Rapid onset of late Paleozoic glaciation on Gondwana: Evidence from Upper Mississippian strata of the Midcontinent, United States

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ABSTRACT

Direct evidence of the late Paleozoic glaciation of Gondwana from glacial deposits suggests that geographically extensive continental glaciation began some time in the Namurian (Late Mississippian). However, the timing and characteristics of the onset of glaciation are poorly understood because of a lack of reliable paleontological control and reworking of initial glacial deposits by subsequent glacial advances. Indirect evidence of glaciation preserved in unconformity-bounded, low-latitude ramp sequences in the Illinois basin, United States, suggests that geographically extensive continental glaciation of Gondwana actually began in the late Visean. An abrupt change from carbonate-dominated sequences bounded by disconformities with little evidence of erosion to mixed carbonate-siliciclastic sequences bounded by unconformities with deep incised valleys was likely produced by a three-fold increase in the magnitude of eustatic sea-level fluctuations. The increase in the magnitude of sea-level fluctuations was likely driven by an equally abrupt increase in ice volume and marks the onset of the geographically extensive late Paleozoic glaciation of Gondwana. A possible explanation for the rapid onset of glaciation is the closing of the equatorial seaway between Laurussia and Gondwana. Closing of this seaway would have led to an abrupt change in oceanic and atmospheric circulation patterns that could have initiated major continental glaciation in the Southern Hemisphere.

Keywords: sequence stratigraphy, incised valley, glaciation, eustasy, mixed carbonate-siliciclastic.

INTRODUCTION

Most efforts to reconstruct the history of Paleozoic glaciation events have focused on recognition of glacial deposits interbedded with terrestrial and, less commonly, marine strata (Crowell, 1978; Caputo and Crowell, 1985; Veevers and Powell, 1987; Frakes et al., 1992). Such work is essential to proving the existence of global ice in the past, but it is difficult to obtain reliable ages for some glacial deposits and they may not always be preserved. This is especially true of the early stages of major continental glaciation because deposits generated by the first ice sheets are likely to be reworked during larger subsequent glacial advances. Consequently, there is little information on the timing and characteristics of the transition from periods of little global ice to periods of extensive continental glaciation.

Crowell (1978) suggested that more precise details of the late Paleozoic glaciation of Gondwana might best be learned from indirect evidence preserved in cyclothems deposited in lower latitudes. The Pennsylvanian cyclothems, some of which are thought to have been produced by fourth-order (400 k.y.) sea-level changes in excess of 100 m (Heckel, 1986), have long been linked to glaciation on Gondwana (Wanless and Shepard, 1936; Heckel, 1986; Veevers and Powell, 1987). Miller and Eriksson (1999) suggested that similar cyclothems or unconformity-bounded sequences in the lower Namurian (uppermost Mississippian) strata of West Virginia were also produced by high-amplitude glacio-eustatic sea-level changes and associated climate fluctuations. The purpose of this paper is to show that the character and age of the onset of the major late Paleozoic glaciation can be determined from upper Visean (Upper Mississippian) unconformity-bounded sequences of the Illinois basin.

LATE PALEOZOIC GLACIAL DEPOSITS

Isolated occurrences of glacial deposits in the Late Devonian and Early Mississippian (Tournasian and middle Visean) of South America suggest the existence of relatively small ice sheets on Gondwana during these times (Crowell, 1983; Caputo and Crowell, 1985; Veevers and Powell, 1987) (Fig. 1). A more continuous record of glaciation starts in the Namurian (Upper Mississippian–Lower Pennsylvanian) and builds into the Westphalian (Pennsylvanian). This episode of continental glaciation may have been the most extensive of the Phanerozoic and there is evidence from glacial deposits and paleomagnetic data that suggests that ice sheets extended from the South Pole to lat 35°S (Frakes et al., 1992).

The first Namurian-aged glacial deposits were recognized in South America and Australia (Caputo and Crowell, 1985), but the lack of reliable associated paleontologic indicators makes it difficult to assign a precise age within the Namurian for these deposits. Thus, based on the record of glacial deposits, the best estimate for the onset of geographically extensive glaciation is sometime in the early Namurian (Frakes et al., 1992). Our data from the tropical platform deposits in the Illinois basin suggest that the onset of major glaciation was prior to the Namurian, in the late Visean.

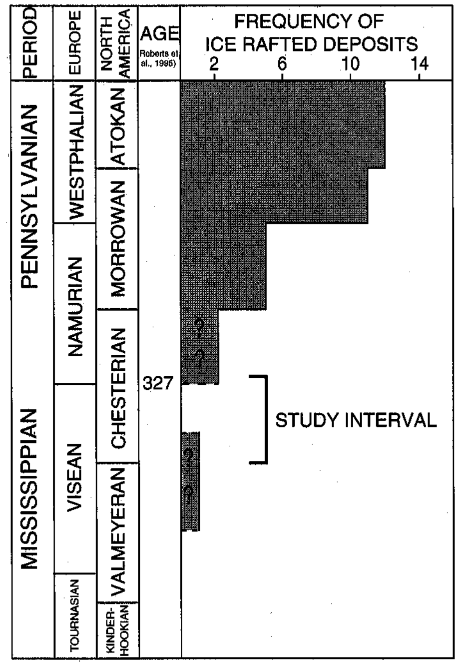

Figure 1. Occurrence of ice-rafted deposits in Mississippian and Early Pennsylvanian strata (modified from Frakes et al., 1992). Question marks illustrate poor age constraints for lower Namurian and Visean glacial deposits (Frakes et al., 1992). Age for Visean-Namurian boundary is from Roberts et al. (1995).

GEOLOGIC SETTING

The Illinois basin was a south-facing tropical marine embayment located 5°–10° south of the equator during the Late Mississippian (McKerrow and Scotese, 1990; Fig. 2). In the Late Mississippian there was a change from the shallow-marine carbonate deposition, that had prevailed throughout the middle Mississippian, to mixed carbonate-siliciclastic sedimentation, which continued to the end of the Mississippian (Fig. 3). Here we focus on that transition and discuss the uppermost portion of the shallow-marine carbonate interval (Ste. Genevieve through Paoli Formations) and the lower half of the mixed carbonate-siliciclastic interval (Bethel through Glen Dean Formations).

HIGH-RESOLUTION SEQUENCE STRATIGRAPHY

There are 10 disconformity-bounded high-frequency sequences in the Ste. Genevieve to Glen Dean interval (Fig. 3) (Smith, 1996; Smith and Read, 1999). These sequences and their internal facies were correlated more than 500 km from central Indiana to central Kentucky and to western Illinois using 75 detailed measured sections of outcrops and cores.

Sequences 1 to 5 in the carbonate-dominated Ste. Genevieve to Paoli interval are bounded by basinwide paleosols with little evidence for significant erosion (Smith and Read, 1999). The paleosols consist of caliche and brecciated carbonate horizons as much as 3 m thick in the eastern and central portions of the basin and red, slickensided, blocky mudrock paleosols in the western part of the basin.

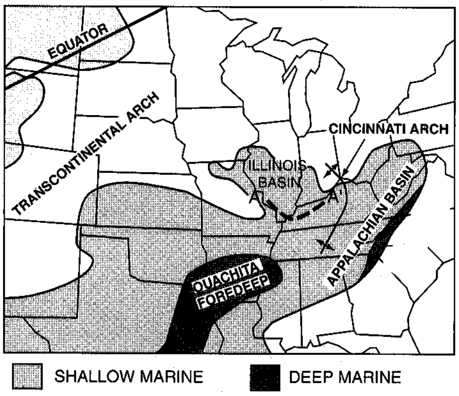

Figure 2. Paleogeographic map for Late Mississippian. Illinois basin was embayment open to south and was 5°–10°south of equator in Late Mississippian (McKerrow and Scotese, 1990). Dashed line is approximate trend of simplified schematic cross section in Figure 3.

Sequences 6 to 10 in the mixed carbonate-siliciclastic Bethel to Glen Dean interval are bounded by basinwide unconformities characterized by red mudrock paleosols that can be correlated laterally to the erosional bases of incised valleys (Fig. 3; Table 1; Smith, 1996). The sequences are typically composed of (1) transgressive incised valley fills composed of possible fluvial facies at the base overlain by tidally influenced estuarine and shallow-marine siliciclastic deposits; (2) marine carbonates deposited during the maximum flooding interval; and (3) late highstand tidally influenced siliciclastic deposits. The sequences with the deepest incised valleys (6, 8, and 10) also have thin coal beds in and above the incised valley fills and deeper water carbonate facies in their maximum flooding intervals.

Age constraints are poor for the Mississippian of the Illinois basin, but recent SHRIMP zircon dating of volcanic rocks interbedded with marine strata in Australia suggest that the duration of the study interval (upper V3b through V3c) was ~3 m.y. (Roberts et al., 1995). From 9 sequences divided by 3 m.y. we obtain an average duration of 333 k.y., which is suggestive of the long-term Milankovitch eccentricity signal (~414 k.y.) and the period calculated for Late Mississippian (Namurian) sequences in the Appalachian basin (Miller and Eriksson, 1999) and some of the overlying Pennsylvanian cyclothems (Heckel, 1986).

GLACIO-EUSTATIC ORIGIN OF THE SEQUENCES

The basinwide extent of the unconformities, the presence of deep incised valleys that can be traced laterally to paleosols, and the frequency of the sequences suggest that they were produced by fourth-order (~400 k.y.) glacio-eustatic sea-level fluctuations. Neither cyclic climate change, autocyclicity, nor local tectonics could have produced all of these features (Smith and Read, 1999). The eustatic interpretation is bolstered by the occurrence of a similar change from carbonate-dominated disconformity-bounded fourth-order sequences to mixed carbonate-siliciclastic sequences with deep incised valleys in the late Visean strata of Kansas (Montgomery and Morrison, 1999) and Great Britain (Walkden, 1987).

The incised valleys could only have been formed by downcutting rivers during lowstands of sea level because they can all be correlated laterally to well-developed paleosols that formed on the exposed interfluves (Ambers and Robinson,

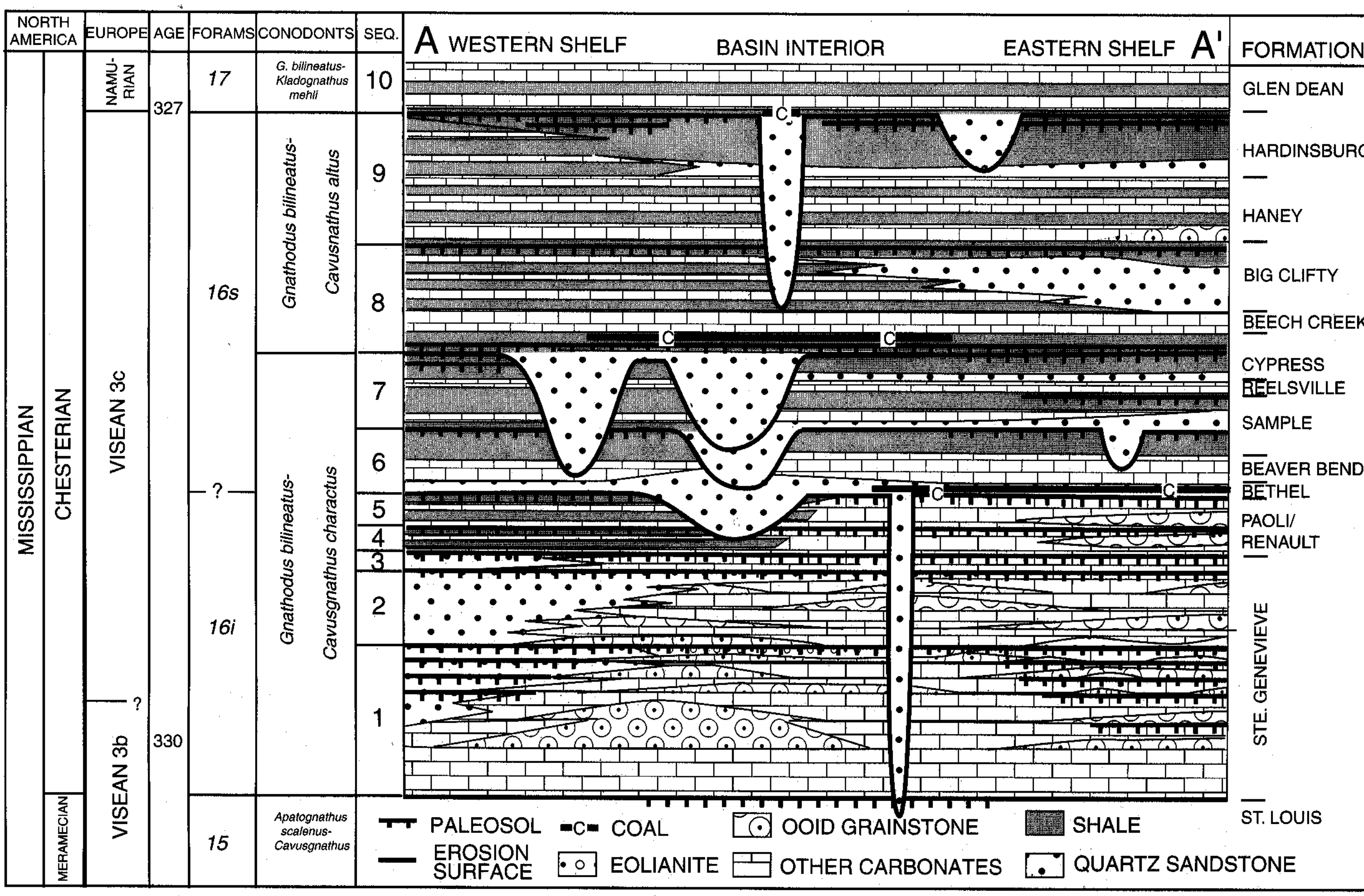

Figure 3. Simplified schematic cross section of upper Visean strata of Illinois basin based on 75 measured sections (biostratigraphy from Maples and Waters, 1987). Variations in thickness have been removed to emphasize upward change from sequence boundaries marked by paleosols (sequences 1–5) to sequences bounded by paleosols that can be traced into incised valleys (sequences 6–10). Boundary between sequences 5 and 6 marks onset of extensive glaciation on Gondwana. For more detailed cross sections see Smith and Read (1999) and Smith (1996).

TABLE 1. INCISED-VALLEY DEPTH, WIDTH AND FILL DESCRIPTION FOR SEQUENCES 6 THROUGH 10

Sequence	Depth (m)	Width (km)	Incised-valley fill
6	75 (Friberg et al., 1969)	1-2(?)*	Basal portion is fine- to medium-grained quartz sandstone with unidirectional downstream oriented crossbeds (Friberg et al., 1969) that may be fluvial. Upper portion is composed of tidally influenced siliciclastic strata, coal, and skeletal limestone.
7	15 (Ambers and Robinson, 1992)	0.5-2(?)*	Tidally influenced siliciclastic strata with marine trace fossils (Ambers and Robinson, 1992). One location has a paleosol at the base of an incised valley, which suggests that it was eroded, abandoned and exposed for an extended period of time (Smith, 1996).
8	45 (Smith, 1996)	1 to tens	Fill is composed of fine to medium tidally influenced sandstone grading upward to flaser-, wavy- and lenticular-bedded sandstone and shale.
9	0 (Treworgy, 1988)	0	There is no known incised-valley associated with this sequence boundary, which is marked by a basin-wide paleosol (Treworgy, 1988).
10	55 (Potter, 1962)	1-3	Fill is quartz sandstone that grades upward to sandstone and shale. Less is understood about this incised-valley because it is confined to the subsurface (Potter, 1962).

*Maximum width for incised-valleys at the bases of sequences 6 and 7 are likely wider (tens of kilometers) where they are amalgamated in the basin interior, but it is not possible to differentiate one formation from another in this location.

1992; Ambers and Petzold, 1992; Smith, 1996). Further support of a lowstand origin is the occurrence of possible fluvial deposits in the incised valley at the base of sequence 6, and a paleosol at the base of the incised-valley fill in sequence 7 (Table 1). The scarcity of fluvial deposits in the remainder of the sequences and the abundance of tidally influenced facies in the incised-valley fills suggest that most fluvial deposits were reworked by strong tidal currents during transgression (see Zaitlin et al., 1994).

Sequences 1 through 5 were likely produced by moderate-amplitude sea-level fluctuations of 20–30 m (Fig. 4). This estimate is based on the amount of sea-level fall necessary to produce regional paleosols with minimal erosion and the sea-level rise necessary to produce high-energy shallow-marine conditions across the basin (Smith and Read, 1999).

Estimates of sea-level changes required to produce sequences 6 through 10 were calculated by adding the depth of incision at the base of the sequence (Table 1) to the estimated water depth of the limestones in the maximum flooding interval. The best estimate for sea-level change is 95 m for sequence 6, 30 m for sequence 7, 65 m for sequence 8, 25 m for sequence 9, and 70 m for sequence 10 (Fig. 4; Smith and Read, 1996). The sea-level curve in Figure 4 is dashed in the lowstands because these can only be estimates of the magnitude of the sea-level fall. Any element of submarine erosion would lead to overestimation of sea-level fall. However, the presence of possible fluvial facies and paleosols at the base of some incised-valley fills suggests that the depth of incision is a minimum estimate for sea-level fall for valley fills with these features. Decompaction of the valley fills and any element of sea-level fall below the base of the valleys would add to the estimated magnitude of the sea-level falls.

TIMING AND RAPID ONSET OF LATE PALEOZOIC GLACIATION

During times of little global ice, the carbonate stratigraphic record is dominated by precessional (20 k.y.) and autocyclic peritidal carbonate cycles (Read, 1995). Sequences 1 to 5 do not resemble typical greenhouse strata and likely formed during a time of minor continental glaciation and moderate-amplitude sea-level changes. This interpretation is supported by the relatively minor occurrences of Visean glacial deposits in South America (Fig. 1; Frakes et al., 1992). The three-fold increase in the amplitude of sea-level changes between sequences 5 and 6 changes suggests a similarly dramatic increase in the volume of ice on Gondwana and marks the onset of the major late Paleozoic ice age (Fig. 4).

The study interval is early to middle Chesterian, which correlates with the uppermost Visean (upper V3b through V3c). Studies of conodonts and foraminifera led to the placement of the Visean-Namurian boundary at the base of the Glen Dean Limestone (Baxter and Brenckle, 1982), which is the uppermost limestone formation included in this study (Fig. 3). The abrupt increase in ice volume occurred in the late Visean (V3c), four sequences below the Visean-Namurian boundary (Fig. 4). If the sequences each formed in ~400 k.y., the major increase in ice volume occurred ~1.6 m.y. before the end of the Visean.

POSSIBLE CAUSES OF THE ONSET OF LATE PALEOZOIC GLACIATION

The abrupt increase in the magnitude of glaciation could have been produced by equally abrupt changes in atmospheric and oceanic circulation or may reflect a threshold response for a more gradual changes in atmospheric CO_2, atmospheric circulation and/or albedo feedback. A possible cause for an abrupt change in atmospheric and oceanic circulation is closure of the subequatorial seaway between Laurussia (North America and Europe) and Gondwana. The initial collision between Gondwana and Laurussia likely occurred in the late Visean (Al-Tawil, 1998) and that collision would have been shortly followed by closure of the seaway between the two land masses (Fig. 5). Closing of the seaway may have caused more warm air and water to circulate toward the south pole, leading to the increased precipitation necessary to build significant ice sheets (Fig. 5). Effective closing of the seaway could have happened over a relatively short period of time and may explain the abrupt nature of the onset of glaciation.

Longer term changes in circulation and atmospheric CO_2 related to uplift of the Allegheny Plateau may have also have contributed to or caused the abrupt climate change. Periods characterized by extensive global ice have been linked to low atmospheric CO_2 and mountain-building events (Raymo et al., 1988). Erosion of the newly uplifted carbonate-rich mountains may have led to uptake of CO_2 by weathering of carbonates, leading to lower atmospheric CO_2 and global cooling.

CONCLUSIONS

1. Characteristics of stratigraphic sequences in the Illinois basin, United States, indicate that there was an abrupt three-fold increase in the amplitude of fourth-order (400 k.y.) eustatic sea-level fluctuations in the late Visean. This increase was likely driven by an equally significant increase in ice volume on Gondwana and marks the onset of the major late Paleozoic glaciation. These data suggest that the glaciation event be-

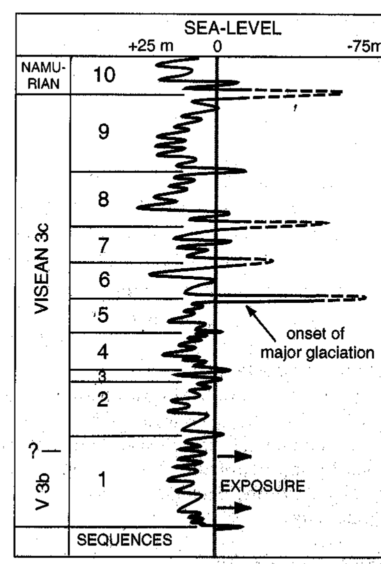

Figure 4. Sea-level curve for study interval based on interpreted water depths for different rock types and depth of incision associated with each sequence boundary. Onset of major glaciation marked by abrupt increase from 20 to 30 m sea-level changes of sequences 1–5 to up to 95 m for sequence 6.

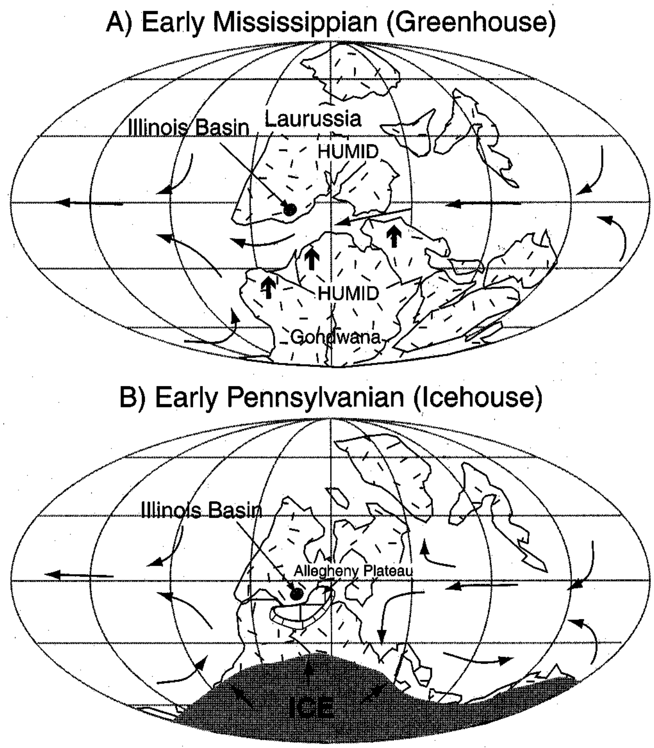

Figure 5. Paleogeographic maps with schematic oceanic current trends (base map from McKerrow and Scotese, 1990). A: Ocean currents flowed freely through subequatorial seaway in Early Mississippian. B: Closure of seaway in Late Mississippian might have caused equatorial currents to be diverted south toward Gondwana and initiated onset of major Southern Hemisphere glaciation.

gan abruptly, rather than gradually, and 1–2 m.y. before the end of the Visean, rather than sometime in the Namurian, as was previously thought.

2. Possible causes for the abrupt onset of glaciation include major rearrangement of oceanic and atmospheric circulation patterns driven by closing of the subequatorial seaway between Gondwana and Laurussia and longer term changes in atmospheric circulation and a decrease in atmospheric CO_2 caused by uplift of the Allegheny Plateau.

3. The three-fold increase in the amplitude of sea-level fluctuations should affect all same-aged marine strata and should serve as an effective global stratigraphic marker in settings where incised valleys are preserved.

4. Future research could include more precise correlation with same-aged strata in other parts of the world, computer modeling of the effect closure of the equatorial seaway would have on atmospheric and oceanic circulation, and further use of high-resolution sequence stratigraphy to learn more about this and other ice ages.

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