differential subsidence in the western Kansas subsurface.

SEQUENTIAL GROUPINGS OF CYCLES

"Megacyclothems" were the first attempt at sequential grouping of cycles in the Midcontinent (reviewed in Heckel, 1984a). Best developed in the lower Shawnee Group (Fig. 2), they consist upward of (1) intermediate or minor cycle ("lower" limestone; e.g., Toronto, Spring Branch); (2) major cyclothem (e.g., Oread, Lecompton, each with "middle" and "upper" limestones separated by black shale; Heebner, Queen Hill); and (3) two minor or intermediate cycles ("super" and "fifth" limestones; e.g., Kereford–Clay Creek, Avoca-Ost). Although megacyclothems may be recognized in the Missourian (e.g., Plattsburg–Stanton–South Bend–Iatan), this and similar groupings below include two major cycles in the same megacyclothem (Iola-Wyandotte-Farley; Swope-Dennis-Cherryvale) and leaves one major cycle (Dewey) orphaned, so that the grouping loses its original distinctive character. Although undetected basinal cycles may round out megacyclothems nucleated around all the major cycles, there is no present evidence for them. In the Iowa Desmoinesian, Swade (1985) recognized that each major cyclothem (e.g., Upper Fort Scott, Pawnee) is followed upward by an intermediate or minor cycle producing a "super" limestone (e.g., Higginsville, Coal City). Including the shale-rich intermediate and minor cycles not detected then in Iowa, one may recognize megacyclothems nucleated around five of the six major Desmoinesian cyclothems, but three of them are incomplete.

"Mesothems," described from slightly older rocks in Great Britain by Ramsbottom (1979), consist upward of progressively more widespread cycles, closed by a major regression. This pattern may exist in the Midcontinent Hogshooter-Dewey and Farley-Stanton sequences (middle of Fig. 2), but because it is essentially the converse of the "super" limestone pattern of the megacyclothem, it is not apparent in the rest of the Midcontinent sequence. Busch (1984) defined mesothem-scale groupings of cycles between widespread "genetic surfaces" of regression in the Appalachian Missourian. These units consist of a widespread transgression followed upward by one or two less widespread transgressions, which is the "super" limestone pattern recognized in the Midcontinent. Although major regressive surfaces provide a more objective way to define boundaries of marine cycle groupings than searching for the megacyclothem or mesothem patterns, the vertical spacing of major regressions in the Midcontinent does not define uniform groupings. For example, the Lost Branch, Swope, and Dewey are major cycles bounded above and below by widespread regressions. Grouping them with either overlying or underlying cycles would include major regressions and also more than one major cyclothem within a grouping. The subdivision of the Midcontinent sequence by Ross and Ross (1985) into transgressive-regressive groupings with the mesothem pattern of Ramsbottom (1979) has disadvantages: omission of significant parts of the sequence (Iola-Wyandotte-Plattsburg; entire Shawnee Group) and lack of recognition that this mesothem pat-

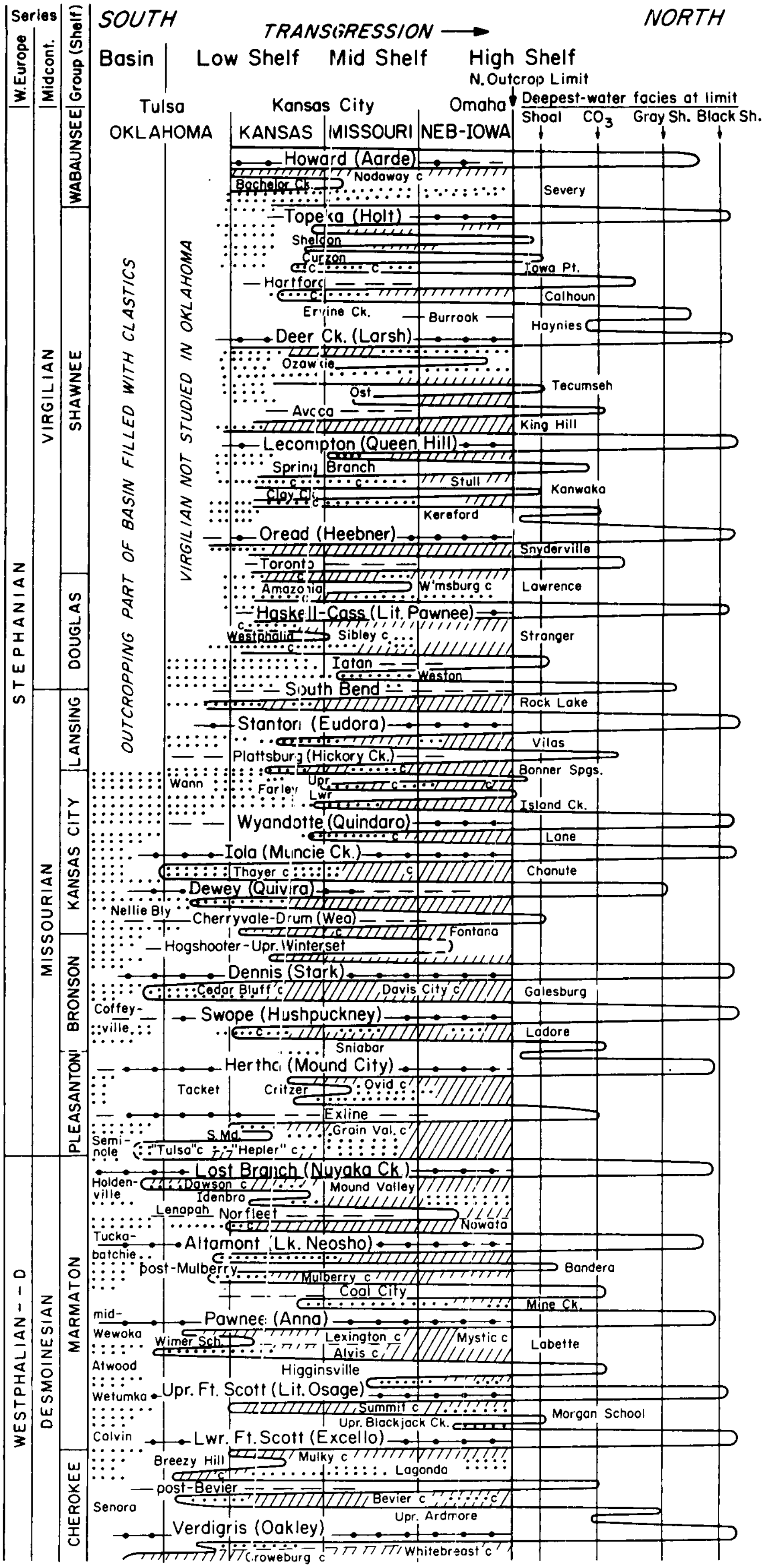
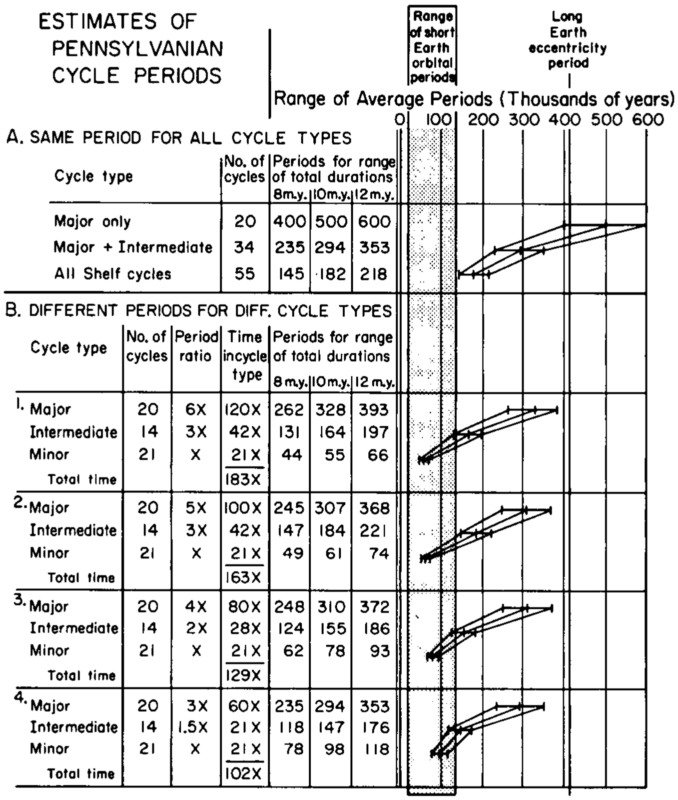


Figure 2. Sea-level curve for part of Middle–Upper Pennsylvanian sequence along Midcontinent outcrop belt, based on shoreline positions estimated from (1) farthest basinward extent of exposure surfaces (///) and fluvial-deltaic complexes (....) for lowstand and (2) farthest shelfward extent of marine horizons or deepest-water facies at northern outcrop limit for highstand. Size of letters in names of marine cycles on left side of curve reflects classification as major, intermediate, or minor for Figure 3. Names in parentheses after cycle names denote conodont-rich offshore shales, both black (solid line with dots) and gray (dashes). Names on right of curve are nearshore to terrestrial shale and coal (c). Names on far left are basinal and southern shoreline facies. After clastics filled basin (on outcrop) from south, sea withdrew southwestward (into subsurface) as shown by breaks in curve at lowstand. Vertical scale approximates time. Data sources include outcrops, long cores for Desmoinesian to lower Shawnee, theses cited in Heckel (1977, 1984b), and State Geological Survey publications. Sequence ranges from 260 m in Iowa to 550 m in Kansas.

tern does not apply to much of the Midcontinent sequence. In any case, mesothem-scale groupings that may exist in the Midcontinent sequence appear strongly obscured by the extraordinary distinctness of the major cyclothems.

PERIODICITY OF CYCLES

The Stephanian of western Europe lasted about 10 m.y. (296 ±5 Ma to 286 ±7 Ma), and its top correlates with a horizon just above the top of the Virgilian (Harland et al., 1982). The base of the Stephanian correlates with the base of the Missourian (Peppers, 1984). The sequence under study extends from near the middle of the Desmoinesian (low Westphalian-D) to near the middle of the Virgilian (about three-fourths through the Stephanian). To accommodate uncertainty of both age determinations and correlations, computations were made for a range of values (8, 10, and 12 m.y.) for the duration of this sequence. Heckel (1980) divided 25 cyclothems into 10 m.y. to obtain a 400 000-yr period, but this method may overestimate cycle length (Fig. 3A) because it ignores the shorter cycles or assumes that all are part of the major cycles. To attain more realistic estimates of cycle periods, the presumably shorter minor cycles were assigned unit durations (X on Fig. 3B), and the presumably progressively longer intermediate and major cycles were allotted four arbitrary sets of different multiples of minor cycles.



A. SAME PERIOD FOR ALL CYCLE TYPES

Cycle type	No. of cycles	Periods for range of total durations 8m.y.	10m.y.	12m.y.
Major only	20	400	500	600
Major + Intermediate	34	235	294	353
All Shelf cycles	55	145	182	218

B. DIFFERENT PERIODS FOR DIFF. CYCLE TYPES

Cycle type	No. of cycles	Period ratio	Time incycle type	Periods for range of total durations 8 m.y.	10m.y.	12 m.y.
1. Major	20	6X	120X	262	328	393
Intermediate	14	3X	42X	131	164	197
Minor	21	X	21X	44	55	66
Total time			183X			
2. Major	20	5X	100X	245	307	368
Intermediate	14	3X	42X	147	184	221
Minor	21	X	21X	49	61	74
Total time			163X			
3. Major	20	4X	80X	248	310	372
Intermediate	14	2X	28X	124	155	186
Minor	21	X	21X	62	78	93
Total time			129X			
4. Major	20	3X	60X	235	294	353
Intermediate	14	1.5X	21X	118	147	176
Minor	21	X	21X	78	98	118
Total time			102X			

Figure 3. Estimates of periods of Pennsylvanian cycle types (major, intermediate, minor). A: Assuming same period for all cycle types. B: Assuming different periods for different cycle types based on four sets of arbitrary "period ratios"; minor cycle period, X, is multiplied by period ratio and by number of cycles of each type to compute "time in cycle type," from which X is derived by dividing sum ("total time") into total duration of sequence; longer cycle periods are products of X and period ratios. Although some minor cycles are parts of major cycles, all were computed separately, which reduced periods of major cycles somewhat. All minor cycles fall within range of short Earth orbital periods, and all cycles fall within range of all orbital periods, for all period ratios shown.

For all ranges of assumptions, the minor cycles show periods from 44 000 to 118 000 yr, which fall within the range of the four shorter dominant periods of Earth's orbital cycles that form the Milankovitch insolation theory for control of the Pleistocene ice ages. The cyclic orbital parameters are *precession*, two dominant periods averaging 19 000 and 23 000 yr; *obliquity*, a dominant period near 41 000 yr; and *eccentricity*, two dominant periods, one averaging about 100 000 yr (but ranging from 95 000 to 136 000 yr) and the other about 413 000 yr (Imbrie and Imbrie, 1980). Although how much these periods may have changed in the 300 m.y. since the Pennsylvanian is not indicated, Fischer (1982) summarized evidence for cycles of approximately these periods from several times during the past 700 m.y.

The major Pennsylvanian cycles show a range of periods from 235 000 to 393 000 yr (Fig. 3B), which approaches the long 413 000-yr eccentricity cycle (and would be closer if the minor cycles that are parts of major cycles were omitted from the computations). Thus, the range of estimates for Midcontinent Pennsylvanian periodicity corresponds well to the range of the dominant periods of Earth's orbital parameters and provides empirical evidence for their basic control over stratigraphic patterns in the distant past. Midcontinent periodicity is less than the 800 000-yr periods estimated by Driese and Dott (1984) and Loope (1985) for Pennsylvanian cycles in Utah; scarcity of marine deposits suggests that Utah was higher on a shelf and therefore lacks many inundations of lesser extent.

In addition to variation in extent onto the shelf (Fig. 2), there are significant differences in thickness and facies in homologous carbonates among cycles that I have classified together. This suggests different rates as well as extents of transgression and regression, hence different periods among cycles of the same type. Thus, cycles appear distributed in an irregular continuum across the range of types, rather than in a regular hierarchy of discrete types. This irregular pattern is expected from the quasi-periodic nature and amplitude variations in especially the eccentricity cycles, because all orbital parameters interfere, dampen, and amplify, to produce the complex patterns through time illustrated by Imbrie and Imbrie (1980). This irregularity is accentuated by the local threshold and feedback effects inherent in the linkage between insolation values of the orbital curves and the formation and melting of the ice caps that actually control sea level. Busch and Rollins (1984) suggested a hierarchical ranking of Pennsylvanian cycles into fourth-order mesothems, fifth-order cyclothems, and sixth-order minor cycles. The problems with recognizing mesothems addressed previously, along with the problem of where to fit the intermediate cycles, call for caution in applying the ranked hierarchy to the Midcontinent because of the discrete groupings that it implies. A statistical spectral analysis is needed to detect all dominant periods in the Midcontinent data.

It is noteworthy that the estimated periodicity of the minor Pennsylvanian cycles corresponds to the 40 000- and 100 000-yr cycles observed in Pleistocene deep marine cores and terrestrial deposits, whereas that of the major Pennsylvanian cyclothems corresponds to the 250 000- to 400 000-yr cycles observed in Tertiary deep marine cores by Moore et al. (1982). They attributed the Tertiary dominance of longer cycles to the glacial control of Antarctica alone, which is consistent with the control of Gondwanan glaciation alone over Pennsylvanian Midcontinent cyclicity, where the longer-period cyclothems are the dominant stratigraphic feature.

The actual linkage between the insolation variation caused by the orbital parameters and the buildup and melting of ice caps, modeled theoretically by Imbrie and Imbrie (1980) and actualistically by Denton and Hughes (1983) for the Pleistocene, involves slow buildup and rapid melting of ice caps, which translates into slow regressions and rapid transgressions of the sea. This trend is seen in the shapes of Pleistocene sea-level curves inferred from oxygen-isotope data (Imbrie and Imbrie, 1980; Denton and Hughes, 1983) and would accentuate the sedimentological tendency toward thin transgressive limestones and thick regressive limestones in the Pennsylvanian. These Pleistocene curves also show a strong tendency toward minor reversals during the slow buildup of ice caps, which is the pattern seen in the minor transgressive "super" limestones during regressions closing most major Pennsylvanian cyclothems. Thus, despite the difference in scale of the dominant periodicity between the Pennsylvanian and Pleistocene, similar patterns of change are common to both. This similarity suggests that the linkages between the climatic effects of the orbital parameters and the waxing and waning of ice caps had similar characteristics at these two different scales in widely separated times.

The punctuated aggradational cycles (PACs) recently recognized in the regressive phase of the Dennis cyclothem (Heckel and Watney, 1985) record minor reversals of sea-level fall not shown in Figure 2. These would decrease the period length of shorter cycles in Figure 3 and reflect more directly the shorter orbital parameters as suggested by Goodwin and Anderson (1985). Further minor cycles can be added to the sea-level curve when these PACs and other features, such as fluctuations in conodont abundance or episodes of detrital influx, are corroborated as eustatic by correlation over substantial distances.

With time, increasingly accurate Pennsylvanian sea-level curves, particularly when correlated among several basins, may provide more accurate glimpses of the nature of the interaction of the orbital parameters at 300 Ma. In view of the uncertainties of extrapolation expressed by Berger (1980), these curves may serve as calibrators for extending our knowledge of the parameters into the distant past. After learning that the present is a key to the past, several of us have suggested that the Pleistocene is a key to the Pennsylvanian. Perhaps the Pennsylvanian will become a key to the Phanerozoic.

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Reviewer's comment

A most significant paper that makes giant strides between the stratal record and major Earth events.

John Crowell