Early history of the Michigan basin: Subsidence and Appalachian tectonics

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ABSTRACT

Geometries of Cambrian to Silurian stratigraphic sequences in the Michigan basin record discrete episodes of basin-centered subsidence separated by periods of regional tilting. Backstripping reveals irregular subsidence rates that argue against a simple thermal contraction model. Depositional facies architecture also reflects episodic subsidence patterns, basin-centered facies tracts dominating during subsidence reactivations. These three lines of evidence indicate that subsidence cessations and reactivations characterize the early history of the Michigan basin. Periods of episodic subsidence correlate temporally with orogenic events in the Appalachians, suggesting that reactivation of basin subsidence is related to tectonic activity. We propose that Appalachian orogenic activity caused the episodic subsidence of the Michigan basin, possibly through weakening of the lower crust and reactivation of a preexisting upper-crustal isostatic imbalance.

INTRODUCTION

The Michigan basin is a simple, essentially undeformed cratonic basin 250 km in radius and nearly 5 km deep (Fig. 1). Although numerous hypotheses have been suggested for the origin of this structure, including thermal contraction, deep crustal metamorphism, and lithospheric stretching, no consensus has been reached concerning the tectonic development of the basin (Quinlan, 1987). Herein we present findings of a detailed stratigraphic investigation of the early subsidence history of the Michigan basin. Using sequence stratigraphy and backstripping, we show that Cambrian through Silurian subsidence consists of a series of subsidence reactivations and cessations, a history that is incompatible with simple thermal contraction models. We also demonstrate a temporal correlation between Michigan basin subsidence reactivations and major orogenic events in the Appalachians. On the basis of these observations and rheologic models for continental lithosphere, we suggest an alternative subsidence mechanism, which links the subsidence of the Michigan basin to Appalachian orogenic activity and mechanical weakening of the lower crust.

SEQUENCE STRATIGRAPHY

Deep drilling since the early 1980s has considerably expanded the database of stratigraphic information available for Cambrian through Silurian units of the central Michigan basin. This allows the division of the section into four genetic stratigraphic sequences defined by significant changes in the basin-subsidence patterns. Regional isopach maps of these four sequences show distinct changes in the morphology of the Michigan basin through time (Fig. 2).

Upper Cambrian to Lower Ordovician units define an elongate trough (Fig. 2A), suggesting that the proto–Michigan basin represented a northern continuation of the Reelfoot rift–Illinois basin area that formed as a result of Cambrian extension (Sleep et al., 1980). The first basin-centered subsidence of the Michigan basin began in the Middle Ordovician (sequence B, Fig. 2B) and represents the structural separation of the Michigan basin from the Illinois basin. In contrast, isopachs of Upper Ordovician to Lower Silurian sequence C units (Fig. 2C) record no basin-centered subsidence and suggest that the Michigan basin region tilted eastward toward the rapidly subsiding Appalachian basin foreland during this time (Quinlan and Beaumont, 1984; Beaumont et al., 1988). This period of basin quiescence in Michigan was followed by the Early to Late Silurian basin-centered subsidence of sequence D (Fig. 2D).

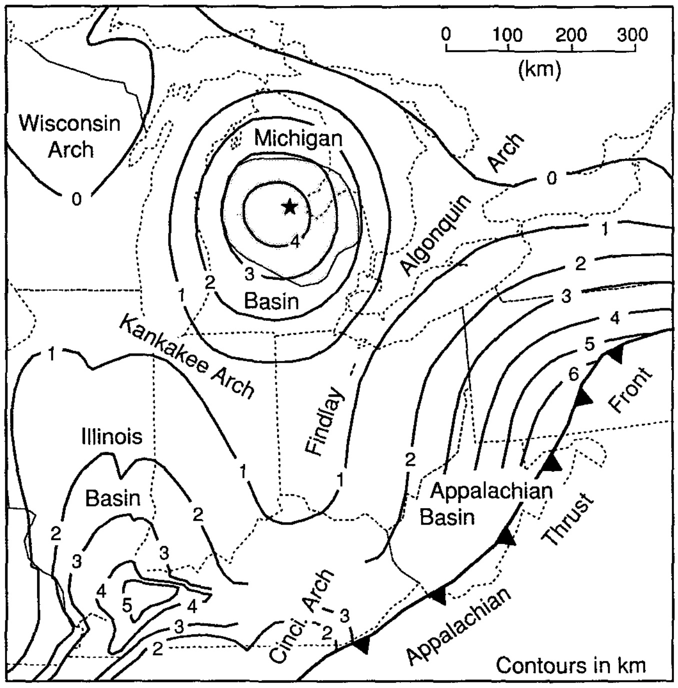


Figure 1. Total thickness of Phanerozoic sedimentary rocks in Michigan basin region (contours in kilometres). Shaded area represents positive gravity anomaly in central Michigan corrected for basin fill (after Haxby et al., 1976; Nunn and Sleep, 1984). Star is location of well used for subsidence analysis.

Thus, the Michigan basin displays four distinct subsidence episodes: (A) early extension-related subsidence, (B) initial basin-centered subsidence, (C) regional eastward tilting toward the Appalachian basin, and (D) renewed basin-centered subsidence. The basin geometry during deposition of sequence C records a complete cessation of basin-centered subsidence for a period of nearly 40 m.y. shortly after subsidence began in the Middle Ordovician, a pattern inconsistent with a continuous thermal contraction subsidence model.

TECTONIC SUBSIDENCE

Changes in the rate of tectonic subsidence further support a model of episodic subsidence. Backstripping separates total subsidence into two components, subsidence due to tectonic driving forces and that due to sediment loading (Steckler and Watts, 1978). Figure 3 shows the backstripped Cambrian to Silurian subsidence from a deep (4850 m) exploration well near the structural center of the basin (star in Fig. 1).

Sequence A consists of a rapid early subsidence (lithospheric extension) that slows from the latest Cambrian to Early Ordovician. Sequence B corresponds to a subsidence-rate increase associated with the first basin-centered subsidence. Sequence C represents a slower phase of subsidence in Michigan corresponding to the cessation of basin-centered subsidence and the regional eastward tilting into the Appalachian foreland basin. This phase was followed by rapid, basin-centered tectonic subsidence during deposition sequence D. This episodic subsidence record contrasts with the thermal-contraction subsidence of the Illinois basin to the south, which appears to have a smoother Ordovician to Silurian subsidence history without evidence of the significant subsidence reactivations corresponding to sequences B and D (Sleep et al., 1980; Heidlauf et al., 1986; Watso and Klein, 1989).

Previous studies of the Michigan basin have emphasized the approximate fit of a thermal model to this "noisy" subsidence record (Sleep, 1971; Nunn and Sleep, 1984). We believe, however, that the "noise" is real and that these episodic subsidence variations represent significant deviations from a simple thermal model, and hence require a fundamentally different subsidence mechanism.

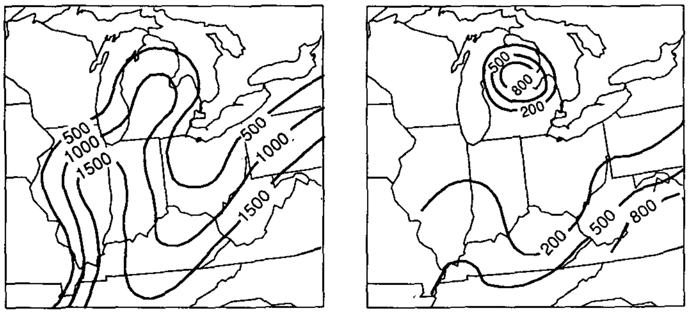
DEPOSITIONAL FACIES

Episodic subsidence is also recorded in the depositional-facies architecture of the basin. During basin-centered subsidence (sequences B and D), facies tracts tend to encircle the basin. Upper Prairie du Chien Group carbonate rocks (Middle Ordovician, sequence B) contain a thick, basin-centered anhydrite facies, and Niagara Group carbonate rocks (Lower Silurian, sequence D) display a concentric facies pattern of barrier reef, slope with pinnacle reefs, and a central, deep-water basin that was subsequently filled in by Upper Silurian evaporite rocks (Fisher et al., 1988). In contrast, the Utica Shale and Cincinnatian carbonate rocks of sequence C are laterally monotonous, shallow-marine shelf deposits across the entire basin, reflecting gentle eastward tilting toward the Appalachian foreland and the absence of basin-centered subsidence. Thus, three different lines of stratigraphic evidence (isopach patterns of stratigraphic sequences, tectonic subsidence rates, and depositional-facies relations) suggest that episodic subsidence dominated the early history of the Michigan basin.

APPALACHIAN TECTONICS

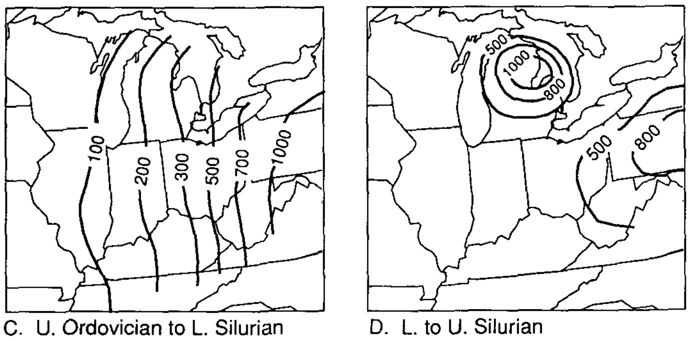
The Appalachian margin of cratonic North America has had a protracted orogenic history, characterized by periods of peak deformation and magmatism when various tectonic elements (e.g., volcanic arc, microcontinent) collided with the Laurentian margin. Several orogenic pulses have been recognized in the Appalachians (see summaries in Williams, 1984; Hatcher, 1989; Horton et al., 1989), but we emphasize that their spatial and temporal occurrences vary along as well as across the orogen.

The earliest collisional event proposed in the central part of the Appalachian orogen is Late Cambrian(?)–Ordovician in age (Penobscot; ca. 510–490 Ma), although the full significance of this event remains incompletely understood. An orogenic pulse associated with collision of an early Paleozoic volcanic chain with North America and obduction of



A. U. Cambrian to L. Ordovician

B. Middle Ordovician



C. U. Ordovician to L. Silurian

D. L. to U. Silurian

Figure 2. Regional isopach maps for sequences A to D. A: Mt. Simon through Oneonta. B: Shakopee through Glenwood. C: Black River through Cabot Head. D: Clinton through Bass Islands. Stratigraphic nomenclature is after Fisher et al. (1988). Contours are in metres and are based on this study, Fisher et al. (1988), Collinson et al. (1988), and Cook and Bally (1975).

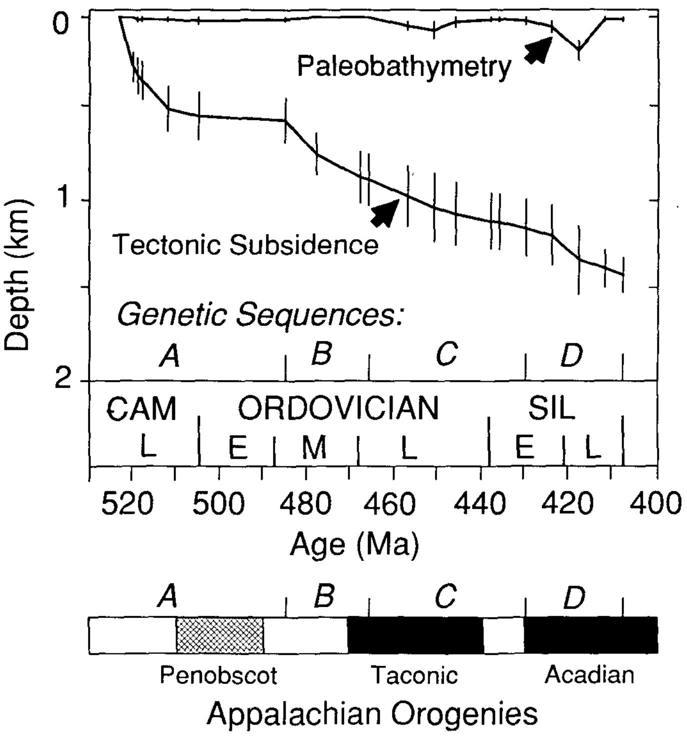


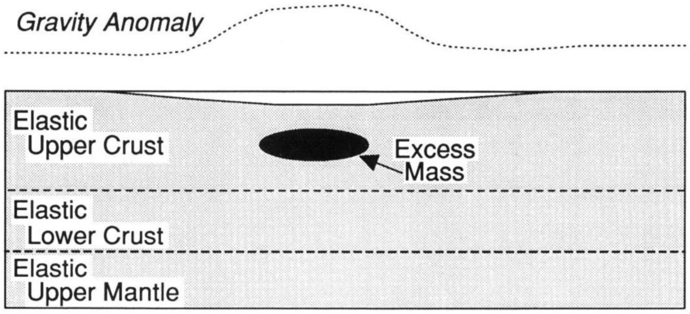
Figure 3. Cambrian to Silurian tectonic subsidence curve for Hunt Martin 1-15 well (permit #35090, sec. 15, T. 11 N., R. 2 E., Gladwin County, Michigan) and temporal correlation of orogenic events in Appalachians with sequence stratigraphy of Michigan basin. Variance bars represent minimum and maximum compaction and paleobathymetry estimates (after Bond et al., 1988). No eustatic corrections are used owing to uncertainties in Paleozoic sea-level record. Numeric age assignments after Fisher et al. (1988) and Palmer (1983). Episodes of basin-centered subsidence (sequences B and D) show as distinct increases in tectonic subsidence rate in contrast to slower regional tilting of sequence C. These sequences correlate temporally with Appalachian orogenic events (sequence B: early Taconic; sequence C: late Taconic; sequence D: early Acadian).

ophiolites during the Middle to Late Ordovician is well documented (Taconic; ca. 470–440 Ma). Studies of the younger orogenic history of the Appalachians, and the northern Appalachians in particular, increasingly emphasize the significance of Silurian activity (e.g., Bevier and Whalen, 1990; van der Pluijm et al., 1990). Accretion of the Avalon-Armorica microcontinent that was accompanied by widespread magmatism during the Late Silurian represents a third event (early Acadian or Caledonian; ca. 430–400 Ma). Continued closure of the basin that separated Laurentia from Gondwana is recorded in the Devonian Acadian event and the Permian-Carboniferous Alleghenian event, but these are outside the scope of the current study.

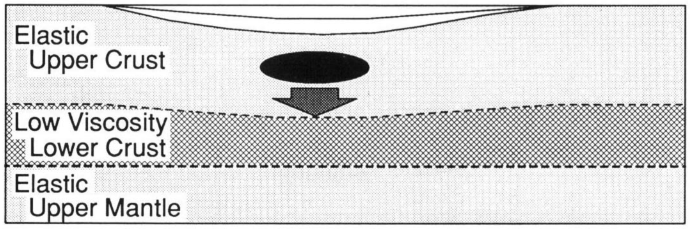
The timing of the orogenic pulses (Taconic and early Acadian; Middle to Late Ordovician and Silurian, respectively) is coincident with the depositional sequences in the Michigan basin discussed above (Fig. 3). This temporal correlation suggests that orogenic events at the plate margin and reactivations of interior-basin subsidence are related and, thus, that Appalachian orogenic activity provides a possible explanation for the episodic subsidence in the Michigan basin.

SUBSIDENCE MECHANISM

Several studies have suggested that a low-viscosity lower crust can serve as a crustal "asthenosphere" and cause decoupling of the mechanical behavior between the upper crust and upper mantle (Turcotte et al., 1984; DeRito et al., 1986). Periods of basin-centered subsidence in the Michigan basin may be explained by a mechanism of tectonically induced crustal weakening and development of a low-viscosity zone in the lower crust. During tectonically quiet periods, an upper-crustal excess mass is flexurally supported by a thick lithosphere (Fig. 4A). Development of a crustal low-viscosity zone, however, causes a mechanical decoupling of the upper crust from the upper mantle. The excess mass is then supported only by a thin upper-crustal plate, causing the upper crust to subside into the low-viscosity lower crust (Fig. 4B).



A. Lithospheric Flexural Support: No Tectonic Subsidence



B. Upper-Crust Flexural Support: Subsidence Reactivation

Figure 4. Simplified lithospheric section to demonstrate subsidence due to tectonically induced crustal weakening. A: Entire crust and uppermost mantle behave elastically and provide regional flexural support for load caused by upper-crustal excess mass. B: During peak orogenic activity at plate margin, elevated intraplate stresses and/or fluid events cause reduction of effective viscosity in crust to point at which lower crust can no longer sustain bending stresses imposed by overlying upper-crustal load. This causes mechanical decoupling between upper crust and upper mantle and results in subsidence of upper-crustal plate into lower crust.

Two elements are required for such a subsidence mechanism, a large excess mass in the upper crust and a mechanism for reducing the viscosity of the lower crust. A significant Bouguer and free-air gravity anomaly exists in the central Michigan basin (Fig. 1), and modeling by Nunn and Sleep (1984) suggests that it is located in the upper crust. This feature may in part relate to the Keweenawan rift sequence (Hinze et al., 1975), but the gravity anomaly is most positive in central Michigan and does not track the Keweenawan rift sequence to the north when corrected for the sedimentary fill of the basin (Haxby et al., 1976).

The rheology of the lower crust is largely controlled by power-law creep, and thus its effective viscosity can be reduced by (1) increased temperature (Karner et al., 1983), (2) increased intraplate stress (DeRito et al., 1983, 1986), and (3) elevated fluid pressure (Etheridge et al., 1984). Evidence is lacking for repeated heating events in the craton during the early Paleozoic. Intraplate stress variations, however, are to be expected as a consequence of repeated orogenic events along the eastern margin of the North American plate. Several studies (e.g., England et al., 1985; Cloetingh and Wortel, 1986; Craddock and van der Pluijm, 1989) have suggested that stresses originating at plate margins can be transferred over hundreds of kilometres into intraplate regions. Stress-induced crustal weakening, therefore, is an attractive mechanism for the episodic basin subsidence because of the intimate association of subsidence reactivations with major orogenic pulses. We note that regional fluid-migration events, which may also be associated with orogenic activity (Oliver, 1986), provide an alternative crustal-weakening mechanism. Our hypothesis does not imply that we understand the precise triggering mechanism for reactivations of Michigan basin subsidence, but rather, we recognize that a mechanism exists that can explain the observed temporal correlation between Appalachian orogenic activity and the irregular subsidence history of the Michigan basin.

CONCLUSIONS

The geometry of major stratigraphic sequences, combined with tectonic subsidence rates and facies architecture, suggests a history of episodic subsidence for the Michigan basin. These new data from this basin conflict with some previous models for its origin, especially those involving thermal contraction (Sleep, 1971; Nunn and Sleep, 1984) and lithospheric stretching (Klein and Hsui, 1987), and pose significant limitations for mechanisms involving deep-crustal metamorphism (Haxby et al., 1976; Middleton, 1980; Ahern and Dikeou, 1989). Temporal correlation of basin-centered subsidence with major orogenic events in the Appalachians suggests that "starts and stops and changes of pace" in the subsidence record (Sloss, 1982) may be related genetically to events at the active plate margin. On the basis of this model, subsidence of the Michigan basin began in the Late Cambrian as a northern extension of lithospheric stretching associated with the Reelfoot rift. A Middle Ordovician Appalachian orogenic event initiated basin-centered subsidence and the deposition of sequence B. Basin-centered subsidence waned by the Late Ordovician and was replaced by regional tilting toward the Appalachian foreland. Renewed tectonism during the Silurian caused a reactivation of basin-centered subsidence in Michigan and the accumulation of sequence D.

The Michigan basin has been interpreted in previous models as an isolated structural feature. Our proposed link between Appalachian events and Michigan basin reactivations, however, would place basin subsidence within a plate-tectonic framework.

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ACKNOWLEDGMENTS

Partly supported by American Chemical Society–Petroleum Research Fund Grant 20755, Shell Oil, and a grant to S. E. Kesler and associates from the Michigan Research Excellence and Economic Development Program. We thank Joyce Budai, Henry Pollack, Bruce Wilkinson, George deVries Klein, and Judson Ahern for helpful reviews.

Manuscript received April 5, 1990
Revised manuscript received July 9, 1990
Manuscript accepted July 18, 1990

Reviewer's comment

Documents changes in style of basin subsidence in a cratonic basin and proposes a reactivation model involving far-field tectonic influences. . . . Model is novel and may well be correct.

George deV. Klein