Evidence for eustasy at the Kinderhookian-Osagean (Mississippian) boundary in the United States: Response to late Tournaisian glaciation?

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ABSTRACT

Evidence for eustasy at the Kinderhookian-Osagean boundary is presented here in a new synthesis based on detailed analysis of the boundary in the central Appalachian Basin and regional mapping of the Kinderhookian-Osagean boundary unconformity in the conterminous United States. Detailed stratigraphic analysis within the central Appalachian Basin shows that coarse-grained, fluvial sandstones (Black Hand, Burgoon, Big Injun, Purslane) are associated with valley incision up to 60 m and a widespread sequence boundary (SB2) that is inferred to have resulted from a forced regression during the Kinderhookian-Osagean boundary interval. The extent of unconformity at the boundary was evaluated by mapping the inferred positions of shorelines during the Kinderhookian, Kinderhookian-Osagean boundary interval, and early Osagean based on stratigraphic data from Correlation of Stratigraphic Units of North America (COSUNA) charts. This analysis shows areas of extensive unconformity at the Kinderhookian-Osagean boundary across the United States inferred to be the result of sea-level fall and recovery during a period of ~2 m.y. or less, based on missing conodont zones. The Kinderhookian-Osagean boundary is equivalent in age to the global Tn2-Tn3 boundary, and supporting evidence for global regression and eustasy at this boundary is also reviewed.

The combination of this evidence for eustasy with recently reported middle to early late Tournaisian (Tn2a-Tn3b) diamictites in South America permits the inference of continental glaciation at this time. Previous studies of oxygen and carbon isotope data from marine carbonates and fossils have shown strong positive anomalies suggestive of global cooling at the Kinderhookian-Osagean and Tn2-Tn3 boundary, providing further support for the hypothesis of continental glaciation in the late Tournaisian.

Keywords: eustasy, Kinderhookian, Osagean, Tournaisian, glaciation, Black Hand Sandstone, Burgoon Sandstone, incised valley, Appalachian Basin, sea-level maps.

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INTRODUCTION

The purpose of this paper is to present a new synthesis of the available data on both the stratigraphic and geographic extent of the unconformity, and the correlative sequence boundary, at the Kinderhookian-Osagean boundary across the conterminous United States. The synthesis is based on our own detailed analysis of the Kinderhookian-Osagean boundary stratigraphy; newly constructed shoreline, or sea-level, maps for the early Mississippian; and proxy data from other studies. The Kinderhookian-Osagean boundary is equivalent to the late Tournaisian Tn2-Tn3 global boundary (Ross and Ross, 1985; Jones, 1996), and we briefly review the evidence for unconformity, or the correlative sequence boundary, outside of North America as well. These data are then used to support the hypothesis of an episode of eustasy at the Kinderhookian-Osagean and Tn2-Tn3 boundary during which there was a global fall in sea level followed by a relatively rapid recovery. The hypothesized eustasy is then related to evidence for early late Tournaisian glaciation, including diamictites in South America (Caputo et al., 2006a, 2006b, this volume), and carbon and oxygen positive isotope anomalies in marine limestones and fossils from North America and Europe, which indicate apparent global cooling (Mii et al., 1999; Saltzman, 2002a; Buggisch and Joachimski, 2006). Together, these various lines of evidence are discussed in support of the hypothesis for late Tournaisian glaciation.

Two brief ice ages apparently occurred in the Late Devonian and early Mississippian prior to the late Mississippian Gondwanan ice age (Crowell, 1999; Crowley and Berner, 2001; Royer et al., 2004). The older ice age occurred in the late Famennian at the Devonian-Mississippian boundary, evidence for which includes glacial deposits and a wide range of proxy records (Crowell, 1999; Isaacson et al., 1999, 2005). Isaacson and Hladil (2003) estimated a minimum of 60 m for the sea-level fall. The younger ice age apparently occurred in the middle to late Tournaisian (Tn2-Tn3), at or near the Kinderhookian-Osagean boundary; it is supported by evidence of diamictites in the Solimões Basin of Brazil (Caputo et al., 2006a, 2006b, this volume).

Indirect, or proxy, evidence for a late Tournaisian ice age is robust and consists of (1) a massive incised valley (60 m) (Matchen and Kammer, 2006), and associated sequence boundary and fluvial sandstones in the Appalachian Basin of the eastern United States; (2) a widespread unconformity over much of North America at the Kinderhookian-Osagean boundary, presented herein; (3) a global sequence boundary associated with widespread regression and unconformity at the Tn2-Tn3 boundary in Saudi Arabia, Belgium, Czech Republic, Germany, western Russia, Siberia, and China (Ross and Ross, 1985; Swennen et al., 1986; Kalvoda, 1989, 1991, 2002; Isaacson et al., 1999; Hance et al., 2002; Haq and Al-Zahtani, 2005); and (4) stable isotope anomalies (Mii et al., 1999; Saltzman, 2002a; Buggisch and Joachimski, 2006).

STRATIGRAPHY OF THE KINDERHOOKIAN-OSAGEAN BOUNDARY

To argue the case for eustasy at the Kinderhookian-Osagean boundary in North America, we present a review of previous studies interpreted under the hypothesis of sea-level fall at the boundary. Additionally, lithostratigraphic cross sections are presented in support of regression at the Kinderhookian-Osagean boundary.

North American Midcontinent

The Kinderhookian-Osagean boundary is defined in the Mississippi Valley stratotype region at Kinderhook, Pike County, Illinois, and along the Osage River, St. Clair County, Missouri (Lane and Brenckle, 2005). Two conodont zones (upper part of the upper crenulata-isosticha and punctatus biozones) are missing in the stratotype region where a physical unconformity is recognized (Lane and Brenckle, 2005).

The unconformity at the Kinderhookian-Osagean boundary has long been recognized (Ham and Wilson, 1967; Craig and Connor, 1979, pl. 9-A). In the subsurface of western Illinois, Workman and Gillette (1956) documented extensive erosion of the upper Kinderhookian formations. In Missouri, the early Osagean Burlington Limestone may directly overlie the Hannibal Formation (Thompson, 1986) (Fig. 1).

Appalachian Basin

General Stratigraphy

The Kinderhookian and Osagean stages in the central Appalachian Basin (consisting of eastern Ohio, southwestern Pennsylvania, western Maryland, and West Virginia) (Fig. 2) comprise a 200–300-m-thick siliciclastic succession. This siliciclastic succession was deposited near the end of the Acadian orogeny on a foreland ramp (Castle, 2000) that extended as far west as the Illinois Basin (Matchen and Kammer, 1994, 2006). The succession is bounded by unconformities at the upper and lower contacts (SB1 and SB3 on Figs. 1 and 2). A third sequence boundary (SB2 on Figs. 1 and 2) occurs at the Kinderhookian-Osagean boundary (Matchen and Kammer, 2006). Interpretation of SB2 includes evidence for incised valley fill at the Kinderhookian-Osagean boundary in Ohio (Matchen and Kammer, 2006) and corroborating evidence for the sequence boundary over a wider area in at least West Virginia and Pennsylvania.

Incised Valley Fill in Ohio

Matchen and Kammer (2006) interpreted the Black Hand Sandstone Member of the Cuyahoga Formation (Fig. 1) as incised valley fill. The Black Hand Sandstone extends across southeastern Ohio (Fig. 2), and it is a multistory, cross-bedded, coarse-grained sandstone up to 60 m thick that is surrounded on all sides by finer-grained marine sediments of the underlying Cuyahoga Formation and the overlying Logan Formation.
Figure 1. Lower Mississippian chronostratigraphy in the eastern United States. (1) European stage names; Fam.—Famennian; (2) Tournaisian subdivisions (Jones, 1996); (3) North American stage names, based upon Mississippi Valley type localities (Lane and Brenckle, 2005). Sequence boundaries, denoted by SB1, SB2, and SB3, are discussed in text. Stratigraphy is from a—Harrell et al. (1991); b—Hyde (1953); c—Holden (1942); d—Bjerstedt and Kammer (1988); e—Matchen and Vargo (1996); f—Vargo and Matchen (1996); g—Berg (1999); h—Brezinski (1999); i—Inners et al. (2003).

Figure 2 (on following two pages). Lower Mississippian lithostratigraphic correlations in the central Appalachian Basin of eastern Ohio, southwestern Pennsylvania, western Maryland, and West Virginia. The extent of the Lower Mississippian on the index map is from the geologic maps for each state: West Virginia (Cardwell et al., 1968); Ohio (Slucher et al., 2006); Pennsylvania (Berg et al., 1980). Distribution of the Black Hand Sandstone in Ohio is from Wolfe et al. (1962). Stratigraphic cross sections are based on gamma-ray (left) and density (right) wireline logs. Section A–A’ demonstrates that the drillers’ Big Injun sandstone of the West Virginia subsurface and the Black Hand Sandstone of Ohio are correlative sandstones from south to north. Section B–B’ demonstrates that the Burgoon Sandstone of Pennsylvania and the Big Injun sandstone of West Virginia are discontinuous with the Black Hand Sandstone of Ohio from east to west. The Black Hand Sandstone is a braided-stream deposit surrounded on all sides by marine deposits. The Big Injun sandstone and Burgoon Sandstone are more extensive in their distribution, covering northern West Virginia and southwestern Pennsylvania. Despite the discontinuous nature, the sand bodies occupy a similar stratigraphic position and were apparently deposited as part of the same pulse of coarse-grained sedimentation during regression at or near the Kinderhookian-Osagean boundary. For both sections, datum is the base of the Sunbury Shale overlying the Berea Sandstone. The Mississippian-Pennsylvanian unconformity is at the base of the Sharon Sandstone. Sequence boundaries are shown in black. SB1 is placed at the base of the Berea Sandstone. SB2 is placed at the base of the Big Injun and Black Hand sandstones. SB3 is placed at the top of the Lower Mississippian succession beneath the Upper Mississippian Greenbrier and Maxville limestones. Logs for Pennsylvania were obtained from Harper and Laughrey (1987, cross section D–D’).
Lithofacies of the Black Hand Sandstone include massive gravel, gravel with intraclasts, and medium- to coarse-grained sandstone. Interpreted architectural elements (Miall, 1985) for these lithofacies include channel lags, gravel bars, dunes, and transverse bars that formed in a braided-stream setting (Matchen and Kammer, 2006, their Tables 1 and 2). The contact between the Black Hand Sandstone and the underlying Cuyahoga Formation is sharp and scoured, and large (up to 1 m) intraclasts of the Cuyahoga Formation are incorporated into overlying conglomeratic sandstone. Limited paleocurrent data and the geographic distribution of the Black Hand Sandstone suggest that the paleoriver flowed from the southeast to the northwest (Holden, 1942; Ver Steeg, 1947; Hyde, 1953; Kittredge and Malcuit, 1985). Matchen and Kammer (2006) hypothesized that the paleoriver flowed to the Michigan Basin, where it deposited the early Osagean Marshall Sandstone (Richardson, 2006a, 2006b) (Fig. 1).

The age of the Black Hand Sandstone is constrained between latest Kinderhookian and earliest Osagean based on the age of marine invertebrates and miospores in the surrounding rocks. The underlying Cuyahoga Formation is mostly, if not entirely, Kinderhookian. The overlying Logan Formation is early Osagean in age based on biostratigraphic data from ammonoids, brachiopods, conodonts, and miospores reviewed in Matchen and Kammer (2006). Ammonoids from the Logan Formation have previously been assigned a Kinderhookian age (Manger, 1971; Manger et al., 1999), but more recent work indicates that these taxa are Osagean in age (Sandberg et al., 2002; Work and Manger, 2002; Work and Mason, 2003). Miospores from the Logan Formation are from the PC (Spelaeotriletes pretiosus-Raistrickia clavata) Biozone, which ranges from the late Tn2 to early Tn3 in Europe (Higgs et al., 1988; Clayton et al., 1998). Manger et al. (1999) interpreted the Logan Formation as late Kinderhookian in age (Tn2) on this basis, but the miospore zonation also supports an early Osagean age (Tn3), which agrees with the recent ammonoid studies. The Black Hand Sandstone is inferred to have been deposited during the interval represented by the two missing conodont biozones in the Mississippi Valley.

To better understand the mechanisms that produced the Kinderhookian-Osagean unconformity and the incised-valley-fill Black Hand Sandstone, the time available to produce these features must be estimated. The duration of the Tournaisian has been estimated at either 11 m.y. (Jones, 1996) or 14 m.y. (Gradstein et al., 2004). There are 12 conodont biozones (Lane and Brenckle, 2005) spanning the Tournaisian; thus, each conodont biozone is ~1 m.y. in duration. Therefore, the two missing conodont biozones at the Kinderhookian-Osagean boundary unconformity in the Mississippi Valley may represent as much as 2 m.y., or possibly less, of missing time during which the Kinderhookian-Osagean unconformity was formed and the Black Hand Sandstone was deposited. This is similar to the 2 m.y. duration estimate made by Saltzman (2001) for the δ¹³C event at the Kinderhookian-Osagean boundary. This is the best estimate because there are no reported radiometric dates specifically at the Kinderhookian-Osagean boundary (Gradstein et al., 2004).

**Regressive Sandstones in the Central Appalachian Basin**

A thick, coarse-grained sandstone occurs near the top of the Lower Mississippian succession in the central Appalachian Basin. This sandstone is known by several names, including the Burgoon Sandstone in Pennsylvania (and the correlative Purslane Sandstone of Maryland) (Brezinski, 1999), and the drillers’ informal “Big Injun” sandstone (Vargo and Matchen, 1996) of the subsurface in West Virginia (Fig. 1). Regional stratigraphic cross sections produced for this study show that the Black Hand Sandstone occupies the same lithostratigraphic position as the Big Injun and Burgoon sandstones (Fig. 2). The base of the Burgoon/Big Injun sandstone in northern West Virginia is at approximately the same elevation above the top of the Berea Sandstone as is the base of the Black Hand Sandstone in Ohio. In southwestern Pennsylvania, the Burgoon Sandstone is 25–90 m thick and “exhibits abundant cross-bedding, basal lag deposits, clay galls, plant fossil debris, scour and fill sequences, sole markings, and other features typical of fluvial sandstones” (Harper and Laughrely, 1987, p. 16).

Although the Big Injun sandstone does not crop out, lithostratigraphic correlation to the Burgoon Sandstone (Harper and Laughrely, 1987) and the Black Hand Sandstone (Fig. 2) suggests that it is fluvial in origin as well. Reports from the subsurface of West Virginia indicate coarse-grained fluvial facies within the Big Injun sandstone (Hohn et al., 1993; Vargo and Matchen, 1996). Based on the lithostratigraphic correlations, we hypothesize that all these sandstones were deposited during the Kinderhookian-Osagean and Tn2-Tn3 boundary interval, and their bases are likely time correlative with SB2 beneath the Black Hand Sandstone (Fig. 1).

Biostratigraphically, how well constrained is the time of deposition for these sandstones? The Marshall Sandstone of the Michigan Basin, which is the inferred marine lowstand wedge for the Black Hand Sandstone (Matchen and Kammer, 2006), contains miospores interpreted as early Osagean (Richardson, 2006b). The Black Hand Sandstone apparently can be dated to the Kinderhookian-Osagean boundary, as summarized already. The Burgoon Sandstone has been dated as Osagean-Meramecian in age on the basis of the plant fossil *Triphyllopteris* (Read, 1955; Scheckler, 1986; Brezinski, 1999), which in Europe ranges from the late Tournaisian through Visean (Read and Mamay, 1964; Wagner, 1984). However, recent work (Knaus, 1994, 1995) has determined that the Appalachian specimens are not *Triphyllopteris*, rendering the previous correlation invalid. Until independent palynological evidence is available for the age of the Burgoon Sandstone, the previous age determination of Osagean-Meramecian based on the *Triphyllopteris* zone is unreliable (Knaus, 1994, p. 112). In central Pennsylvania, Streel and Traverse (1978) reported that the strata beneath the Burgoon Sandstone contained earliest Kinderhookian miospores. Thus, the Burgoon Sandstone may be as old as late Kinderhookian, but it sits unconformably on the underlying sediments (Harper and Laughrely, 1987), making a younger Tn2-Tn3 age possible.
MAPPING EARLY MISSISSIPPIAN SEA-LEVEL CHANGES

We constructed new maps to show the changing positions of shorelines, a proxy for sea-level change, during the early Mississippian in the conterminous United States. Three intervals were mapped: (1) the Kinderhookian (Tn1b-Tn2 interval) maximum marine transgression (Fig. 3A); (2) the Kinderhookian-Osagean and Tn2-Tn3 boundary (Fig. 3B); and (3) the early Osagean (Tn3) maximum marine transgression (Fig. 3C).

These maps were constructed using COSUNA (Correlation of Stratigraphic Units of North America) charts (Ballard et al., 1983; Hills and Kottlowski, 1983; Bergstrom and Morey, 1984; Hintze, 1985; Patchen et al., 1985a, 1985b; Shaver, 1985; Mankin, 1986; Adler, 1987; Kent et al., 1988). Each chart lists stratigraphic data distributed across several columns, and each column represents a geographic area within a single U.S. state. Each data point plotted on the maps is centered in the area for its column on the chart (see Fig. 3 caption for explanation of symbols). Thus, the data points are generalized in their locations, but they are sufficient to show major patterns on a continental scale.

The designation of marine versus nonmarine rocks was based on the paleontologic and stratigraphic literature for the Kinderhookian and Osagean formations listed on the COSUNA charts. Data points on the maps (Fig. 3) are designated as marine if fossils include typical marine organisms such as crinoids, corals, brachiopods, bryozoans, cephalopods, trilobites, conodonts, etc. Nonmarine rocks lacked such fossils and included typical terrestrial features such as plant fossils, coals, or red beds. Primary sources for information on the depositional environments of individual formations are the chapters on each state in U.S. Geological Survey Professional Paper 1110 (1979), The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States; the regional chapters in Craig and Connor (1979); and Dutro et al. (1979). Depositional environments of Lower Mississippian formations in the Appalachian Basin are summarized in Bjerstedt and Kammer (1988), Carter and Kammer (1990), Matchen and Kammer (2006).

Shorelines were drawn on each map with a hachured boundary line between areas of marine deposition and nondeposition in the central and western United States, or between marine and nonmarine rocks in the eastern United States. Positions of the interpreted shorelines are approximate and are dependent on the density of data points; they are more precise where data points were denser. Eastern and western shorelines of the Mississippian epicontinental sea were constrained on all three maps by the Appalachian orogen in the east and the Antler orogen in the west (Craig and Varnes, 1979). From Maine to Minnesota, the northern shoreline was constrained by the northern limit of Mississippian rocks. The Mississippian sea extended north into Canada from North Dakota and Montana and south into Mexico from Texas and New Mexico (Craig and Connor, 1979). There is little data control along the Gulf of Mexico coastal plain because of destruction of any original Mississippian rocks by the Ouachita orogeny (Craig and Connor, 1979). We consulted previous paleogeographic reconstructions, including those of Craig and Varnes (1979, pl. 12) and Gutschick and Sandberg (1983), but these were generalized and did not resolve changes in paleogeography for the three time slices shown here (Fig. 3). They were also produced prior to the COSUNA charts used in this study (1983–1987).

Many areas of the U.S. interior lack Mississippian rocks because of post–early Mississippian uplift and erosion, which must be considered when reconstructing early Mississippian paleogeography. Based on timing of uplifts, many of these areas can be assumed to have been covered by early Mississippian seas (Fig. 3). Late Mississippian to Permian uplift associated with the Appalachian-Ouachita orogeny produced or reactivated the Ozark Dome (McBride and Nelson, 2000; Hudson, 2002), the Nemaha anticline (Kansas-Nebraska) (Merriam, 2005), central Kansas uplift (Rascoe and Adler, 1983), the Cincinnati and Kankakee arches (Root and Onasch, 1999), and the Nashville Dome (Kolata and Nelson, 1990). The Transcontinental arch (extending through New Mexico, Colorado, Nebraska, South Dakota, and Minnesota) is a series of highs and lows (or sags) (Gutschick and Sandberg, 1983, their Figs. 5 and 6) associated with Phanerozoic reactivation of basement zones of weakness (Carlson, 1999, 2004). Craig and Varnes (1979, pl. 12) showed an extensive marine connection across the Transcontinental arch in their paleogeographies for both the Kinderhookian and Osagean.

DISCUSSION

Interpretation of Sea-Level Maps

The Kinderhookian map (Fig. 3A) shows the maximum extent of marine rocks during either the early (Tn1b) or the late Kinderhookian (Tn2). The epicontinental sea was widespread throughout the eastern and western United States. A large emergent area was situated over parts of Colorado, New Mexico, and Texas. The central Kansas uplift appears to have been emergent, as well as a forebulge of the Antler orogeny in Utah.

Marine rocks are less extensive on the Kinderhookian-Osagean boundary map (Fig. 3B), which we interpret as resulting from the widespread unconformity associated with a sea-level fall. In the northeastern United States, the shoreline receded westward from a combination of siliciclastic progradation (Bjerstedt and Kammer, 1988; Matchen and Kammer, 1994) and forced regression (Matchen and Kammer, 2006). In the southeastern United States, the Kinderhookian emergent area in Alabama and Mississippi expanded into Georgia and Tennessee. In the central United States, a large peninsula formed over parts of Iowa, Illinois, Missouri, and Kansas, presumably from a fall in sea level. The Kinderhookian emergent area in Colorado, New Mexico, and Texas expanded further into Colorado and Texas. The western seaway was less affected by the fall in sea level where most sections are conformable (Chen et al., 1994; Saltzman, 2002a). Foreland basin development associated with the Antler orogeny on the western edge of the craton may have kept the western sea...
Figure 3 (on this and following page). Sea-level, or shoreline, maps during early Mississippian (Miss.) time in the conterminous United States, based on COSUNA (Correlation of Stratigraphic Units of North America) charts (Ballard et al., 1983; Hills and Kottlowski, 1983; Bergstrom and Morey, 1984; Hintze, 1985; Patchen et al., 1985a, 1985b; Shaver, 1985; Mankin, 1986; Adler, 1987; Kent et al., 1988). (A) Maximum extent of marine rocks at any time during the Kinderhookian (Tn1b-Tn2). (B) Extent of marine rocks at the Kinderhookian-Osagean (K-O) (Tn2-Tn3) boundary. Areas on the maps where Mississippian sedimentary (sed.) rocks are absent are denoted by a cross (+). These data points indicate Mississippian rocks were either never present or were subsequently eroded. A filled circle (•) indicates that rocks are missing for the mapped interval, but younger Mississippian sedimentary rocks are present, thus indicating that the missing rocks were either never deposited or were eroded during the Mississippian, rather than later. An open square (□) indicates that marine rocks are present for the mapped interval. Two other data types include an asterisk (*) for the latest Kinderhookian marine Gilmore City Limestone on the Kinderhookian-Osagean boundary map, and a solid triangle (▲) for Osagean nonmarine rocks.
Evidence for eustasy: Response to late Tournaisian glaciation?

Regression at the Kinderhookian-Osagean Boundary

North American Midcontinent

Witzke and Bunker (1996, their Fig. 8) placed a sequence boundary at the Kinderhookian-Osagean boundary in southeast Iowa. They recognized sub-Burlington erosional beveling of the Wassonville Formation (Chouteau Group equivalent). Witzke and Bunker (2002, 2005) further commented that this seemed anomalous because the beveling is in an offshore direction, and strata are thicker and more complete toward the Transcontinental arch in northwest Iowa, where the latest Kinderhookian Gilmore City Limestone occurs. They suggested the cause was either structural upwarping of the southeast Iowa area before deposition of the Burlington Limestone, or submarine erosion. They did not suggest a eustatic drop in sea level. Brenckle and Groves (1986) reported that foraminifera from the earliest Osagean Humboldt oolite, which immediately overlies the Gilmore City Limestone in north-central Iowa, were previously unknown east of the Transcontinental arch, indicating...
their probable migration from the western epeiric sea across Nebraska. This eastward extension of the western part of the epeicontinental sea, expressed as the Gilmore City Limestone, can be seen along the west side of the Midcontinent peninsula on the Kinderhookian-Osagean boundary map (Fig. 3B), and it explains the more complete section in northwest Iowa.

Appalachian Basin

Incision of the Black Hand Sandstone paleovalley and subsequent deposition of sandstone fill within the valley require a 60 m fall in relative sea level to produce the incision and sequence boundary (SB2). The Black Hand Sandstone lies between two marine units, the Cuyahoga and Logan Formations (Fig. 1), which together exceed 250 m in thickness in central Ohio (Fig. 2). To produce this stratigraphic package, incision must have been followed by a rebound in sea level to fill the valley with terrestrial sediment and deposit marine sediments above. Based on the biostratigraphic estimates, incision, fill, and transgression must have occurred within a 2 m.y. period, or less.

If tectonic uplift was responsible for incision of the Black Hand Sandstone paleovalley, sediments should be substantially thinner in Ohio, rather than representing the thickest Lower Mississippian depocenter in the central Appalachian Basin (Matchen and Kammer, 2006, their Fig. 4). Structure contour maps drawn on the underlying Berea Sandstone show a broad ramp dipping eastward into the basin (Matchen and Kammer, 2006, their Fig. 3) and no evidence for uplift in eastern Ohio, beneath the Black Hand Sandstone. The combination of the predominantly marine origin of Lower Mississippian rocks in Ohio with the absence of evidence for uplift requires an explanation other than tectonics for incision of the Black Hand Sandstone paleovalley.

If tectonic uplift as the driver for incision is excluded, we are left with the interplay of tectonics and glacio-eustasy. The Black Hand, Big Injun, and Burgoon sandstones represent an influx of coarser-grained, fluvial sediments to the Appalachian foreland (Fig. 2). The high sediment supply was probably the result of postorogenic rebound of the hinterland. In the postorogenic phase, subsidence had slowed considerably, producing a foreland ramp (Castle, 2000) and allowing coarse-grained orogenic phase, subsidence had slowed considerably, producing a foreland ramp (Castle, 2000) and allowing coarse-grained sediments to spread across the region. Increasing sediment supply may produce a sequence boundary, and it is a primary control on the architecture of sedimentary basin fill because it alters the amount of accommodation space available for sediment deposition (Posamentier and Allen, 2000, p. 19–21); however, it does not produce valley incision.

The 60 m of relief on the paleovalley requires at least an equal magnitude of relative sea-level fall. Presumably, a continental-scale fall and rebound of sea level over a brief time period (~2 m.y.) is indicative of a global eustatic event. Such an event would be linked to changing ice volumes because this is the only mechanism capable of producing a rapid global change in sea level over a short period of time. Glacio-eustasy may be up to 1000 times more rapid than tectono-eustatic mechanisms (Plint et al., 1992; Coe, 2003, p. 101).

Regression at the Global Tn2-Tn3 Boundary

The Kinderhookian-Osagean boundary is equivalent to the global Tn2-Tn3 boundary (Ross and Ross, 1985; Jones, 1996). The fall in sea level at the Tn2-Tn3 boundary has been interpreted as a global event (Ross and Ross, 1985; Isaacson et al., 1999). A major unconformity is present in the middle to late Tournaisian of the Arabian Platform (Haq and Al-Qahtani, 2005). In Belgium, the boundary is the sequence boundary at the Hastarian-Ivorian boundary (Hance et al. 2002). In Moravia (Czech Republic), the boundary is marked by regression and microfaunal changes thought to be associated with global cooling (Kalvoda, 1989, 1991, 2002). In northeast Siberia, Swennen et al. (1986) recognized a regional fall in sea level just below the Tn2-Tn3 boundary associated with anhydrite pseudomorphs indicating evaporite deposition. The sea-level fall at the end of Tn2 is also recognized in Germany (the Rhenish area) and in south China (Isaacson et al., 1999).

Glacial Eustasy?

These several lines of evidence all point to a clear record of eustasy at the Kinderhookian-Osagean and Tn2-Tn3 boundary on several continents, particularly North America, where the data are most abundant (Fig. 3). Although the global extent of the sequence boundary at the Kinderhookian-Osagean and Tn2-Tn3 has long been recognized (Ross and Ross, 1985), a clear argument for glacial eustasy previously has not been made, although Rygel et al. (2007) argued that the record of Tournaisian eustasy is supportive of glaciation.

Diamictites

Direct evidence for a middle to late Tournaisian ice age has recently been confirmed from miospore dating of diamictites in the Solimões Basin of Brazil (Caputo et al., 2006a, 2006b, this volume). Diamictites in the Jaraqui Member of the Jandiatuba Formation from wells in the Juruá subbasin contain miospores of the BP (Spelaeotriletes balteatus-Rugospora polypticha) Biozone and PC biozones of western Europe (Caputo et al., this volume). The BP biozone is Tn2a-Tn2b (late Kinderhookian) in age, and the PC biozone is Tn2c-Tn3a,b (Kinderhookian-Osagean boundary) in age (Higgs et al., 1988). Caputo et al. (this volume) report that these diamictites occur over 300 km in the subsurface and directly overlie Famennian-age diamictites. Caputo et al. (this volume) also discuss other diamictites of apparent middle to early late Tournaisian age in Bolivia and Argentina.

Crowell (1999) reported Tournaisian-age tillites from Libya. Four episodes of Early Carboniferous glacial deposits in Tibet are bracketed between marine rocks of early Tournaisian and Bashkirian ages (Garzanti and Sciuennach, 1997). These glacial deposits are presumably Visean and Serpukhovian in age, but a middle to late Tournaisian age for at least the oldest deposit cannot be ruled out without a definitive biostratigraphic study, which is lacking (Garzanti and Sciuennach, 1997).
Stable Isotopes of Carbon and Oxygen

Strong positive anomalies for both oxygen and carbon isotopes occur in brachiopod shells and marine carbonates from the latest Kinderhookian of North America (Mii et al., 1999; Saltzman et al., 2000; Saltzman, 2002a) and at the Tn2-Tn3 boundary in western Europe (Bruckschen and Veizer, 1997). During the Kinderhookian, $\delta^{18}O$ values rose ~6‰, and $\delta^{13}C$ values rose ~5‰. Values decreased again in the Osagean, although they did not fall to the levels of the early Kinderhookian. An increase in $\delta^{18}O$ values would be associated with some combination of global cooling or sequestration of lighter oxygen in glacial ice (Hudson, 1977; Marshall, 1992). Parallel positive anomalies of both oxygen and carbon isotopes in conodont apatite have been cited as evidence for global cooling in the early late Tournaisian at the upper crenulata-isosticha conodont biozones (Buggisch and Joachimski, 2006).

Saltzman et al. (2000) and Saltzman (2002a) reported a very strong $\delta^{13}C$ anomaly of up to +7.1‰ Peedee belemnite (PDB) that spans the latest Kinderhookian and earliest Osagean in limestones from Idaho and Nevada. Increased $\delta^{13}C$ values indicate a shift in the global carbon cycle that may have been related to enhanced organic carbon burial associated with cooler temperatures during glaciation, or sequestration of light organic carbon in deep-ocean water (Brenchley et al., 1994, 2003; Saltzman et al., 2000; Joachimski and Buggisch, 2002; Saltzman, 2003; Saltzman and Young, 2005). Currently there is debate as to whether or not the primary environment of organic burial at the Kinderhookian-Osagean boundary was marine or terrestrial (Gill et al., 2006). Burial of organic carbon would reduce atmospheric CO$_2$ and contribute to global cooling (Berner, 2003, 2004; Royer et al., 2004). Alternatively, increased $\delta^{13}C$ values may have been related to weathering of exposed carbonate platforms during regression (Kump et al., 1999; Saltzman, 2002b).

Studies have clearly linked high $\delta^{13}C$ values with global cooling (Bruckschen et al., 1999; Brenchley et al., 2003; Saltzman and Young, 2005). Brenchley et al. (2003) found carbon and oxygen isotope anomalies at the end of the Ordovician, a time of major Gondwana glaciation (Brenchley et al., 1994; Sheehan, 2001), that were similar in magnitude to those at the end of the Kinderhookian. Saltzman (2002b) reported that the three largest positive shifts in $\delta^{13}C$ values occurred in the Late Ordovician, at the Silurian-Devonian transition, and in the early Mississippian (Tournaisian), all of which were apparently associated with a eustatic fall in sea level caused by Gondwanan glaciation.

CONCLUSIONS

Both direct and indirect evidence for glacial eustasy at the Kinderhookian-Osagean and Tn2-Tn3 boundary consists of:

1. Middle to early late Tournaisian (BP and PC biozones) diamictites in South America (Caputo et al., 2006a, 2006b, this volume).

2. Valley incision in Ohio up to 60 m at the Kinderhookian-Osagean boundary followed by an early Osagean transgression (Matchen and Kammer, 2006).

3. The sequence boundary, SB2, associated with valley incision in Ohio can be traced along the base of the Burgoo, Big Injun, and Purslane sandstones throughout the central Appalachian Basin, suggesting a forced regression at this time (Figs. 1 and 2).

4. Sea-level maps for the Kinderhookian, Kinderhookian-Osagean boundary interval, and the early Osagean in the conterminous United States indicate extensive regression and unconformity at the Kinderhookian-Osagean and Tn2-Tn3 boundary (PC biozone) (Fig. 3).

5. Global evidence for regression in the form of an unconformity, or correlative sequence boundary, at the Tn2-Tn3 boundary has been reported in Saudi Arabia, Belgium, Czech Republic, Germany, western Russia, Siberia, and China (Ross and Ross, 1985; Swennen et al., 1986; Kalvoda, 1989, 1991, 2002; Isaacson et al., 1999; Hance et al., 2002; Haq and Al-Qahthani, 2005).

6. Strong positive anomalies in both $\delta^{18}O$ and $\delta^{13}C$ indicate global cooling at or near the Kinderhookian-Osagean and Tn2-Tn3 boundary, which is consistent with the hypothesis of glaciation (Bruckschen and Veizer, 1997; Mii et al., 1999; Saltzman et al., 2000; Saltzman, 2002a; Buggisch and Joachimski, 2006).

Together these data support the hypothesis of a glaciation event that produced a substantial, ~60 m eustatic sea-level fall and recovery at the Kinderhookian-Osagean and Tn2-Tn3 boundary spanning an interval of ~2 m.y., or possibly less. The global distribution and relative rapidity of the event support the hypothesis of glacial eustasy.

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