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WENLOCKIAN AND LUDLOVIAN SEDIMENTARY AND BIOTIC EVENTS IN THE MIDWESTERN CRATONIC AREA, U. S. A.

Abstract. A series of Silurian sequences of the Great Lakes area and the history of the basin development record a cyclic pattern in sedimentation and in biotic developments. Such cyclicity seems to be caused both by tectonism and relative sea-level changes. A strong argument exists that the reason for two major cycles was eustasy.

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Global Bioevents

Introduction

During the Wenlockian and Ludlovian ages, the midwestern U. S. A., as a part of the large North American craton, experienced one of its greatest shallow-marine submergences of Phanerozoic time. Although general tectonic quiescence prevailed in this area then, three intracratonic basins subsided. They were separated by a platform that ultimately became the named broad arches of today (Fig. 1). This area was then south of the equator, mostly in what would be the drying climate of the Southeast Trade Winds belt if Silurian climates paralleled those of today. Eastern and southern highlands of the Laurentian subcontinent, which shed siliciclastic sediments, were distant from the midwestern part of the craton. These sediments had only modest intermittent (early and late Wenlockian) influence in the Midwest until after the close of Wenlockian time. Then an appreciable early Ludlovian siliciclastic influx occurred. Deep-water regimes were rare because basin and platform sedimentation proceeded at about the same rates as did subsidence and/or sea-level rise. A deep-water regime may have prevailed in the central Illinois Basin during later Silurian time.

These circumstances resulted in overwhelming dominance by carbonate sedimentation, which had a strong cyclical overprint for reasons that are debated. Major exceptions occurred in the central Michigan Basin, where evaporites became far more abundant than did carbonate rocks, and in the Appalachian Basin, where evaporitic and siliciclastic deposition became dominant after a carbonate beginning.

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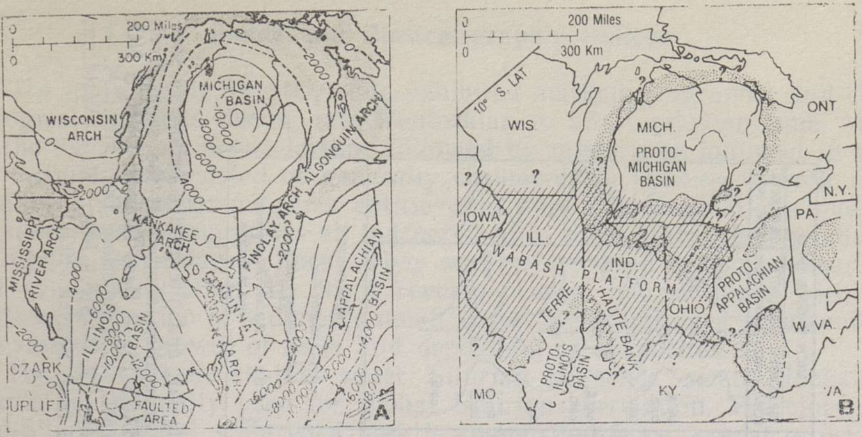

Fig. 1. Maps showing the study area and major tectono-sedimentational features. *A* — Area of present outcrop of Silurian rocks (shaded) and present structure shown by contours drawn on top of Precambrian basement rocks (interval 610 m). *B* — Loci of some Silurian structural features that differed partly or wholly from present features and loci of some major Wenlockian-Pridolian carbonate-bank-and-reef complexes (stipple); approximate area of Wabash Platform is crosshatched. Adapted from Droste and Shaver (1983, 1987a).

At one sedimentational extreme, individual salt beds, including some potash-salt beds, reached as much as 150 m in thickness in the central Michigan Basin. There, salts constitute most of the nearly 1,200 m of Silurian rocks. At another extreme, the Wenlockian rocks include the beginnings and some termini of probably the greatest single generation of Silurian reefs (Fig. 2), which number in many thousands, if not millions, in the Midwest. The thickest of these reefs, whose substance was furnished largely by cosmopolitan biotas, are pinnacle reefs in the peripheral Illinois Basin, some of which are about 300 m thick. Thicknesses this great span an age range of early Wenlockian through probably the entire Pridolian. The bulk of the extremely high-purity, skeletally derived carbonate rocks, however, is Wenlockian to early Ludlovian in age and is found in enormous biostromes and carbonate-bank-and-reef complexes that cover thousands of square kilometers and have their greatest thicknesses (as much as 160 m) along the basin-platform transitions.

Although minor unconformities in some places separate the two major sedimentational end members, the overall regional relationship is thought here to be one of general facies (time sense) between evaporite- and reef-bearing rocks. In single sections, the evaporite-bearing rocks are on top.

The entire Silurian System in the platform part of the midwestern cratonic area probably did not exceed 300 m in thickness before erosion. It is dominated by skeletally derived Wenlockian and Ludlovian rocks. The Silurian System in the Michigan Basin is four to five times thicker; in the Appalachian Basin, about three times thicker. Thickness hardly reached 300 m in the Illinois Basin, which contains no Silurian evaporites and fewer siliciclastic sediments than does the Appalachian Basin.

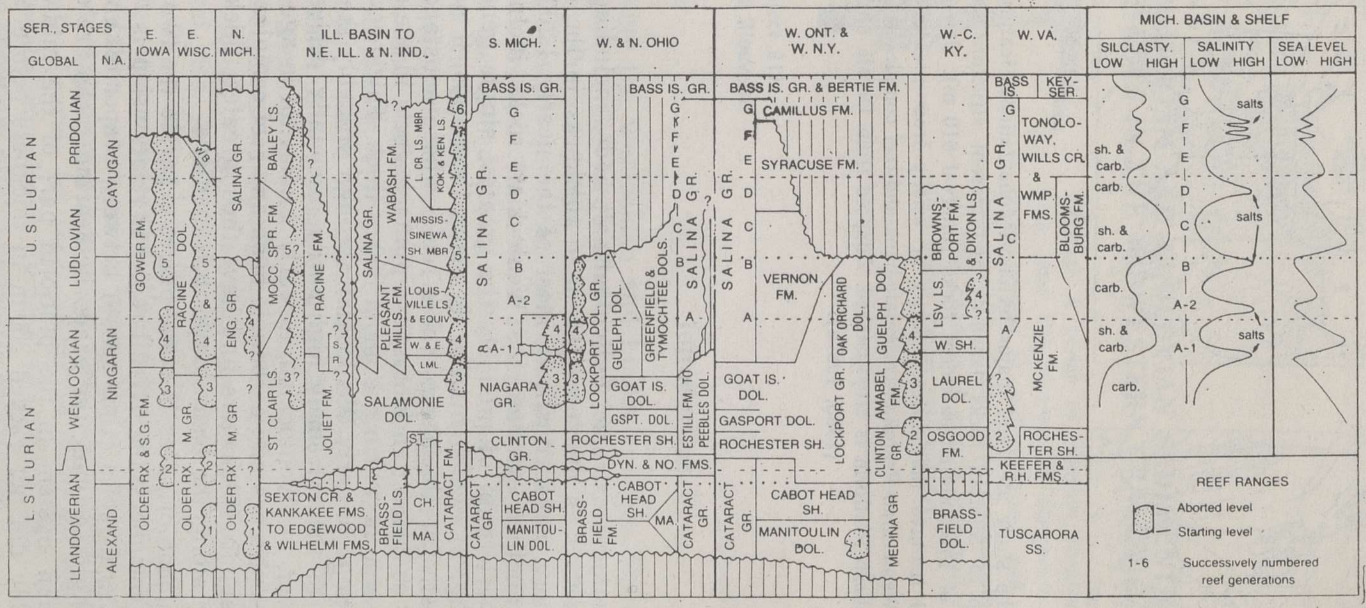

Fig. 2. Chart showing stratigraphic nomenclature for the study area, ranges of six principal reef generations (stipple), and interpretive factors in sedimentation. Note: common starting levels are the basis for a numbered reef generation, but not all reefs of one generation aborted at the same level; for example, some generation-3 reefs survived to near the end of Silurian time. Explanation of abbreviations: BASS IS. — Bass Islands; DYN. & NO. — Dayton and Nolan; ENG. — Engadine; KEN. — Kenneth; KOK. — Kokomo; L. CR. — Liston Creek; LML. — Limberlost Dol. Mbr.; M. — Manistique; MOCC. SPR. — Moccasin Springs; R. H. — Rose Hill; S. G. — Sugar Grove; S. R. — Sugar Run Fm.; ST. — Stroh Mbr.; W. — Waldron; WB. — Waukakee Dol.; W. & E. — Waldron and equiv.; and WMP. — Williamsport. Adapted from Shaver (1991).

Biotas and Biostratigraphic Indices

The midwestern Silurian biota exhibited marked geographic and chronological contrasts during mid-Wenlockian to mid-Ludlovian time. Much of the biota experienced fortune followed by misfortune followed in turn by fortune. It consisted of generally cosmopolitan entities in both reefs and level-bottom communities, entities that were distinct from one another. At times these communities all but perished in some places, being reduced to high-salinity-tolerant floras. They were rejuvenated in some places but not everywhere (Fig. 3). Such reversals went hand-in-hand with the cyclical production of sediments noted above, including most spectacularly the reciprocal growth of reefs and deposition of evaporites.

The midwestern shallow-water Silurian sequence mostly lacks the graptolites normally used for global Silurian correlation. Therefore, the mid-Silurian zonal scale used here is composited from several groups of fossils (Fig. 4), and the Wenlockian—Ludlovian boundary has been placed with a working accuracy within the midwestern rocks. As shown by Fig. 4, the boundary depends on several types of fossils, including *Monograptus bohemicus* (Ludlovian); boundary-transitional conodont lineages made up of *Ozarkodina* and *Kockelella*; the conodont *O. eosteinhornensis* (late Ludlovian? and younger); the pentameracean brachiopod lineage ranging from smooth-shelled *Pentamerus oblongus* (Wenlockian and older), through the intermediate *Lissocoelina* (late Wenlockian), into such ribbed forms as *Rhipidium* and *Kirkidium* (latest Wenlockian? and younger); and various dizygopleurid and thlipsurid ostracods (Ludlovian and younger). All these named taxa have been found consistently in vertically collated strata, especially in the platform area; fewer have assured positions in the basins.

Rocks and Depositional Events

Wenlockian Stage. The bulk of the midwestern Wenlockian Stage that was deposited outside the Michigan Basin is made up of light-colored, high-purity, skeletally derived (nonreef and reef) carbonate rocks, now mostly dolomite. Some have purity as high as 99% (e. g., St. Clair, McKenzie, and geographically intermediate equivalents as shown in Fig. 2). Although partly eroded, these rocks remain in a blanket extending from western New York and Ontario to Iowa and Arkansas and beyond (Fig. 5*A*). They are the thickest, possibly more than 150 m, in some of the places where they begin descent into basins. In some places a part of this thickness is made up of early Ludlovian rocks of similar origin that are not lithologically distinct from latest Wenlockian rocks (Fig. 5*C*). These pure carbonate rocks thin out in central platform areas and in some parts of the structurally deeper sections of basins to as little as 12 m. The thickest tracts describe impressive carbonate bank-and-reef complexes that marked the effective edges of then-active basins.

The thin lower part of these Wenlockian rocks, rarely more than a few meters thick, is impure, having both chert and fine siliciclastic fractions (e. g., lower Joliet, Stroh, Clinton, Rochester, and Osgood; Fig. 2). The units named above are partly Llandoverian in age, and they relate to a late Llandoverian—early Wenlockian transgression (deepening) that followed the development of an unconformity in some structurally high places.

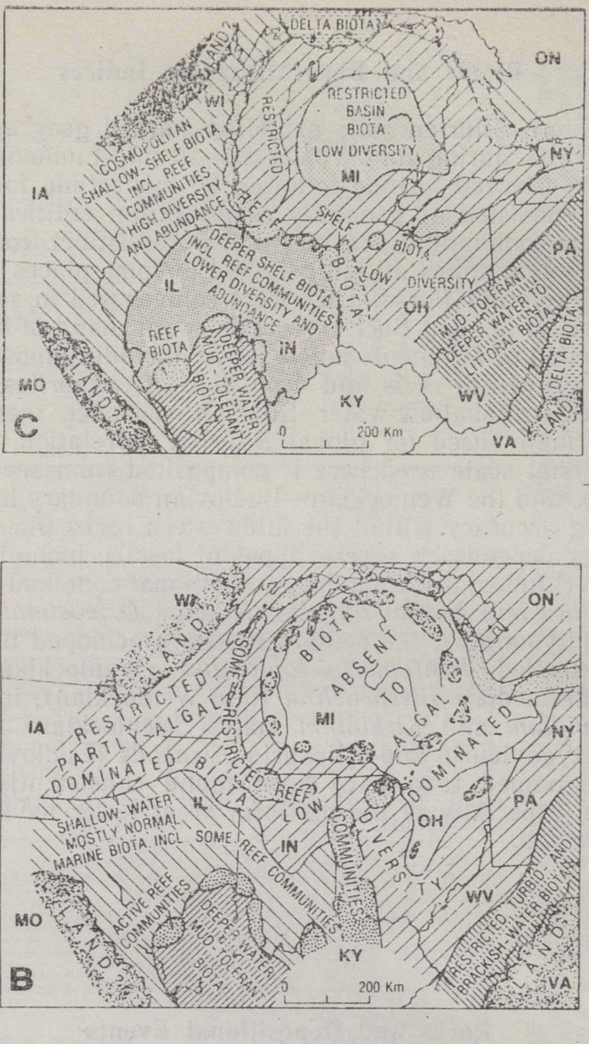

Fig. 3. Maps showing dominant biotic character. *A* — Mid-Wenlockian time; *B* — late Wenlockian—early Ludlovian time; *C* — mid-Ludlovian time. From Droste and Shaver (1987b).

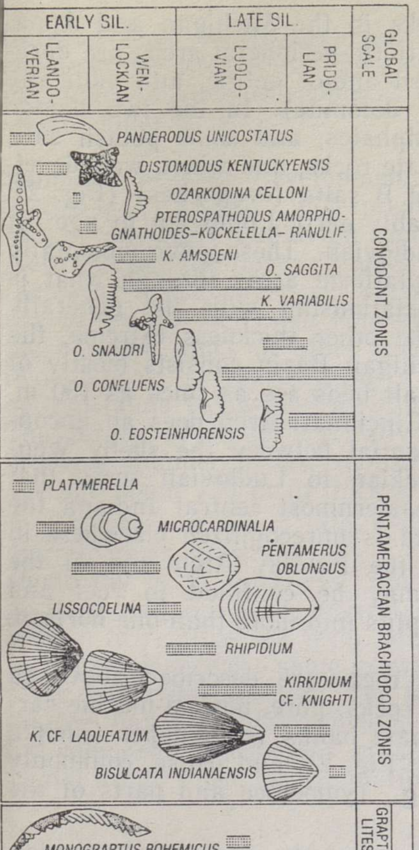

Fig. 4. Chart showing use of some key fossils for regional and global correlation of midwestern Silurian rocks. Adapted from Droste and Shaver (1985). (See Fig. 2 for abbreviations.)

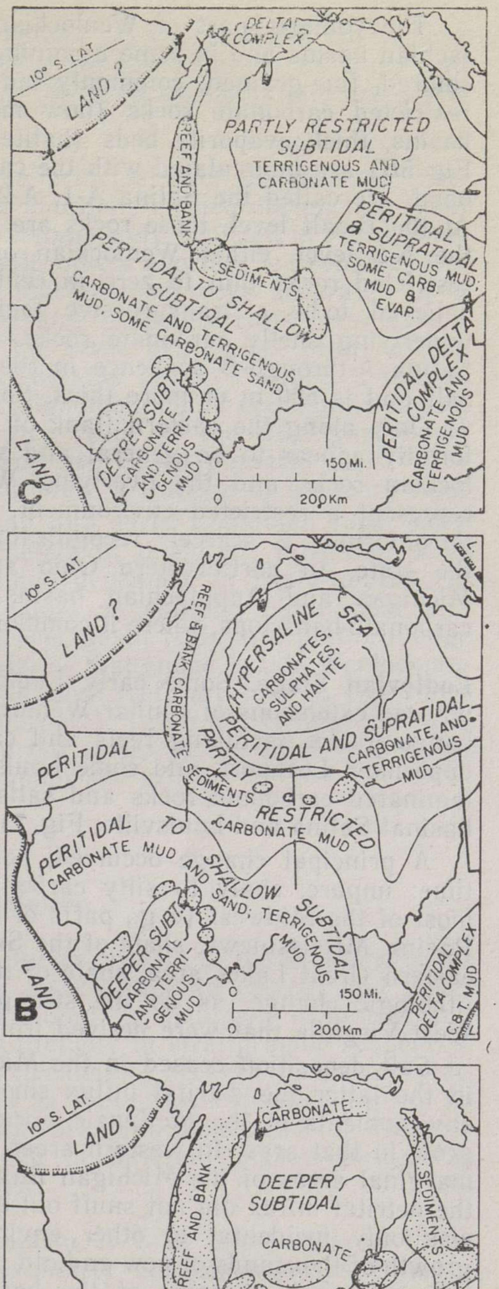

Fig. 5. Maps showing paleogeography and dominant sedimentational character. *A* — Mid-Wenlockian time; *B* — late Wenlockian—early Ludlovian time; and *C* — mid-Ludlovian time. From Droste and Shaver (1983).

The younger part of Wenlockian rocks in the Michigan and Appalachian basins and in some adjoining platform-peripheral areas are dark-colored, fine-grained, commonly laminated and/or oolitic, and biotically restricted carbonate rocks (now mostly dolomite). In the two named basins, thick evaporite beds (halites, sulphates, and some potash salt; Fig. 5*B*) are intercalated with the carbonate rocks, and where well developed, are called the Salina A-1, A-2, and B salts (evaporites) (Fig. 2). At the B-salt level, these rocks are probably early Ludlovian in age; at the A-2 level, either Wenlockian or Ludlovian. These environmentally restricted rocks thin to zero in central platform areas through what is believed to be a transgressive facies relationship with the generally underlying shelly carbonate rocks. At the other thickness extreme, the Salina A-through-B sequence in the Michigan Basin consists mostly of salt and is 500 m or more thick. Some salt beds are as thick as 150 m.

Only along the eastern flank of the Cincinnati Arch does an unconformity appear to be general and substantial between the shelly Wenlockian rocks and the overlying Wenlockian to Ludlovian rocks that represent a restricted environment. In easternmost central Indiana the unconformity is scarcely recognizable and is unrecognized elsewhere in the state. In northwestern Ohio along the Findlay Arch and in the Michigan and Appalachian basins it may be confined to reef and carbonate-bank tops, where it commonly splits into more than one horizon.

Ludlovian Stage. Some early Ludlovian rocks are described above as upward extensions of similar Wenlockian rocks: pure, normal-marine carbonate rocks, including reefs and carbonate banks (e. g. upper Guelph, uppermost Lockport, and some Louisville; Fig. 2), and dense, commonly laminated carbonate rocks and salts (e. g., Tymochtee and parts of the basinal Salina and Louisville; Fig. 2).

A principal change occurred, however, near the onset of Ludlovian time: impure, shaly to silty carbonate rocks were deposited widely in most of the Midwest (e. g., parts or the wholes of the Moccasin Springs, Racine, Mississinewa, shale of the Salina C unit; Figs. 2 and 5*B*). In the eastern Great Lakes area, shale of the Vernon Formation represents this lithologic change, as do the strongly siliciclastic deltaic sediments in West Virginia that were derived from eastern rising highlands.

Salt deposition ceased in the Michigan and Appalachian basins, and in the latter the detrital influx smothered the reef and other carbonate environments of the McKenzie Formation. Silurian reefs did not again grow in that area. In western areas, including the southern and western marginal areas of the Michigan Basin and the peripheral Illinois Basin, the detrital influx did not snuff out extant reef growth; rather, this influx was only incidental to other environmental change that fostered the growth of thousands of new and old platform-situated reefs and continued-to-new growth in some of the basin-fringing carbonate bank-and-reef complexes.

The most impressive phases of this new reef growth are represented in the Moccasin Springs, Racine, and Wabash formations (Fig. 2). There, the thickest pinnacle reefs, which have St. Clair bases within the Illinois Basin, eventually reached nearly 300 m in thickness by the end of Silurian time. The greatest thickness was attained during post-Wenlockian time. By Ludlovian time, the main loci of carbonate bank-and-reef deposition around the Michigan Basin had shifted platformward, mostly beyond Michigan's borders. Therefore, the Michigan Basin was effectively expanded, and salt deposition was eventually resumed therein in latest Ludlovian and Pridolian time (D unit and younger, Fig. 2). Many reefs of this early Ludlovian generation were not aborted until the close of

Silurian time. Where they are less eroded on the platform in western Indiana, the largest examples of these generally elliptical buildups and irregularly coalesced complexes exceed 130 m in thickness and are a few square miles in area.

Summary of Reef Development. Three principal reef generations (nos. 3—5, Fig. 2) and two widespread reef abortions ensued during late Wenlockian and early Ludlovian time. As incompletely depicted in Fig. 2, some reefs aborted and never resumed growth; others aborted, rejuvenated, and reaborted; some developed vertically stacked reef rocks separated by a few to several meters of nonreef rock; and still other reefs grew during the abortive times of other reefs of the same generation. Many of the two-stage reefs (representing a start-and-stop history) exhibit a cosmopolitan fauna below and a restricted, algae-dominated community above. The larger of these vertically complex reefs in the Michigan Basin probably number in few thousands and are called pinnacle reefs. They average about 120 m in thickness and cover a fraction of a square mile.

For parts or all of late Wenlockian and early Ludlovian time, some discrete reefs grew only to 1 or 2 meters in thickness; others grew to about 150 m in thickness. Size attained depended on basin-to-platform position and on such interrelated factors as salinity, circulation, and change in relative sea level. Many deeper basin reefs and platform-edge reefs experienced the same growth histories that ended in late Wenlockian-early Ludlovian abortion. The basin-situated reefs are four to five times thicker than their platform-edge counterparts. This ratio is near the ratio for composite thicknesses of all Silurian rocks in the Michigan Basin (1,200 m) to those on the platform (about 300 m).

Interpretation

A Midwestern Testing Ground. The Silurian System of the southern Great Lakes area is especially strategic for testing the two current and somewhat opposed schools of thought that tend to champion tectonism and global eustasy respectively to explain cyclicity in stratigraphic sequences. The differentiation in lithologies and thicknesses between basin and platform deposits demands interpretation in these two causative lights. So does the multiple-scale cyclicity in both rocks and biotas and the different magnitudes of unconformity developed in different places during the Wenlockian—Ludlovian time transition.

Evidence Favoring a Dominant Tectonism. A 4- or 5-to-1 ratio of thicknesses between, for example, approximately contemporaneous Silurian rocks of the Michigan Basin and the southern platform area suggests a differential rate of subsidence (tectonism) to eventually accommodate respective original thicknesses of about 1220 m and an estimated maximum 250 m. The generally shallow water lithologies do not support the idea of initial Silurian depths that in time accommodated the total thicknesses. Further, sediments accumulated in some places to or near sea level only to be covered by new rocks deposited below sea level.

Another evidence of dominant tectonism is the differential magnitude of the approximately late Wenlockian unconformity developed along the Cincinnati, Kankakee, and Findlay arches. This unconformity has significant magnitude east of the axis of the Cincinnati Arch in southwestern Ohio, where most or all the Ludlovian rocks are omitted, but is less prominent and even disappears northward and westward.

Evidence Favoring Relative Sea-Level Change or Other Cause. The cyclicity in sedimentation and in biotic fortune that has been described must be related at least in part to fluctuation in relative sea level. Two or more scales of periodicity are evident, however. One periodicity is of the scale approximating the lengths of the Wenlockian and Ludlovian ages.

The Wenlockian began with the lingering effects of a late Llandoverian to early Wenlockian development of an unconformity. The transgression (relative sea-level rise) that followed gave rise to a thin deepening-upward sequence changing to a thicker shallowing-upward sequence.

The upper part of this shallowing-upward sequence was complicated by comparatively rapid relative deepenings and shallowings, if not also by other cyclical factors such as climatic changes, so that a series of alternating evaporite and carbonate rocks was deposited in two separate basins. Additional phenomena, such as reef abortion/generation and development of local unconformities also occurred generally. The changes in relative sea level seem necessary to explain such events as influxes of far-travelled siliciclastics in the normal-marine Waldron Shale Member (Fig. 2) that separates strata representing more restricted, high-salinity environments. Periodically high salinities, accompanied by biotic restrictions and development of oolite shoals, suggest shallowings that fostered reduced circulation.

The Wenlockian ended at about the time of deposition of the Salina A-2 salt, but the principal shallowing-upward event, culminating in the B salt and equivalent rocks, may have ended during early Ludlovian time.

A similar major cycle of relatively quick transgression and deepening (represented, for example, in about 10 m of transitional Louisville-Mississinewa and equivalent rocks) began during early Ludlovian time. It was followed by longer regression and shallowing-upward deposition until somewhere within Ludlovian time or near the beginning of Pridolian time. Both cycles seem to compare best with what would be a third-order cycle of global sea-level change described by Vail et al. (1977) and also seem to be the same cycles recognized globally by Johnson et al. (1991). Here, therefore, is strong evidence for global eustasy being reflected in midwestern cratonic Silurian rocks.

The smaller scale cyclicity that is evident on either side of the Wenlockian—Ludlovian boundary and that finds expression in alternating salts and carbonate rocks in two basins has not been collated precisely in the more continuously normal marine history of the southern platform area and the Illinois Basin. Such cyclicity may be of fourth-order or lesser magnitude in its periodicity and remains somewhat problematical as to its cause, although relative deepening and shallowing is favored here as being most important. Is such a phenomenon related to eustasy, local tectonism, climatic changes, or some combination of these?

The two longer cycles are here estimated to have required 4 or 5 million years each for completion. The three next smaller scale cycles, corresponding to three major salts (Salina A-1, A-2, and B) and intervening carbonate rocks, possibly required about an average 750,000 years each for completion.

Great differences of opinion have arisen over the magnitude of sea-level change needed to bring about these cycles. For example, for deposition of the A-1 salt was the drop in the Michigan Basin as much as a 122 m to 150 m, and did such a drop apply about equally to the southern platform area so that a major unconformity should have developed there? Or was such a large drop applicable only to that basin so that it experienced "an excursion from eustasy"? (See Shaver, 1991, for a review of these ideas.)

The view much favored here is neither of the above, although the latter view does not directly contradict the facts of platform stratigraphy. Most evidence, I believe, favors very modest changes in sea level of a few tens of meters at most, as has been proposed by the Indiana workers and others (see Shaver, 1991).

Summary

Both tectonism and relative sea-level change seem necessary to explain the phenomena noted here. In the latter category, a strong argument exists for global sea-level change (eustasy) to account for the two cycles of greater periodicity, but evidence sufficient for sorting out the cause or causes of the lesser cycles is lacking.

The purpose here does not extend to discussing the fundamental natures of tectonism and eustasy and their interrelations. To date, Sloss (1988) has reconciled disparate assessments of their relative importance as well as anyone. He did not deny the operation of a global eustasy. Nevertheless, he observed that much of its cause seems to rest with sea-floor spreading and thermal changes within the earth. Further, he noted that many eustasy enthusiasts invoke glacio-eustatic events without hard evidence of glaciation. He insisted, therefore, that big-picture stratigraphers ultimately are recorders of tectonic evolution: "cratons, their margins, and interior basins 'do not just lie there' passively waiting to be encroached upon by rising sea levels or laid bare to erosion as sea levels fall" (Sloss, 1988, p. 1665).

Obviously, reconciliation is still needed between ideas favoring tectonism or eustasy to explain various midwestern Silurian phenomena. To facilitate resolution, fuller understanding first must be attained in these areas of study: (1) exact stratigraphic relations between the reef-bearing and evaporite-bearing rocks and, therefore, (2) the mechanism for evaporite deposition, and (3) the nature of the carbonate buildups and their degree of control on sedimentation, including that of evaporites.

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Regrets are expressed to the many persons who could have been cited as references but were not because of space limitations assigned for this article. Most of these, however, were cited by Shaver (1991) in a general review of Silurian studies in the Great Lakes area.

Publication has been with the permission of the Indiana State Geologist.

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WENLOCKI JA LUDLOW' SEDIMENTATSIOONILISED JA BIOOTILISED SÜNDMUSED KESK-LÄÄNE KRATOONSEL ALAL (USA)

On kirjeldatud Kesk-Lääne alal siluris eksisteerinud settebasseini arengut, milles on selgesti märgatav tsükliline kulgemine. Selle põhjusena on esile toodud nii tektoonilisi tegureid kui ka ookeani taseme eustaatilisi kõikumisi. Viimast on peetud oluliseks kahe kõrgemat järku tsükli kujunemisel.

Роберт Х. ШЕЙВЕР

СЕДИМЕНТАЦИОННЫЕ И БИОТИЧЕСКИЕ СОБЫТИЯ В ВЕНЛОКЕ И ЛУДЛОВЕ КРАТОНА В РАЙОНЕ СРЕДНЕГО ЗАПАДА США

Рассматривается развитие седиментационного бассейна, существовавшего в венлокское и лудловское время в пределах Среднего Запада США. Отложения характеризуются четко выраженной цикличностью, что обусловлено как тектоническими факторами, так и эвстатическими колебаниями уровня мирового океана. Доказывается первостепенное значение эвстатики при формировании двух крупнейших циклов.