

Incised valley fill interpretation for Mississippian Black Hand Sandstone, Appalachian Basin, USA: Implications for glacial eustasy at Kinderhookian–Osagean (Tn2–Tn3) boundary

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Abstract

Lower Mississippian strata of east-central Ohio are predominantly fine-grained marine deposits of the Cuyahoga and Logan formations. Within these sediments is the Black Hand Sandstone of the Cuyahoga Formation. The Black Hand Sandstone is a multistory, crossbedded, coarse-grained conglomeratic sandstone. The contact between the Black Hand Sandstone and the subjacent Cuyahoga Formation is sharp and scoured, with intraclasts of the Cuyahoga Formation incorporated into the basal Black Hand Sandstone. The Black Hand Sandstone was previously thought to represent a distributary channel deposit; however, the combination of lithofacies and architectural elements indicates deposition in a braided stream setting. The Cuyahoga Formation was deposited in a shallow marine setting. The erosional basal contact of the Black Hand Sandstone and the juxtaposition of fluvial and marine sediments suggests a sequence boundary. The geographic distribution of the Black Hand Sandstone combined with the evidence for a sequence boundary suggests deposition in an incised valley.

The age of the Black Hand Sandstone is key to inferring the causes of valley incision. The Black Hand Sandstone is nearly devoid of body fossils, necessitating a biostratigraphic analysis of the surrounding Cuyahoga and Logan formations. Analysis indicates the Logan Formation is early Osagean age. Data from the Cuyahoga Formation suggest a Kinderhookian age with a possible transition to the Osagean in the uppermost Cuyahoga Formation. This constrains the age of the Black Hand Sandstone to the transition at the Kinderhookian–Osagean boundary.

Recent reports indicate late Kinderhookian (Tournaisian, Tn2) Gondwanan glaciation based upon tillites and sharp excursions in stable-isotope curves. A glacio-eustatic fall in sea level is inferred to have caused incision of the Cuyahoga Formation, followed by deposition of the Black Hand Sandstone and Logan Formation during the subsequent sea level rise. The associated unconformity correlates to the sequence boundary at the Kinderhookian–Osagean boundary in the stratotype area of North America, and the correlative Tn2–Tn3 boundary worldwide, supporting the hypothesis of a global eustatic event at this time.

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1. Introduction

Lower Mississippian strata of the central Appalachian basin, which includes eastern Ohio and the adjacent areas of western Pennsylvania, West Virginia, and eastern Kentucky, represent the final pulse of sedimentation from the eroding Acadian highlands (Ettensohn et al., 2002). These rocks contain dominantly coarse-grained terrestrial facies in the east and fine-grained marine facies in the west (Bjerstedt and Kammer, 1988). The rocks are diachronous being predominantly Kinderhookian in the east with the Osagean portion expanding towards the west (Matchen and Kammer, 1994).

Within the predominantly marine sediments of Ohio lies the anomalously thick conglomeratic Black Hand Sandstone, which is typically up to 60m thick and is surrounded on all sides by finer-grained marine sediments. The Black Hand Sandstone lies within the Cuyahoga Formation, of which it is a member, and is always overlain by the Logan Formation. The most recent previous study interpreted the Black Hand Sandstone as a distributary channel deposit within prograding marine deltaic deposits of the Cuyahoga Formation (Bork and Malcuit, 1979). In this paper, we present evidence that the Black Hand Sandstone is younger than the rest of the Cuyahoga Formation and is an incised valley fill composed of braided stream deposits that formed at the end of Cuyahoga deposition and before the overlying marine Logan Formation.

This study has several goals: (1) examine the Black Hand Sandstone in detail and reconsider its environment of deposition; (2) use knowledge of its depositional environment to place it correctly within the stratigraphic framework of central Ohio; (3) analyze available biostratigraphic data to determine the age of the Black Hand Sandstone within the context of the surrounding lithologic units; and (4) use all of this information to recognize changes in relative sea level associated with deposition of the Black Hand Sandstone and surrounding Lower Mississippian strata of the central Appalachian basin.

2. Setting

2.1. Extent of study area

The study area includes both outcrops and well logs of the Black Hand Sandstone in east-central Ohio (Fig. 1). The Lower Mississippian section in the Appalachian basin represents the final pulse of

sediment from the eroding Acadian highlands (Ettensohn et al., 2002). By latest Devonian time, the rate of subsidence had decreased considerably in the foreland basin, which then filled, producing a foreland ramp system (Castle, 2000). Sediment from the Acadian highlands filled any remaining accommodation space and prograded to the west and south towards the Cincinnati Arch (Matchen and Kammer, 1994). The high sediment flux combined with minimal accommodation space resulted in a relatively thin, widespread sheet of interbedded sandstones, siltstones, and shales that eventually reached as far as the Illinois basin (Kepferle, 1977). Upper Devonian sediments reached thicknesses of 1900–3300m in the deep Acadian foreland basin of eastern Pennsylvania and eastern West Virginia (Faill, 1985). By comparison, Lower Mississippian sediments rarely exceed 235m at any location in the study area or surrounding regions (Dennison and Wheeler, 1975; Harper and Laughrey, 1987; Bjerstedt and Kammer, 1988; Brezinski, 1999).

2.2. Stratigraphy

The Mississippian–Devonian boundary is placed at the base of the Sunbury Shale (Fig. 2), a regional marker throughout the central Appalachian basin (De Witt, 1970). The top of the Lower Mississippian section is placed at the base of the Meramecian/Chesterian Maxville Limestone (Smosna, 1996), or its equivalents. Lower Mississippian rocks are subdivided into the Cuyahoga and Logan formations (Fig. 2). Stratigraphic summaries can be found in Holden (1942), Fagadau (1952), Hyde (1953), Szmuc (1957), Wolfe et al. (1962), and Bork and Malcuit (1979).

2.2.1. Cuyahoga Formation

The Cuyahoga Formation is a facies mosaic of interbedded shale, siltstone, and sandstone 129–161 m thick in east-central Ohio (Fig. 2). It thins southward, where along the Ohio River the majority of the Lower Mississippian section is composed of the Logan Formation (Holden, 1942; Bork and Malcuit, 1979). Both marine invertebrate and trace fossils are common in the Cuyahoga Formation, except for the Black Hand Sandstone Member.

The absence of regional marker beds and the lateral variability of stratigraphic units makes lithostratigraphic correlation difficult within the Lower Mississippian section. To deal with this difficulty, a series of geographic facies were defined by earlier workers including the Hocking Valley Facies (in the Hocking Hills south of Lancaster), the Granville Facies, and the

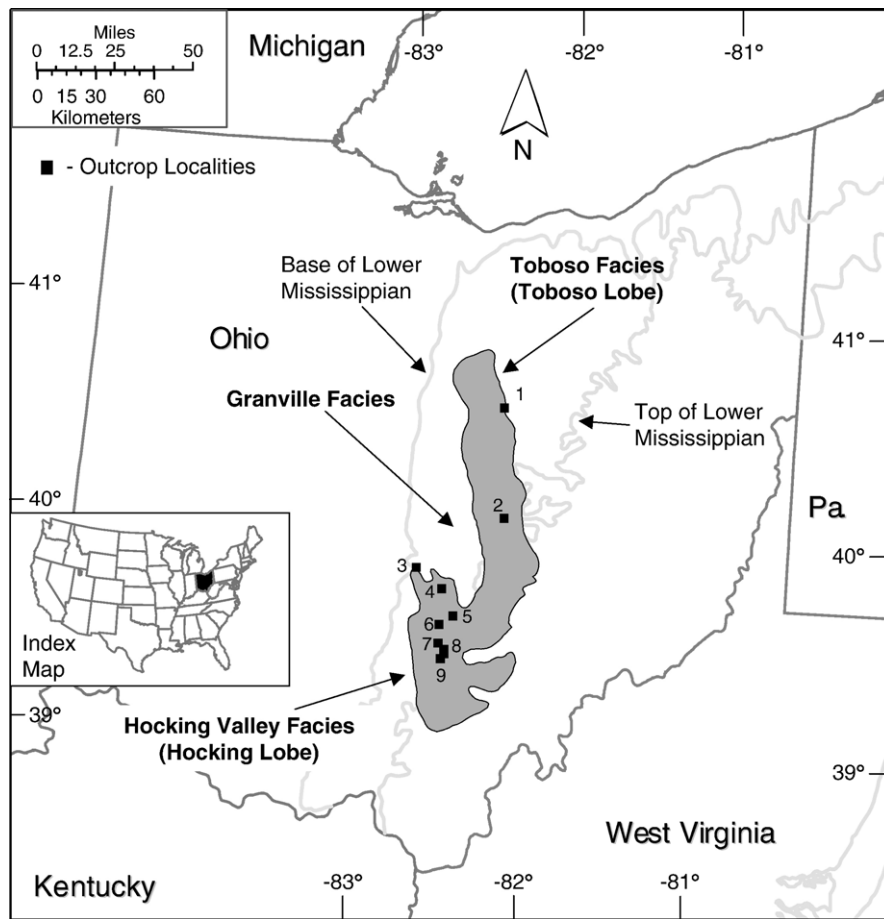


Fig. 1. Distribution of Lower Mississippian outcrop in Ohio (dotted line) and the Black Hand Sandstone (shaded) in outcrop and in the subsurface (modified from Wolfe et al., 1962). The general position of geographic facies for the Cuyahoga Formation and the Black Hand Sandstone lobes defined by Holden (1942) and Hyde (1953) are indicated by arrows. Numbered squares represent study localities: (1) Pleasant Hill Dam (Szmuc, 1957; UTM 17S 387863E, 4497687E), (2) Black Hand Sandstone Gorge, type section (Hyde, 1953; Bork and Malcuit, 1979; UTM 17S 395319E, 4434338N), (3) Chestnut Ridge Metropark (UTM 17S 349473E, 4408011N), (4) Mt. Pleasant (UTM 17S 363329E, 4398434N), (5) Rockbridge Nature Preserve (UTM 17S 370971E, 4381772N), (6) Cantwell Cliffs (UTM 17S 364460E, 4378300N), (7) Conkles Hollow (UTM 17S 364526E, 438399N), (8) Old Man's Cave, Lower Falls and Cedar Falls (UTM 17S 367004E, 4365945N), (9) Ash Cave (UTM 17S 367009E, 4362277N). Localities 6–9 are located in Hocking Hills State Park.

Toboso Facies (Holden, 1942; Hyde, 1953; Wolfe et al., 1962) (Figs. 1 and 2). This system is cumbersome and outdated, but it is useful for linking this study to earlier work. The lobes of the Black Hand Sandstone are named for these facies (Fig. 1).

Based on field evidence, the composition of the Black Hand Sandstone ranges from quartz arenite to sub-litharenite. The majority of the pebbles within the conglomeratic portions are quartz; less than 10% are feldspars.

2.2.2. Logan Formation

The Logan Formation is a 79–85-m-thick siliciclastic unit (Szmuc, 1957) (Fig. 2). In southern Ohio, it is up to 150m and comprises the majority of the Lower

Mississippian (Holden, 1942). Like the Cuyahoga Formation, the Logan is a facies mosaic of shaly and sandy marine stratigraphic units. The most distinctive unit, and most important for correlation purposes is the Berne Member (Bork and Malcuit, 1979). The Berne Member consists of reworked pebbles from the Black Hand Sandstone, and contains marine invertebrate fossils. Where the Black Hand Sandstone is absent, the Cuyahoga and Logan formation contact is recognized by the presence of the Berne (Bork and Malcuit, 1979). The Berne pinches out beyond the distribution of the Black Hand Sandstone.

The Rushville Member is at the top of the Logan Formation and is a shaly mudstone, with a thin crinoidal limestone at its base (Thompson et al., 1971).

Hocking Valley Facies		Granville Facies		Toboso Facies (Black Hand Type area)		Northeastern Ohio	
Logan Formation	Rushville Member Vinton Member Allensville Member Byer Member Berne Member						
	Black Hand Sandstone (Hocking Lobe)	Raccoon Shale		Black Hand Sandstone (Toboso Lobe)	Wooster Sh. Armstrong Ss. Rittman Ss.		
Fairfield Member	Raccoon Shale		Raccoon Shale	Meadville Sh.		Cuyahoga Formation	
Lithopolis Member				Strongsville Ss.			
				Sharpsville Ss.			
				Orangeville Sh.			
Sunbury Shale							

Fig. 2. Stratigraphic nomenclature for Lower Mississippian strata within the study area (Holden, 1942; Hyde, 1953; Wolfe et al., 1962; Szmuc, 1970). Locations of geographic facies and Black Hand Sandstone lobes are shown in Fig. 1.

Previously, it has been treated as a separate formation, but the Rushville is considered to be a member of the Logan because of its similar lithology to the Vinton Member, and its very limited extent both vertically (8m) and areally (one locality). The conodont study by Thompson et al. (1971) provides a youngest possible age for the Logan Formation.

2.3. Regional structure

Structure contour maps on the top of the latest Devonian Berea Sandstone show a broad structural basin (Fig. 3). Eastern Ohio lies on the western flank of this basin with low structural dip ($<1^\circ$) to the east. The current basin morphology is the result of Alleghenian-age tectonism that occurred following deposition of Lower Mississippian strata (Faill, 1998). Isopachs for the Lower Mississippian show a range of thickness from less than 60m along the eastern flank of the basin to its greatest thickness over 240m along the outcrops of central Ohio (Fig. 4).

This distribution is the combined result of tectonic activity and erosion. There was likely uplift to the east of the study area, which was partly emergent during the Early Mississippian (Bjerstedt and Kammer, 1988). This uplift may have contributed to the generally thin Lower Mississippian succession in West Virginia. The study area was apparently unaffected by this activity as the structure contour map shows no local evidence for uplift (Fig. 3). The relatively thick Lower Mississippian succession in central Ohio was likely preserved in a region generally unaffected by tectonic uplift.

3. Methodology

Depositional environments of the Black Hand Sandstone were evaluated via measured profiles constructed for Hanover, Cantwell Cliffs, Old Man's Cave, and Chestnut Ridge. Supplementary sections included Ash Cave, Cedar Falls, Conkles Hollow, Mt. Pleasant and Rockbridge State Nature Preserve (Fig. 1).

The analysis was carried out through construction of lateral profiles with concentration on bounding surfaces and lithofacies. This process was developed by Allen (1983) and later modified (Miall, 1985; Luttrell, 1993; Yu et al., 2002; Miall and Jones, 2003). The most common means of analysis is by photomosaic; however, the location of these sections within deep narrow gorges in the Hocking Hills precluded the construction of suitable photomosaics. Instead, profiles were produced by combining closely spaced vertical sections into horizontal profiles.

Paleocurrent data are particularly difficult to acquire from the Black Hand Sandstone. The paucity of three-dimensional surfaces and the coarse-grained nature of the sandstone obliterate bedding details. Estimates of paleocurrent direction based upon bed orientation are noted on the profiles. In some cases it was possible to identify only a bi-directional orientation of flow from channel-fill deposits or planar crossbeds, these are displayed on the outcrop profiles as double-headed arrows. The goal of paleocurrent analysis was to determine the flow orientation in relation to the trend of the Black Hand Sandstone (Fig. 1).

There are few fossils, terrestrial or marine, available for direct determination of the age of the Black Hand

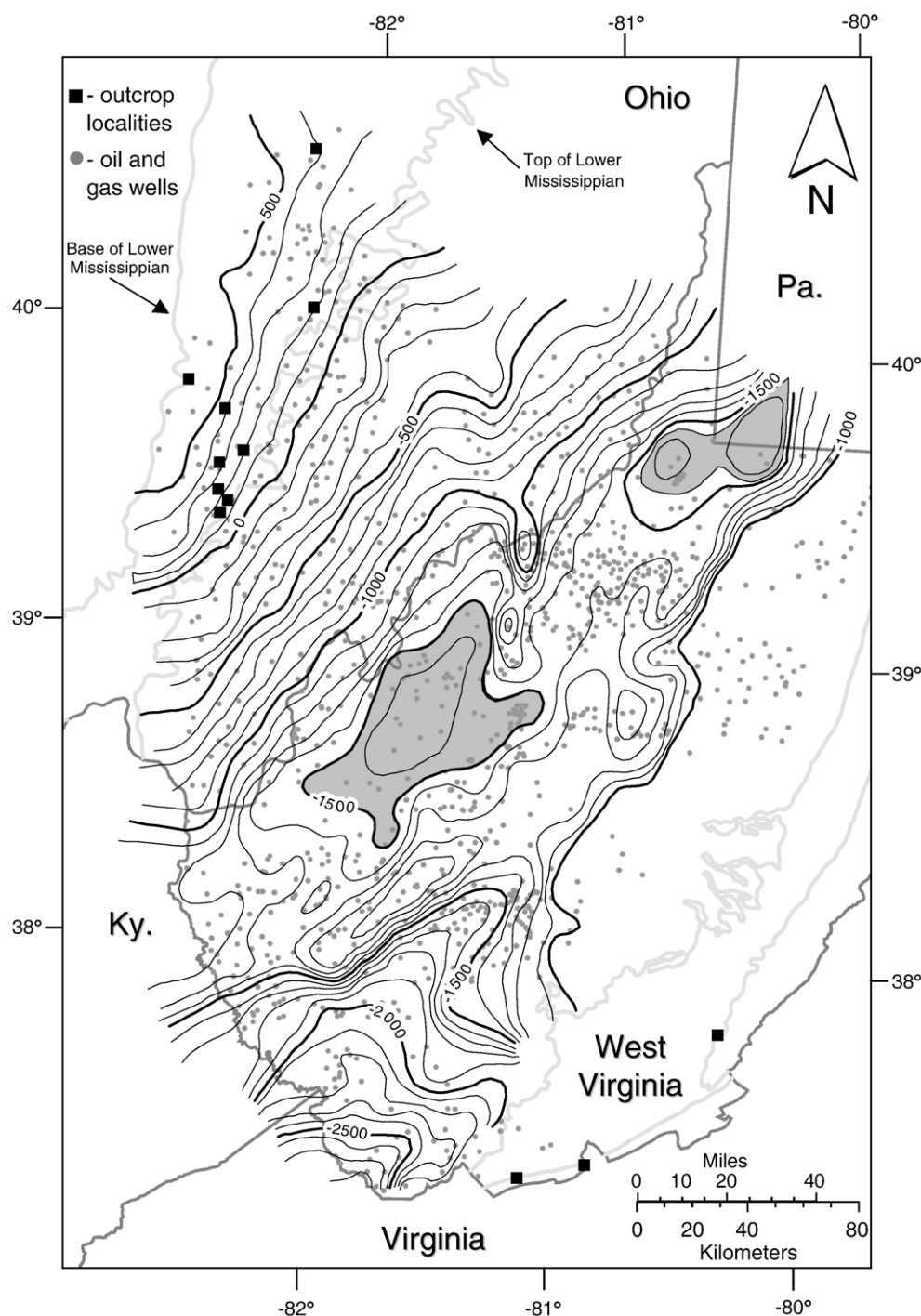


Fig. 3. Structure map on the top of the Berea Sandstone in southeastern Ohio, western Pennsylvania, and West Virginia. Contour interval is 100 ft (30m); index contours every 500 (150m) ft. Well data from West Virginia and Ohio geological surveys.

Sandstone. The surrounding Cuyahoga and Logan formations contain diverse suites of marine invertebrates, allowing for an indirect age determination for the Black Hand Sandstone. Reports of fossil species and

their ranges from the Cuyahoga and Logan formations were evaluated in light of their currently known distributions outside of Ohio rather than simply accepting the biostratigraphic conclusions of previous

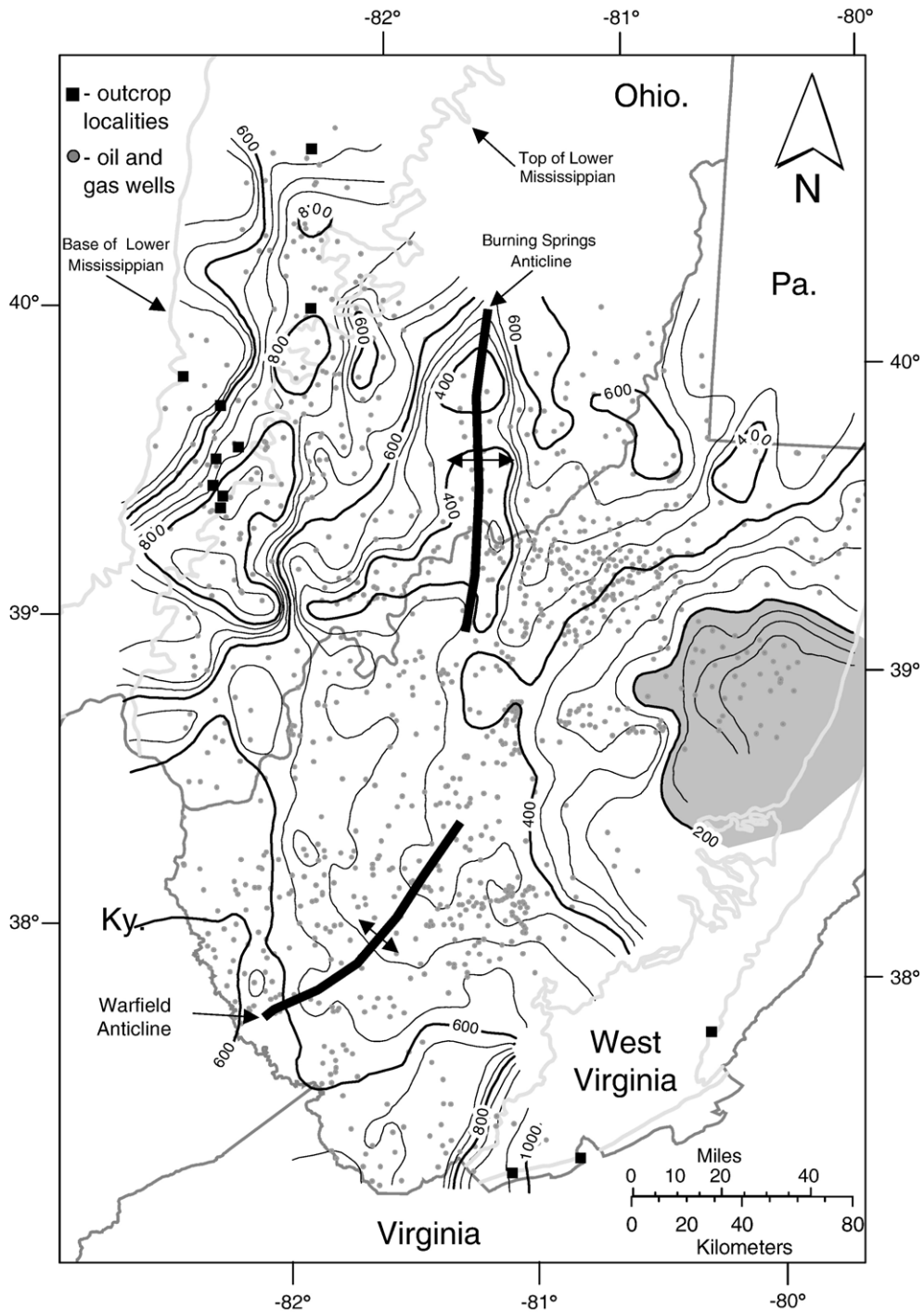


Fig. 4. Lower Mississippian isopach of the same region in Fig. 3. Base of the section is placed at the contact of the Berea Sandstone and Sunbury Shale. Top of the section is placed at the contact of the Lower Mississippian siliciclastics and the Upper Mississippian carbonates. Contour interval is 50 ft (15 m); index contours every 200 ft (60 m). Maximum extent of West Virginia Dome is shown, in light gray, as are the trends for the Warfield and Burning Springs anticlines. Note that some of the thickest sections are in southeastern Ohio. Well data from West Virginia and Ohio geological surveys.

Ohio studies. No new primary data were collected for this study because there are several previous studies of macroinvertebrates, and we were unable to find any faunas not previously described. Data from all previously published studies of both invertebrates and spores were analyzed to create an updated synthesis based on the current biostratigraphic literature for the Lower Mississippian of North America and Europe.

4. Lithostratigraphy

The lithofacies associations defined herein (Table 1) correspond to stratigraphic units identified by previous workers. The *crossbedded-conglomeratic* lithofacies is the Black Hand Sandstone, whereas the *hummocky sandstone* and the *siltstone and shale* associations represent different portions of the Cuyahoga Formation.

Planar and trough crossbedded (Sp and St) sandstones (Fig. 5A and E) and massive gravel (Gm) (Fig. 5B) dominate the *crossbedded-conglomeratic sandstone* association. Other lithofacies include massive gravel with intraclasts (Gi), laminated fines (Fl), ripple bedded sandstone (Sr) and horizontally bedded sandstone (Sh) (Fig. 5D), which are rare. Conglomeratic sandstone is scattered throughout the association. Within lithofacies Sp and St, conglomeratic material is commonly found at the base of individual beds that fine-upwards. Scour

surfaces are common within this association. Many scours are concave-up, and restricted to a single outcrop, are 0.5 m to 5 m in width and 0.1 m to 1 m thick. Larger, outcrop-wide scour surfaces are also common. These surfaces display strong relief, are broadly concave upwards, and can be traced across entire outcrops, but cannot be traced from one outcrop to the next. These surfaces are commonly overlain by lithofacies Gi/Gm and grade upwards into lithofacies Sp and St. Only fragmentary plant fossils were found within the association.

The *hummocky sandstone* association is best expressed in the Fairfield Member. The primary component of the association is hummocky crossbedded sandstone (lithofacies Shcs) with minor amounts of lithofacies Sp and Sr. A few trace fossils, including *Scalarituba*, are present.

The *siltstone and shale* association can be observed in many places in the Hocking Hills, generally in the deepest portions of the gorges below the *crossbedded-conglomeratic sandstone* association. The primary lithofacies are Fl and Sh. Beds are thin and parallel, sandstones are finer-grained than in other associations. Abundant trace fossils include *Teichichnus*, *Pelecypodichnus*, *Paleophycus*, *Scalarituba* and *Rusophycus*. Marine body fossils have been reported (Hyde, 1953, p. 88; Franklin, 1961).

Table 1
Lithofacies of the Cuyahoga Formation, including the Black Hand Sandstone

Facies Code	Lithofacies	Sedimentary Structures	Interpretation	Shape	Frequency	Lithofacies Association*
Gm	Massive Gravel	Primarily structureless; poorly preserved trough crossbedding is rare	Channel lags, gravel bars	Scoop-shaped	Common	CCS
Gi	Gravel with intraclasts	Massive conglomerate with large intraclasts	Lag/channel slump, scour	Scoop-shaped	Common at base of Black Hand; rare elsewhere	CCS
St	Medium-coarse grained sandstone	Trough crossbeds	Dunes	Sheet	Common	CCS
Sp	Medium-coarse grained sandstone	Planar crossbeds	Transverse bars	Sheet	Common	CCS; HS
Sh	Fine-coarse grained sandstone	Horizontal lamination	Floodplain, waning flow?	Sheet	Rare	CCS; SS
Shcs	Medium-coarse grained sandstone, locally pebbly, interbedded shale	Hummocky crossbedding, rare basal scour	Shallow marine, shoreface	Sheet	Only at Chestnut Ridge	HS
Sr	Medium-coarse grained sandstone	Thin bedded, rippled, horizontal and vertical burrows, small shale intraclasts	Floodplain, exposure surface?	Sheet	Rare	CCS; HS
Fl	Fine-grained sandstone, siltstone, mudstone	Rare trace fossils, horizontal laminations	Waning flood deposits	Sheet	Very Rare; common in Cuyahoga	CCS; SS

* CCS – Crossbedded-conglomeratic sandstone; HS – Hummocky Sandstone; SS – Siltstone and Shale; **BOLD** = primary constituent, NORMAL = minor constituent.



Fig. 5. (A) Lithofacies St/Sp from Cantwell Cliffs unit of Hocking Hills State Park, Ohio. Photo corresponds to unit 5 in Fig. 12. Author (DLM) is 1.8 m tall. (B) Gm/Gi from Conkles Hollow State Nature Preserve, Ohio. Photo is at the base of the Black Hand Sandstone; marker is 13 cm long. (C) Large-scale St: Cedar Falls unit of Hocking Hills State Park, Ohio. Outcrop is approximately 30 m tall. (D) Lithofacies Fl and Sh from Cantwell Cliffs unit of Hocking Hills State Park, Ohio. Fl occurs in the eroded recesses. Horizontal beds have limited numbers of small trace fossils. Sp/St unit overlies the horizontal section. Author (DLM) is sitting on unit 2 of Fig. 12. Overlying Sp/St is in unit 3 of Fig. 12. (E) Element CH, large composite channel fill, Ash Cave unit, Hocking Hills State Park, Ohio. Scour surface is at base of overhang where thinly bedded Sp/St is overlain by thickly bedded Gm, Sp, and St. Person at left is 1.7 m tall. (F) Large-scale lateral accretion deposits, lithofacies Sp, Logan, Ohio (UTM 17S, 376014E, 4378834N); actual depositional dip shown as regional dip is less than 1° .

4.1. Contacts and stratigraphic relationships

The lateral contact between the Black Hand Sandstone and the Cuyahoga Formation is not exposed and is subject to speculation and interpretation in the absence

of continuous exposure. The outcrops in question are a series of individual, isolated exposures between Black Hand Gorge (Wolfe et al., 1962) and Granville, Ohio (Bork and Malcuit, 1979). Sandstones in these exposures are either coarse-grained to conglomeratic (Black

Hand Sandstone), or fine- to very fine-grained interbedded with siltstone and shale containing marine fossils (Cuyahoga Formation). In a few instances, thin (0.5m), coarse-grained sandstones are reported 18m below the top of the Cuyahoga Formation (Hyde, 1953; pp. 70–71; Franklin, 1961). This relationship was inferred to be gradational, with increasingly finer grained sandstone encountered farther from the Black Hand. Examination by the authors suggests that the change in grain-size is abrupt and immediate. Sandstones are either coarse-grained or fine-grained, there does not appear to be a gradational transition. This suggests that coarse-grained conglomeratic sediments characteristic of the Black Hand Sandstone are segregated from the fine-grained marine sediments of the Cuyahoga Formation.

Hyde (1953, pp. 88–89) suggested that the basal contact of the Black Hand Sandstone is a regional erosion surface. At Conkles Hollow and Old Man's Cave, where the contact is exposed, two features are evident. The first is the presence of locally abundant large intraclasts at the base of the Black Hand Sandstone (Fig. 5B). Intraclasts observed by the authors are flat, angular, and coherent, with a maximum linear dimension of 1 m, and are apparently derived from lithofacies Fl. These intraclasts can only be traced a few meters upwards into the Black Hand where they disappear.

The second feature is the “stepped” nature of the contact (Fig. 6). In two exposures near Old Man's Cave (Fig. 1, locality 8), the contact is parallel to the bedding of the underlying Cuyahoga Formation. As the surface is traced along the outcrop, the contact sharply truncates the underlying rock as deep as 0.5m, then parallels bedding for 9.5m to 14.5m, and again cuts downward

through the underlying Fairfield Member. The overlying lithofacies is primarily Gi, and the underlying primarily Fl. The sharp, stepped contact, combined with abundant intraclasts of Fl incorporated into the overlying Gi, suggests that the basal contact between the Black Hand Sandstone and the Fairfield Member of the Cuyahoga Formation is erosional rather than gradational where it can be observed.

4.2. Outcrop descriptions and profiles

4.2.1. Cantwell Cliffs

The *crossbedded-conglomerate* assemblage dominates exposures at Cantwell Cliffs. The *siltstone and sandstone* assemblage (Fl and Sh) can be observed in the lowest parts of the gorge but the contact between associations is concealed. The exposure is subdivided into six stratigraphic units (Fig. 7). Units 1, 3 and 6 are dominated by lithofacies Sp and St. Unit 2 is composed of lithofacies Sh and Fl. Tool marks and a few undifferentiated horizontal burrows can be seen on the base of some beds, and one bed within the section contains numerous narrow vertical burrows identified as a small version of *Arenicolites*. Also present is an unusual epichnial mold with annulations that resembles a mirror image of *Arthropycus*. Unit 4 is composed primarily of lithofacies Gm deposited within small channels, with minor amounts of lithofacies Sp and St. Unit 5 comprises large-scale bedsets of lithofacies Sp (Fig. 5A).

4.2.2. Old Man's Cave and lower falls

The gorges around Old Man's Cave provide several kilometers of lateral exposure suitable for analysis of the uppermost Black Hand Sandstone; unfortunately,



Fig. 6. Contact between Black Hand Sandstone above and Fairfield Member below at Lower Falls in the Old Man's Cave unit of Hocking Hills State Park, Ohio showing three steps eroded into the Fairfield Member bedding. (A) Un-retouched photo. (B) Boundary marked between the two units to

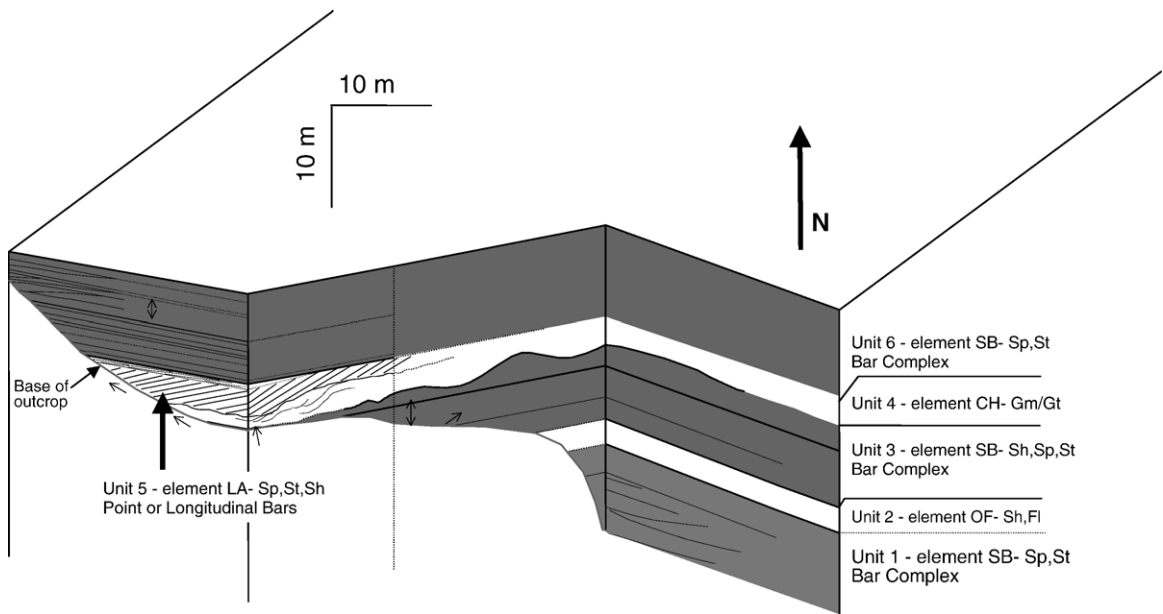


Fig. 7. Fence diagram of the Black Hand Sandstone outcrop at Cantwell Cliffs unit of Hocking Hills State Park, Ohio (UTM 17S 364460E, 4378300N). Section was measured and described following along the “base of outcrop”. Small arrows indicate either paleoflow direction (single head) or orientation (double head). Paleoflow indicators are based upon individual measurements. Dark gray colors highlight the sandy bedform architectural element, which are interpreted to be bar complexes.

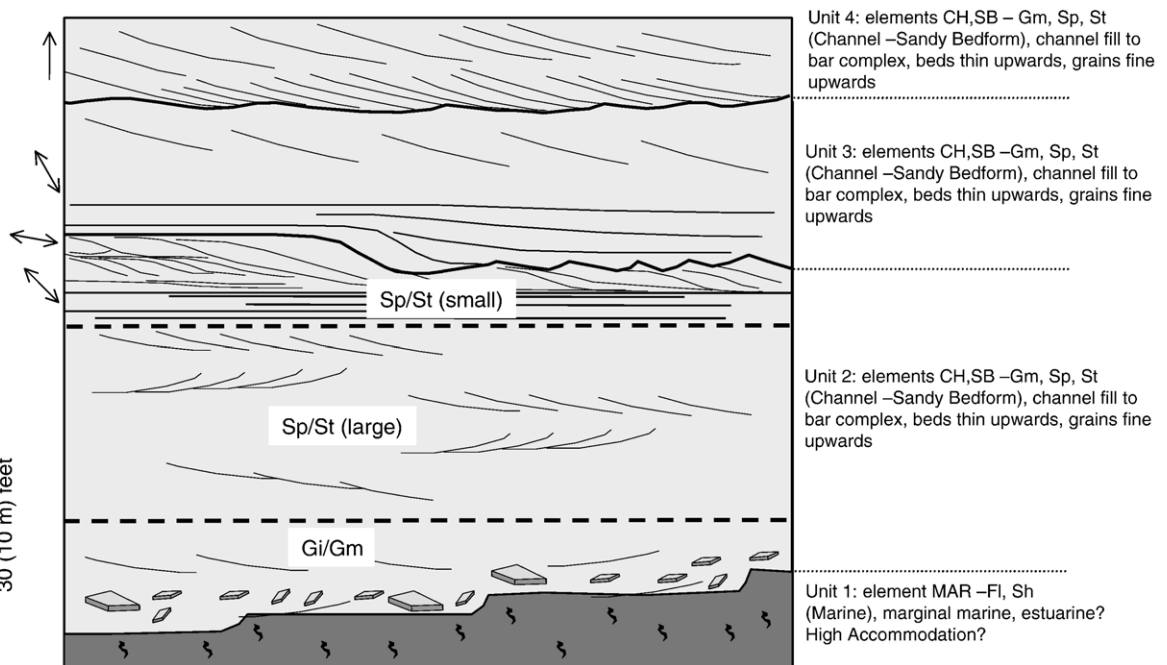


Fig. 8. Composite vertical section summarizing several profiles of the Black Hand Sandstone at Old Man's Cave unit of Hocking Hills State Park, Ohio (UTM 17S 367004E, 4365945N). Boundaries between individual profiles are marked by heavy, dashed lines. Section is subdivided into four stratigraphic units, three within the Black Hand Sandstone. Each unit within the Black Hand Sandstone is bound by a basal scour surface. The scour surface is overlain by lithofacies Gi. Within each unit, Gi grades upwards into lithofacies Sp and St. Scour surfaces are broadly concave upwards and cannot be traced between outcrops. In some cases, these surfaces appear to be basal channel scour, in others, they may represent more widespread erosion with basal relief. No horizontal scale implied. Dark gray color corresponds to siltstone and shale of the Cuyahoga Formation, lighter gray color corresponds to the conglomeratic sandstone of the Black Hand Sandstone.

sections providing good access to the lower Black Hand Sandstone are less common. The Black Hand Sandstone is subdivided into three stratigraphic units, and one Cuyahoga unit (Fig. 8). A typical vertical succession of lithofacies repeats within each of the sandy stratigraphic units. The base of the typical succession is characterized by a scour surface overlain by lithofacies Gm, except the lowest scour (unit 2), which is overlain by lithofacies Gm/Gi. Scour surfaces are broadly concave upwards and cannot be traced between outcrops. In some cases, these surfaces appear to be basal channel scour, in others, they may represent more widespread erosion with basal relief. Bedsets 1–3 m thick of lithofacies Sp and St (Sp/St large in Fig. 8) overlie Gm/Gi. The uppermost portion of the standard succession comprises lithofacies Sp, St, and Sh. Bedsets in the upper sandstones are smaller (0.2–1 m thick), with correspondingly limited lateral extent (Sp/St small in Fig. 8). The upper part of the succession is truncated by a scour surface marking the base of the next unit.

5. Depositional environment of the Black Hand Sandstone

5.1. Previous interpretations

Hyde (1953, pp. 84–85) concluded that the Black Hand Sandstone was deposited as part of a Gilbert-delta with the inclined stratification of the Black Hand Sandstone as the delta foreset beds and the thin horizontal beds of the uppermost Black Hand Sandstone as the delta topset beds. Based upon the orientation of the bedsets and a general decrease in the percentage of conglomerate to the north, it was concluded that the delta prograded northward (Root et al., 1961).

Ver Steeg (1947) interpreted the Black Hand Sandstone as a shoreline deposit. He recognized that the coarse grain size was difficult to explain in terms of shoreline processes. Bork and Malcuit (1979) later modified this interpretation by suggesting that the lower Black Hand Sandstone was deposited as part of a distributary channel system that was later altered by longshore currents, merging the deltaic and shoreline hypotheses. The presence of rare marine fossils and horizontal beds in the uppermost Black Hand Sandstone supported this conclusion (Szmuc, 1957; Bork and Malcuit, 1979).

5.2. Architectural elements

The stratigraphic units identified on outcrop are organized into architectural elements (Miall, 1985)

(Table 2). SB is the most common element within all Black Hand outcrops. It occurs as successions of lithofacies Sp and St. Contacts between the bedsets are commonly parallel and conformable. They are often underlain by outcrop-wide scour surfaces with strong relief. Conglomeratic sandstone is scattered throughout this element, and is commonly found at the base of individual Sp beds. This element is interpreted as a bar complex following Miall (1985). Within each complex, bars were both longitudinal and transverse, with planar crossbeds representing longitudinal bars and trough crossbedding indicative of deposition in transverse or sinuous bars (Miall, 1985).

Element CH displays a basal concave-up scour surface. Lithofacies are commonly Gm, but Gi and St are also present. Small-scale versions (<5 m wide) are identified in every outcrop examined. There are larger outcrop-wide, concave-up scour surfaces that appear to be channel-fill. These features may be up to 90 m wide and 3–9 m deep (Fig. 5E) and may represent a large composite channel fill. Differentiation of these from scour-based element SB is problematic. However, most of the large, concave-up, scour surfaces are overlain by lithofacies Gm, which then grades upwards into element Sp or St, suggesting a basal channel-lag deposit. Lithofacies Gm is not found in element SB, differentiating the two elements.

Element LA is relatively rare in the Black Hand Sandstone. Large-scale, inclined crossbeds occur in the upper Black Hand Sandstone 1.1 mile (1.8 km) west of Logan, Ohio (Fig. 5F). Other examples are rare, but one occurs at Cantwell Cliffs in unit 5 (Figs. 5A and 7). Unit 4 comprises element CH, filled with Gm and scoured into element SB of unit 3. Foresets of unit 5 can be traced off unit 4 and grade upwards into unit 6 (Fig. 7). The sloping foresets apparently represent lateral accretion as opposed to downstream accretion because the beds are dipping to the west, perpendicular to the general trend of the Black Hand Sandstone. In both cases, lateral accretion is interpreted because the dip of the beds is perpendicular to the overall trend of the Black Hand Sandstone.

Table 2
Composition of architectural elements of the Cuyahoga Formation including the Black Hand Sandstone

Element	Lithofacies	Interpretation
CH – channel	Gm/Gi – Sp/St	Channel fill or lag
LA – lateral accretion	Sp – St	Lateral accretion
SB – sandy bedform	Sp, St, Sh, Sr	Bar complex
OF – overbank fines	Fl, Sh	Floodplains
MAR – marine	Shcs, Fl, Sr	Marginal marine (estuarine)

Element OF, overbank fines, contains lithofacies Fl, Sr, and Sh. This element is present in unit 2 at Cantwell Cliffs (Figs. 5D and 7) and at Ash Cave. Trace fossils associated with this element include *Arenicolites* and a variety of undifferentiated horizontal traces. The traces are small and reflect deposition in a stressed environment. Similar suites of trace fossils are found in lacustrine (Buatois and Mangano, 1995; Buatois et al., 2005), marginal marine (De Gibert and Ekdale, 1999) and fluvial floodplains (Ratcliffe and Fagerstrom, 1980). Found within the Black Hand Sandstone, with little evidence for a marine incursion, this element is likely a floodplain deposit.

Element MAR, marine, comprises the *siltstone and shale* and *hummocky sandstone* lithofacies assemblages. This is not a fluvial element defined by Miall (1985), but it is included to contrast the fluvial elements of the Black Hand Sandstone. The element includes marine trace fossils (*Rusophycus*, *Teichichnus*, *Paleophycus*, *Scalarituba*, *Pelecypodichnus*) (Pemberton et al., 1992); invertebrate marine body fossils (brachiopods, bivalves, gastropods); and hummocky bedded lithofacies Shcs. A definitive report of marine invertebrate fossils from the Pleasant Hill Dam section of Szmuc (Szmuc, 1957) suggests this element can be present within the upper part of the Black Hand Sandstone.

5.3. Flow direction of the Black Hand river

The only quantitative study of paleocurrent data from the Black Hand Sandstone (Kittredge and Malcuit, 1985) reported a paleoflow direction of 340°. Some qualitative conclusions about the flow direction of the river can be made. Holden (1942), Ver Steeg (1947), and Hyde (1953, p. 85), all concluded that currents depositing the Black Hand Sandstone were flowing northward, based primarily on the orientation of crossbeds. This is in accord with Kittredge and Malcuit (1985). Additionally, the presence of element MAR at the Pleasant Hill Dam section (Szmuc, 1957; Root et al., 1961; Bork and Malcuit, 1979) suggests a limited marine inundation of the northern part of the study area. The absence of this element in the southern sections suggests a northward flow direction for the Black Hand. The amount of conglomerate, and the grain-size of the conglomeratic material, decreases northward (Root et al., 1961).

Data collected during the progress of this study loosely agree with this broad conclusion. Where they were measured, flow directions and orientations are plotted in Figs. 7 and 8. Measurements were taken from two-dimensional planar and trough crossbed sets, and

obvious channel-fill deposits. Taken as a whole, the data collected for this study agree with the published reports, suggesting that the river in which the Black Hand Sandstone was deposited flowed northward.

5.4. Depositional environment of the Black Hand Sandstone and evidence for valley fill

The lithofacies and elements defined in the Black Hand Sandstone are typical in fluvial, tidal, and shoreface deposits. The most recent previous interpretation for the Black Hand Sandstone is a distributary channel modified by shoreline activity into a north–south trending shoreline spit (Bork and Malcuit, 1979). This interpretation is questioned by the present study.

Tidal and shoreface sandstones have bedding and lithologic characteristics similar to the Black Hand Sandstone (Tye et al., 1999; Tape et al., 2003; Willis and Gabel, 2003), particularly in lithology and size and scale of bedsets. Shoreface and tidal sandstones coarsen-upwards (McCubbin, 1982; Willis and Gabel, 2003; Kirschbaum and Hettinger, 2004) and are often heterolithic and bioturbated (Aitken and Flint, 1994; Tape et al., 2003; Willis and Gabel, 2003; Kirschbaum and Hettinger, 2004). Planar crossbed sets in tidal sandstones often have overlying clay or siltstone drapes (Aitken and Flint, 1994; Tape et al., 2003). Beds within the Black Hand Sandstone are homogenous or fine-upwards with no evidence of bioturbation. Sandstones deposited in a tidal or distributary environment coalesce into relatively thin, widespread sheets 20–30 m thick and 20–40 km wide (Pulham, 1989; Tape et al., 2003; Willis and Gabel, 2003).

The Black Hand Sandstone is primarily homogenous; it contains no clay or silt drapes. Where fine-grained lithofacies are present, they are discrete, thin, horizontal beds associated with lithofacies Fl, Sh and Sr. These are the only deposits that display any bioturbation. The absence of bioturbation or heterolithic crossbed sets suggests that the Black Hand Sandstone is not a tidal or shoreface deposit.

The Black Hand Sandstone is approximately three times thicker and three times narrower than most incised tidal, distributary, or shoreface deposits (Pulham, 1989; Tape et al., 2003; Willis and Gabel, 2003). This suggests a different depositional environment for the Black Hand Sandstone. The coarse grain size indicates deposition in a relatively high-energy environment, and the absence of bioturbation suggests a substrate that was unstable, or the absence of large marine burrowers. During the Mississippian macroscopic vertical bioturbation was present in marine environments but essentially absent in

alluvial environments, where most traces consisted of surface trackways (Buatois et al., 1998). These features, combined with fining-upward beds and the identified architectural elements indicate that the Black Hand Sandstone was deposited in a low-sinuosity braided stream setting (Allen, 1983; Miall, 1985; Luttrell, 1993; Bristow, 1993; Ye and Kerr, 2000; Jones et al., 2001; Batson and Gibling, 2002; Yu et al., 2002) as opposed to distributary, shoreface, or tidal channels.

Incised-valleys are defined (Posamentier and Allen, 2000) as elongate topographic lows larger than a single channel form. The basal contact is characterized by an abrupt seaward shift in depositional facies and should be a regionally mappable sequence boundary (Zaitlin et al., 1994). The criteria for recognition of incised valley fill deposits are still evolving; however, a number of criteria are generally accepted (Table 3). Most of these features can be observed in the Black Hand Sandstone; however, poor exposure and limited subsurface data make the “fit” somewhat speculative.

Valley fill deposits display a valley-type morphology, sometimes with smaller tributaries (Posamentier and Allen, 2000; Ye and Kerr, 2000). Original maps (Holden, 1942; Hyde, 1953) display a narrow, north–south, linear trend (Figs. 1 and 9). This distribution suggests a stream-like map pattern, although the linear geometry could be the result of shoreline processes as originally suggested by Ver Steeg (1947). This is rejected because of the coarse grain size and the nearly total absence of any evidence of marine invertebrate fossils, or trace fossils.

Anomalously thick channel-fill deposits exceed 30 m (Posamentier and Allen, 2000, p. 62). Individual deposits within the Black Hand Sandstone rarely exceed 10 m, although some of the larger composites may

exceed 30 m. The majority of channel-fill deposits within the Black Hand Sandstone are not anomalously thick, however, the multistory deposits and the restriction of the conglomerates to the Black Hand Sandstone trend indicate incised valley fill.

In stratigraphic cross-sections, incised valley fill should “hang” from a stratigraphic horizon (Posamentier and Allen, 2000). Using the Sunbury Shale as a datum, the Black Hand Sandstone hangs naturally from what appears to be the top of the Cuyahoga Formation (Fig. 10). The transition to marine shales of the Cuyahoga Formation appears to be abrupt. The base of the Black Hand Sandstone has at least 48 m of relief.

A fall in relative sea level large enough to produce incision of the Cuyahoga Formation should produce correlative paleosol deposits (Posamentier and Allen, 2000). No paleosol deposits (e.g., red mudstones) have been reported from the Cuyahoga Formation (Hyde, 1953; Szmuc, 1957) and none were observed during this study. An explanation for this absence is provided by the Berne Member of the Logan Formation, which is thought to be a storm deposit (Bork and Malcuit, 1979) and a transgressive lag. Energetic transgressive events may erode 10–20 m of substrate (Posamentier and Allen, 2000, p. 79). Interfluvial sequence boundaries in these settings may be marked by an abrupt transition from fine-grained marine highstand deposits to coarse-grained transgressive lags (Posamentier and Allen, 2000). The Berne Member covers and laterally extends beyond the Black Hand Sandstone throughout the region. In these locations, the transition from the Cuyahoga Formation below to the Berne Member above may be this type of transition.

An unconformity is often present at the base of incised valley fill deposits. The evidence for a basal unconformity in the Black Hand Sandstone can be subdivided into sedimentologic and biostratigraphic data. The physical evidence is discussed in this section, the biostratigraphic evidence is discussed in Section 6.

The basal contact is sharp, stepped, and scoured, with intraclasts of the Cuyahoga Formation incorporated into the basal portions of the Black Hand Sandstone (Figs. 5B and 6). Intraclasts are subangular and polygonal, reach a diameter of 1 m, have a thickness of 2–3 cm, and often display horizontal trace fossils preserved in convex hyporelief, which must be original to the intraclasts. The size, shape, and cohesive nature of the clasts and the underlying shale, suggest that the Cuyahoga Formation had been dewatered and consolidated prior to deposition of the Black Hand Sandstone. Dewatering of shale can occur

Table 3
Evidence for Valley Fill (from Posamentier and Allen, 2000; Ye and Kerr, 2000)

Feature	Black Hand Sandstone
Valley Morphology	Maybe
Anomalously thick channel deposits	No
Multistory fill of channels	Yes
Channels “hang” from strat horizon	Yes
Widespread fluvial erosion with significant relief	Yes
Paleosols on interfluvies	Regional occurrences, not local
Clustered channel fill	Yes
Basal Unconformity	Yes
Valley–fill lithology significantly different from surrounding rock	Yes

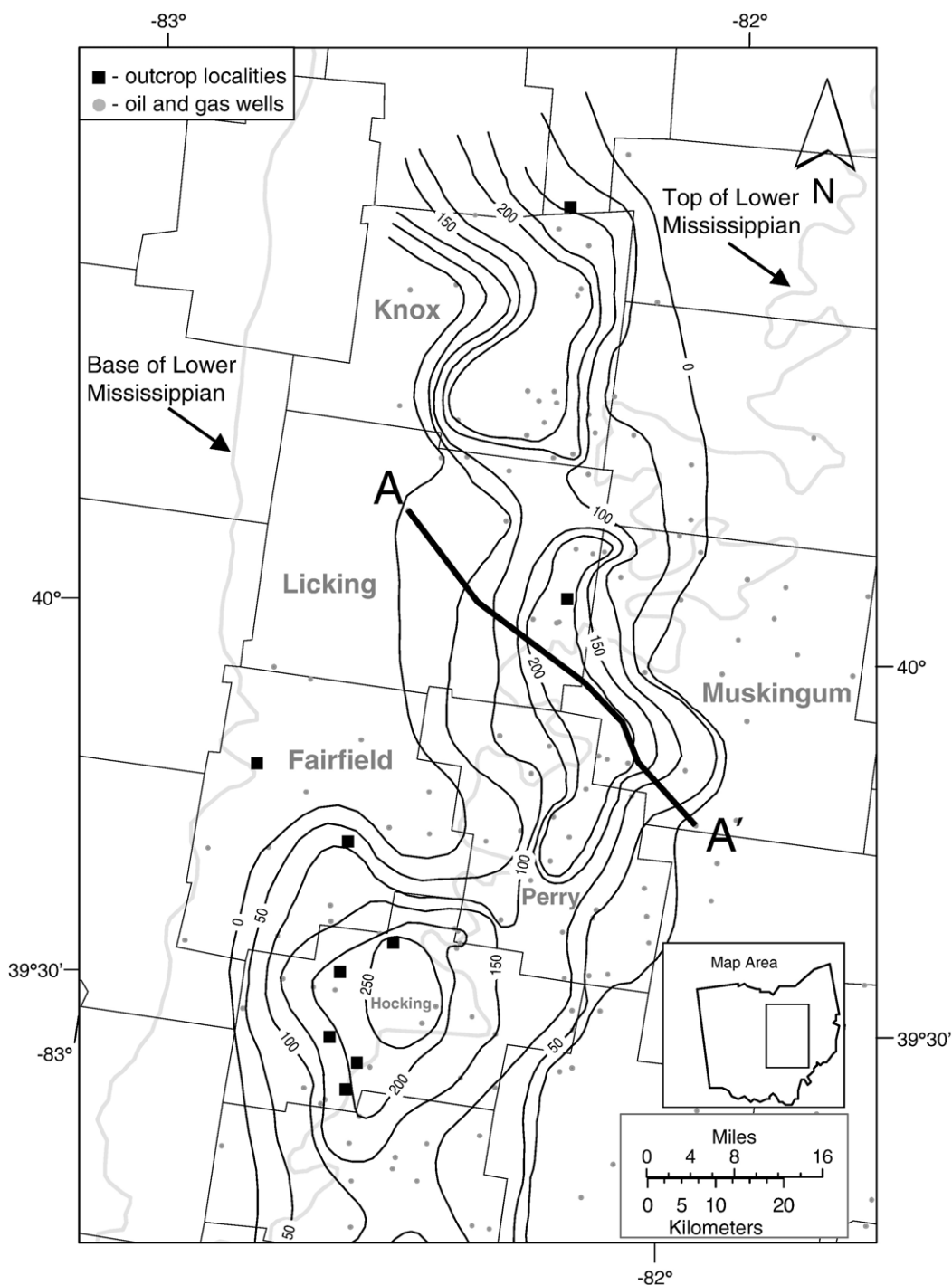


Fig. 9. Isopach map of the Black Hand Sandstone. Thickness determined from gamma ray logs of gas wells (Ohio Geological Survey). Contour interval is 50 ft (15 m), index contours every 100 ft (30 m). The line of section (A-A') for Fig. 10 is shown. One anomalously thick section in Hocking County exceeds 250 ft (76 m), which may reflect the difficulty in separating the Black Hand Sandstone from sandstones of the Fairfield Member on wireline logs.

after deposition in both subaerial and subaqueous environments as well as following burial (Potter et al., 1980). It is nearly impossible, given the existing data,

to determine the cause of dewatering; however, knowing the exact reason is unnecessary, because if the intraclasts represent mudcrack polygons, then the

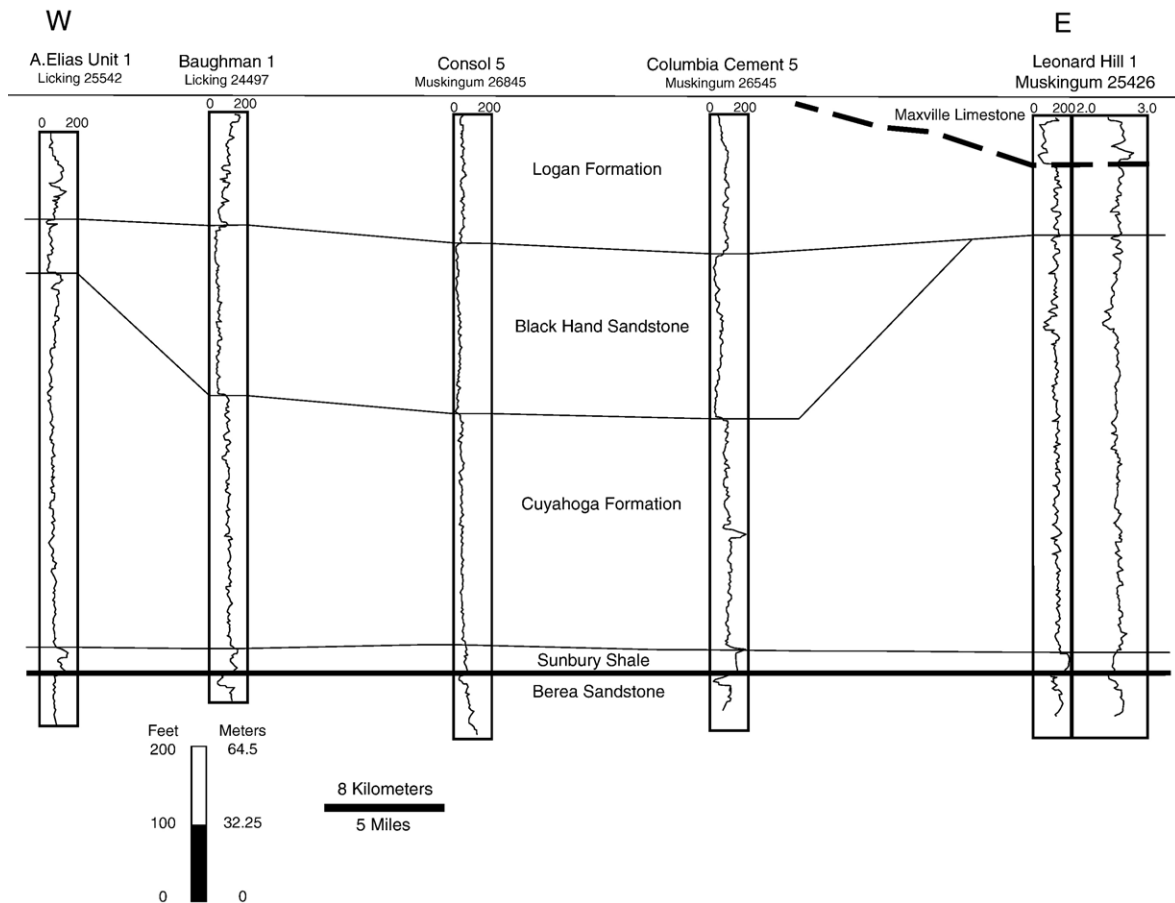


Fig. 10. Stratigraphic cross-section through the Black Hand Sandstone in the northern portion of the study area. Logs are gamma-ray well logs (Ohio Geological Survey). Units are standard API gamma-ray units. Numbers below well names are Ohio permit numbers. The Hill #1 well includes a bulk density curve, which is measured in g/cm^3 . The lateral transitions appear to abrupt, which may be an artifact of the coarse data spread. Relief on the basal contact is approximately 60m. Cross section is located in Fig. 9.

region was subaerially exposed following a fall in relative sea level suggesting formation of a local unconformity prior to deposition of the Black Hand occurred. If the cohesiveness of the Cuyahoga Formation is the result of burial followed by later incision, this is also an indication of the formation of an unconformity following a fall in relative sea level.

The best evidence for interpreting the Black Hand Sandstone as incised valley fill is the lithologic data (Table 3). The Black Hand Sandstone is interpreted as a fluvial sandstone in contact with marine shales and sandstones of the Cuyahoga Formation. The physical evidence for erosion at the base of the Black Hand Sandstone suggests scour and unconformity. The absence of associated paleosols presents a problem; however, if they were present, it is likely that they were eroded during the energetic transgression represented by the Berne Member of the Logan Formation.

Because the Black Hand Sandstone is almost entirely fluvial, excepting a thin incursion of marine sediments in the northernmost portion of the study area, the Black Hand Sandstone probably lies primarily in the fluvial portion of the uppermost valley. This segment of a valley fill system is predominantly fluvial and can extend 10s to 100s of km upstream from the marine/terrestrial boundary. This is the most likely setting for deposition of the Black Hand Sandstone (Zaitlin et al., 1994).

6. Ages of lower Mississippian strata in Ohio

To constrain the timing of valley incision and subsequent deposition of the Black Hand Sandstone, paleontologic data from Lower Mississippian rocks in Ohio is summarized and earlier studies are re-evaluated in light of current biostratigraphic zonations.

6.1. Logan Formation

The Logan Formation is earliest Osagean age based on ammonoids, brachiopods, miospores, and conodonts. The Byer Member contains the ammonoids *Muensteroceras* (Hyde, 1953), *Masonoceras* (formerly *Karagandoceras*), *Protocanites*, and *Kazakhstania* (Manger, 1971a; Work and Manger, 2002). Collectively, these ammonoids are indicative of the early Osagean (Gordon and Mason, 1985; Ramsbottom and Saunders, 1985; Gordon, 1986; Kullmann et al., 1990; Work and Manger, 2002). Brachiopod faunas are interpreted to have early Osagean affinities (Fagadau, 1952; Rodriguez, 1961; Carter and Carter, 1970). Miospores from the Byer Member are from the PC Miospore Biozone, late Tn2 to early Tn3 age, which basically spans the Kinderhookian–Osagean boundary (Clayton et al., 1998). The Rushville Member, at the top of the Logan Formation (Fig. 2), contains conodonts that are from the middle-early Osagean (Thompson et al., 1971).

6.2. Cuyahoga Formation

In the study area, the Cuyahoga Formation is mostly, if not entirely, Kinderhookian in age. Brachiopods in

the Orangeville, Sharpsville, and Meadville members (Fig. 2) are Kinderhookian (Szmuc, 1957). However, the age of the youngest member of the Cuyahoga Formation, the Wooster Shale, is equivocal. Both Szmuc (1957) and Rodriguez (1961) indicated that the brachiopod fauna might be as young as early Osagean. A biostratigraphic analysis of the Wooster Shale brachiopods using Carter and Carter (1970) reveals six species known from both the Kinderhookian and Osagean of the Mississippi Valley stratotype, one species from only the Kinderhookian, and two species from only the Osagean. We suggest that the equivocal age of the Wooster Shale indicates that these rocks were deposited during the Kinderhookian–Osagean transition, which is a hiatus defined by two missing conodont zones in the Mississippi Valley that are divided between the latest Kinderhookian and earliest Osagean (Lane and Brenckle, 2005).

6.3. Black Hand Sandstone

We were unable to find any marine fossils in the numerous outcrops of the conglomeratic sandstones of the Black Hand Sandstone in the study area. Szmuc (1957, p. 206) reports the brachiopods *Syringothyris* sp.

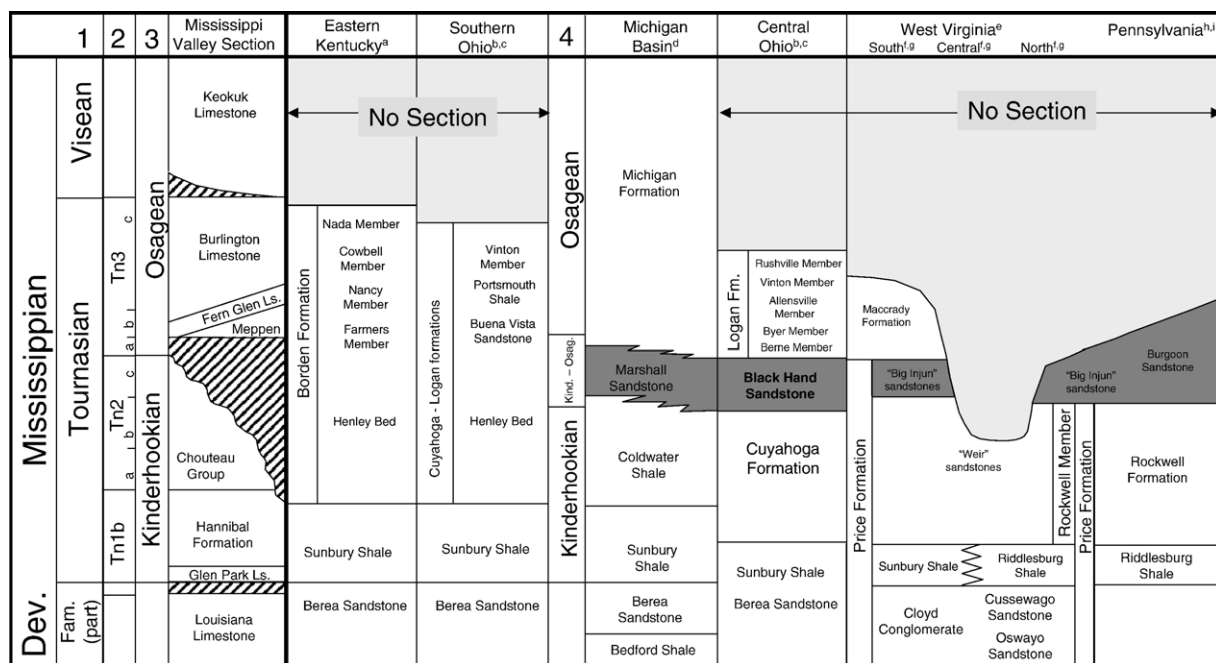


Fig. 11. Lower Mississippian chronostratigraphy for the region. (1) European stage names, (2) Tournasian subdivisions (Jones, 1996), (3) North American stage names, based upon Mississippi Valley type localities (Lane and Brenckle, 2005), (4) stage name divisions based upon Lower Mississippian data from Ohio and adjacent states. Note that the Kinderhookian–Osagean boundary cannot be precisely located; see Section 6.3. Stratigraphy from (a) Sable and Dever (1990), (b) Hyde (1953), (c) Holden (1942), (d) Harrell et al. (1991), (e) Bjerstedt and Kammer (1988), (f) Matchen and Vargo (1996), (g) Vargo and Matchen (1996), (h) Brezinski (1999), (i) Inners et al. (2003).

and *Chonetes* sp., along with unidentified bivalves, in a 10-cm bed 30 m above the base of a 42-m section of the Black Hand Sandstone at Pleasant Hill Dam in Ashland County (Fig. 1). We visited this heavily weathered outcrop, but were unable to find the fossil zone. The long-ranging genera *Syringothyris* (Upper Devonian–Upper Mississippian) and *Chonetes* (Devonian–Pennsylvanian) have little biostratigraphic significance (Carter and Carter, 1970).

We did attempt to directly date the Black Hand Sandstone using miospores. Several samples from thin, interbedded clay shales (Lithofacies F1) within the Black Hand Sandstone were sent to Jeffrey Richardson at Ohio State University (Columbus) for analysis. Richardson (personal communication, 2003) reported that the samples were barren of miospores.

Bork and Malcuit (1979, Table 2) reported a variety of marine fossils from the Black Hand Sandstone, including brachiopods, bivalves, gastropods, bryozoans, trilobites, and crinoids. As far as we can determine, none of these fossils were collected from the thick, conglomeratic sandstones that we consider to be true Black Hand Sandstone. Rather they are from non-conglomeratic marine sandstones within upper Cuyahoga Formation shales laterally adjacent to incised Black Hand Sandstone channels. None of these non-conglomeratic marine sandstones could be laterally traced into the conglomeratic Black Hand Sandstone.

The Black Hand Sandstone can be no younger than earliest Osagean, the age of the overlying Logan Formation, and may even be older. The age of the Wooster Shale, as previously discussed, is equivocal and may be either Kinderhookian, Osagean, or some combination of the two. Because the Black Hand Sandstone is incised within the Cuyahoga Formation, it is younger than the Wooster Shale.

This analysis strongly infers that the Black Hand Sandstone was deposited during the hiatus between the Kinderhookian and Osagean epochs, as defined by the unconformity in the stratotype region of the Mississippi Valley where two conodont zones are missing (Lane and Brenckle, 2005). The time interval that cannot be clearly resolved in Ohio is denoted as Kinderhookian–Osagean on the stratigraphic chart (Fig. 11).

7. Discussion and interpretation

7.1. Regional stratigraphic correlations

The depositional origin of the Black Hand Sandstone takes on greater significance when placed in a regional context. The Black Hand Sandstone is part of an

extensive coarse-grained sandstone complex that also covers much of northern West Virginia and western Pennsylvania (Vargo and Matchen, 1996) (Fig. 11). In southwestern Pennsylvania Lower Mississippian strata are Kinderhookian marine units (Schiner and Kimmel, 1972) capped by the medium- to coarse-grained Burgoon Sandstone (Harper and Laughrey, 1987; Brezinski, 1999). The Burgoon is equivalent to the “Big Injun” sandstone, an informal drillers designation, in the subsurface of Pennsylvania and northern West Virginia (Vargo and Matchen, 1996; Brezinski, 1999), and the Purslane Sandstone of eastern West Virginia (Bjerstedt, 1986). Plant fossils found in the Burgoon and Purslane sandstones indicate an Osagean age (Read, 1955; Scheckler, 1986; Brezinski, 1999).

In Michigan, the Coldwater Shale comprises interbedded marine shales, siltstones, and fine-grained sandstones overlying the Sunbury Shale and is more or less age equivalent to the Cuyahoga Formation (Harrell et al., 1991). The overlying Marshall Sandstone is composed of two members. The lower unnamed member is fine- to medium-grained fossiliferous marine sandstone. The upper member, or Napoleon Member, is medium- to coarse-grained crossbedded sandstone with no report of marine invertebrate fossils (Harrell et al., 1991). The Marshall Sandstone is thought to be entirely Osagean in age (Harrell et al., 1991), but the ammonoid fossil record suggests it may span the Kinderhookian–Osagean boundary (Miller and Garner, 1955). The age and stratigraphic position of the Marshall Sandstone suggests it is correlative with other thick sandstones in the Lower Mississippian section, including the Black Hand, Burgoon, Purslane, and Big Injun sandstones. The relationship between the Marshall and Black Hand sandstones will be further treated in Section 7.6.

7.2. Correlation of the Kinderhookian–Osagean boundary unconformity between Ohio and the Mississippi Valley stratotype region

The Kinderhookian–Osagean boundary was defined in the Mississippi Valley (Lane and Brenckle, 2005). It is now widely recognized that this boundary is unconformable in the stratotype region and that significant erosion occurred there. Two conodont zones are missing in the stratotype region, but are present in southwestern Missouri where sedimentation was apparently more complete (Lane and Brenckle, 2005).

We hypothesize that a fall in sea level at the end of the Kinderhookian produced both the erosion seen in the Mississippi Valley region and the incision of the Black

Hand Sandstone paleovalley. The paleovalley was filled with sandstone during the subsequent rise in sea level at the beginning of Osagean time and was then capped by marine sediments of the Logan Formation (Fig. 12).

The unconformity at the Kinderhookian–Osagean boundary has long been recognized, but is poorly understood. In western Illinois, the youngest Kinderhookian unit, the Starrs Cave Oolite of the Chouteau Group, is present along the Mississippi River with successively older units truncated to the east, with the oldest truncated unit being the lower Kinderhookian Hannibal Formation (Workman and Gillette, 1956; Lane and Brenckle, 2005) (Fig. 11). The early Osagean Burlington Limestone (or the equivalent Meppen Limestone) overlies all these units (Lane and Brenckle, 2005).

In southeast Iowa Witzke and Bunker (1996, Fig. 8) placed a sequence boundary between the Kinderhookian and Osagean on the basis of the sub-Burlington erosional beveling of the Wassonville Formation. Witzke and Bunker (2001, 2002) further commented that this seems anomalous because the beveling is in an offshore direction (west to east), and strata are thicker and more complete towards the Transcontinental Arch in northwest Iowa. They suggested the cause was either structural upwarping, for which there is some evidence,

or submarine erosion. They did not suggest a eustatic fall in sea level. However, if the Black Hand Sandstone paleovalley formed simultaneously with the Kinderhookian–Osagean unconformity, then it seems likely there was a common cause, which we infer to be a eustatic fall in sea level. Why erosion is apparently more extensive in the offshore direction in Iowa is beyond the scope of the present study, but recognizing a sea level fall at this time may help to explain the origin of the sub-Burlington disconformity. Certainly, the new interpretation of the Black Hand Sandstone presented in the present paper suggests that the origin of the Kinderhookian–Osagean boundary in the Mississippi Valley should be re-evaluated in light of a eustatic fall in sea level.

7.3. Sequence stratigraphy and timing of incision

Interpretation of the Black Hand Sandstone as incised valley fill implies that its basal contact is a previously unrecognized sequence boundary. Thus, the Lower Mississippian comprises two sequences in Ohio. The two sequences are designated Lower Mississippian 1 (LM1) and Lower Mississippian 2 (LM2) and are bounded by three sequence boundaries (Fig. 12). Sequence boundaries occur at the base of the Berea

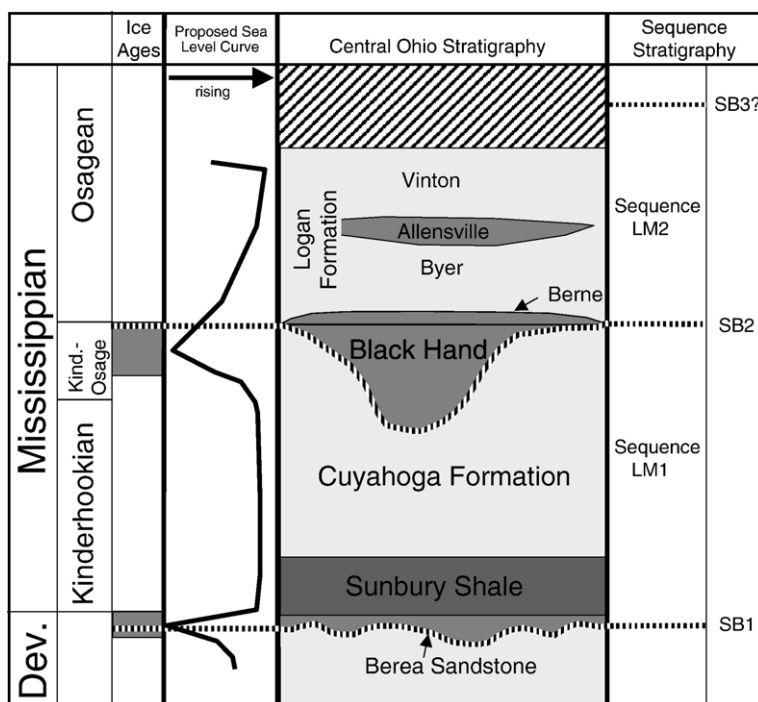


Fig. 12. Correspondence between the Lower Mississippian stratigraphy of Ohio, the Gondwanan ice ages, and the proposed sea level curve for the central Appalachians. Sequence stratigraphy is from Matchen (2004). Temporal extent of ice ages from Crowell (1999).

(sequence boundary 1—SB1), the base of the Black Hand Sandstone (sequence boundary 2—SB2) and at the contact with the overlying carbonates (sequence boundary 3—SB3). SB1 and SB3 have already been widely recognized throughout the region (Matchen and Kammer, 1994; Pashin and Ettensohn, 1995; Yang, 1998; Khetani and Read, 2002).

The extent of SB2 is less certain. The Black Hand Sandstone apparently correlates with the time gap represented by the Kinderhookian–Osagean unconformity in the Midcontinent and is equivalent to Witzke and Bunker's (1996) sequence boundary. The Black Hand Sandstone also correlates eastward to a series of thick sandstones including the Burgoon, Purslane, and Big Injun sandstones (Fig. 11). Underlying these sandstones in Pennsylvania and Maryland are terrestrial red mudstones known as the Patton “red beds” (Bjerstedt, 1986; Bjerstedt and Kammer, 1988). Similar red beds have been observed below the Big Injun sandstone in the subsurface of West Virginia (Zou, 1993). Most likely these red beds represent subaerial exposure associated with either the sea level fall that incised the Black Hand Sandstone paleovalley into the Cuyahoga Formation or the late highstand of sequence LM1.

SB2 can be recognized throughout the central Appalachians, and is correlated to the Kinderhookian–Osagean unconformity in the Mississippi Valley stratotype region. That boundary correlates to the Tn2–Tn3 boundary, which is recognized worldwide as a sequence boundary, e.g., the Hasterian–Ivorian boundary in Belgium and the Cherepetsky–Kizelovsky boundary in Russia (Ross and Ross, 1985; Webster and Groessens, 1990; Jones, 1996; Jones and Somerville, 1996; Hance et al., 2002; Lane and Brenckle, 2005).

7.4. Relative sea level fall: Gondwanan glaciation—cause of the Kinderhookian–Osagean unconformity

This interpretation of the Black Hand Sandstone as incised valley fill requires a fall in relative sea level of up to 60 m. Sea level falls of such magnitude have been recognized at the end of the Ordovician (Brenchley et al., 1994) and in the Pennsylvanian (Ye and Kerr, 2000).

Although the Early Mississippian generally is not known as a time of glaciation, there are recognized Gondwanan glacial events at the Famennian–Kinderhookian boundary and in the mid-Tournaisian, possibly equivalent to the Kinderhookian–Osagean boundary (Crowell, 1999; Crowley and Berner, 2001). Loboziak et al. (1992) recovered late Tournaisian miospores (Higgs et al., 1988) from the tillites of the Poti

Formation of Brazil. We suggest that this glacial event caused a eustatic fall in sea level resulting in the incision for the Black Hand Sandstone, the Kinderhookian–Osagean unconformity in the Mississippi Valley stratotype region, and the Tn2–Tn3 boundary worldwide. This sea level fall may not be clearly evident in all basins. Saltzman (2002) reported that in rocks spanning the Kinderhookian–Osagean boundary in the Great Basin in the western US there is no evidence of subaerial exposure surfaces, which he attributes to subsidence associated with the contemporaneous Antler Orogeny.

The magnitude of this glacial event may have been relatively large as indicated by stable isotopes of carbon and oxygen preserved in calcite of both marine invertebrates and limestones (Bruckschen and Veizer, 1997; Bruckschen et al., 1999; Mii et al., 1999). Saltzman et al. (2000) and Saltzman (2002) reported a very strong $\delta^{13}\text{C}$ anomaly of up to +7.1‰ that spans the latest Kinderhookian and earliest Osagean in limestones from Idaho and Nevada. These studies associated this strong positive excursion with a glacial episode presumably on Gondwana.

7.5. Relative sea level fall: tectonics

Ettensohn (1987) subdivided the Upper Devonian and Lower Mississippian strata of the central Appalachian basin into four tectophases with the Lower Mississippian corresponding to the final tectophase of the Acadian Orogeny. The Acadian foreland basin system had been effectively filled by the end of the Devonian (Castle, 2000) producing a ramp-style geometry. The thickness of Lower Mississippian rock does not increase substantially eastward into the foredeep. Instead, Lower Mississippian strata maintain a relatively consistent thickness from eastern Kentucky (121 m, Matchen and Kammer, 1994) and eastern Ohio (242 m, Fig. 3) to central Pennsylvania (182–212 m, Inners et al., 2003) and Maryland (212 m, Bjerstedt, 1986). This does not suggest differential loading and subsidence, as is evident in the distribution of Upper Devonian sedimentary rock (Ettensohn, 1987), but suggests minimal subsidence or isostatic rebound following an orogenic event (Heller et al., 1988). This interpretation suggests that during the Early Mississippian, the central Appalachians experienced minimal subsidence. The result was a relatively thin apron of sediment as compared to the 1900 m of Upper Devonian strata (Fail, 1985). The Black Hand Sandstone does not overlie a structural high (Fig. 3). In fact, the Black Hand Sandstone lies within the thickest section of Lower

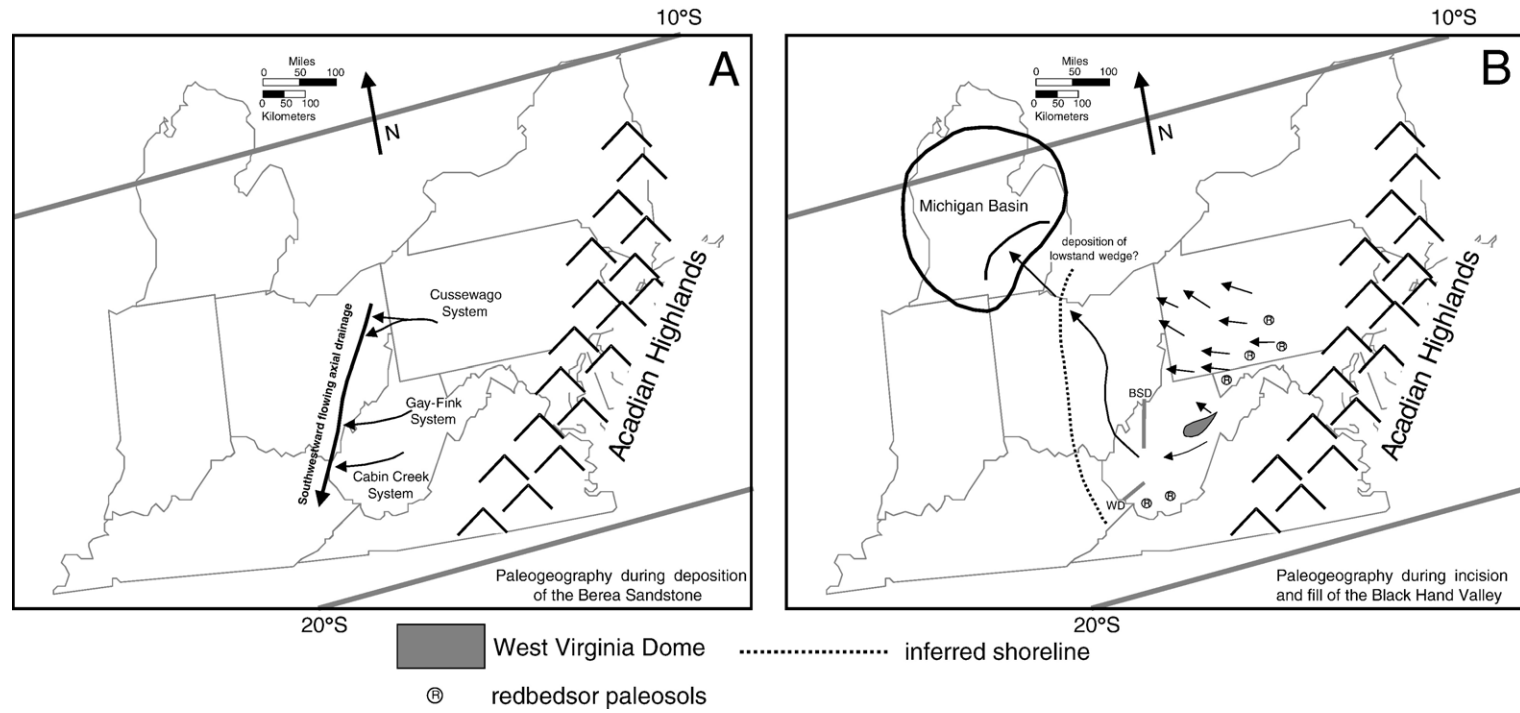


Fig. 13. (A) Paleogeography during deposition of the latest Devonian Berea Sandstone (Pashin and Ettensohn, 1995). (B) Paleogeography of the Black Hand and equivalents. Paleoflow estimates in Burgoon–Purslane from Pelletier (1958) and Brezinski (1999). The paleo-latitude lines are based on the PALEOMAP Project (www.scotese.com).

Mississippian strata (Fig. 4), so local tectonics are unlikely to have contributed to the incision.

Still, there must have been some tectonic influence on the region. Pashin and Etensohn (1995) concluded that distribution of the Berea Sandstone reflects a change from a westward dipping paleoslope to a southwestward paleoslope (Fig. 13A). The shift from southwestward drainage for the Berea Sandstone to northwestward drainage for the Black Hand Sandstone, as indicated by the limited paleoflow evidence (Fig. 13B), is a change that cannot be accounted for by sedimentary supply and glacio-eustasy. This change in basin geometry may be the result of continued relaxation following the Acadian Orogeny.

In summary, the evidence does not support tectonic uplift as the cause of the Black Hand Sandstone valley incision. The Lower Mississippian strata is thickest in east-central Ohio (Fig. 4), with no evidence of uplift on the structure contour map (Fig. 3). Additionally, the overlying Logan Formation records an early Osagean marine transgression. If tectonic uplift were responsible for incision of the Black Hand paleovalley, a corresponding subsidence event is required to produce Osagean transgression. It is hard to imagine the processes necessary for 60 m of rapid uplift followed by rapid subsidence in Ohio, a region far removed from Acadian tectonics. A eustatic fall and rise in sea level associated with Gondwana glaciation is a more parsimonious hypothesis.

7.6. Is there a lowstand wedge?

If the Black Hand Sandstone represents terrestrial, incised valley-fill deposits formed during the hiatus at the Kinderhookian–Osagean boundary unconformity, there should be a correlative marine lowstand wedge of sediment approximately the same age. Paleocurrent analyses are limited, but all agree on a generally north or northwest direction (Pelletier, 1958; Kittredge and Malcuit, 1985; Matchen, 2004). The Illinois Basin and the Michigan Basin are possible candidates to contain such a wedge. The late Osagean Borden Siltstone Delta is the only Lower Mississippian clastic wedge in the Illinois Basin and is thus too young (Lineback, 1969) for the marine lowstand wedge.

The Michigan Basin contains the Coldwater Shale and Marshall Sandstone. The Coldwater Shale reaches its maximum thickness of 333 m in eastern Michigan, and the Marshall Sandstone reaches its maximum thickness of 91 m in southern Michigan (Cohee, 1979; Harrell et al., 1991). By comparison, the Lower Mississippian section in the central Appalachians rarely

exceeds 235 m. The greater thickness suggests that the rate of subsidence in the Michigan Basin was relatively high, producing the necessary accommodation. There are two sandstone lobes within the Coldwater, one on the northeast side of the basin, the other on the southeast side (Cohee, 1979, Fig. 9). The Marshall Sandstone is a coarsening and shallowing upwards sequence. The lower part has diverse marine fossils, whereas the upper part is nonfossiliferous and cross bedded (Harrell et al., 1991). The Black Hand Sandstone river was geographically positioned to have been the source of the sandstones in the Coldwater and Marshall formations.

Ammonoid (Miller and Garner, 1955) and spore data (Richardson, 2006) indicate that the Coldwater Shale is essentially correlative with the Kinderhookian marine rocks of the Cuyahoga Formation, and the Marshall Sandstone is Osagean and may be correlative in part with the Black Hand Sandstone. Thus, the upper Coldwater Shale and the Marshall Sandstone could be part of the distal lowstand wedge deposited by the Black Hand Sandstone river.

8. Conclusions

The Black Hand Sandstone fits most of the accepted criteria for definition of incised valley fill. The most compelling data are juxtaposition of fluvial deposits with marine deposits, combined with the relief on the base of the Black Hand Sandstone. The vertical contact between the Black Hand Sandstone and the Cuyahoga Formation is sharp and scoured, with large intraclasts of the Cuyahoga Formation incorporated into the overlying Black Hand Sandstone. This is an unconformable relationship, although the biostratigraphic data cannot resolve the amount of time represented by the surface.

Biostratigraphic data of surrounding rocks, and lithostratigraphic relationships, indicate that the Black Hand Sandstone is either late Kinderhookian or early Osagean in age. It is essentially correlative with the unconformity at the Kinderhookian–Osagean boundary.

The base of the Black Hand Sandstone is interpreted as a sequence boundary. This boundary is apparently correlative with the Kinderhookian–Osagean unconformity in the North American Midcontinent. This sequence boundary can also be identified throughout the central Appalachians where it is placed at the base of the Burgoon and Purslane sandstones, correlatives of the Black Hand Sandstone.

The Coldwater Shale and Marshall Sandstone of the Michigan Basin are a possible siliciclastic marine lowstand wedge related to the Black Hand Sandstone. The Coldwater shows a sandier lobe in the southeastern

part of the basin where the Marshall is also thickest, indicating possible deposition by the Black Hand Sandstone river from northern Ohio.

The inferred fall in relative sea level necessary for valley incision, and subsequent deposition of the Black Hand Sandstone, may have resulted from Early Mississippian Gondwanan glaciation. Tournaisian til-lites and sharp excursions in stable isotope curves at this time suggest there was a major glaciation, as does recognition of the Black Hand Sandstone incision event in Ohio. A global eustatic event would account for the recognizable sequence boundary at the Tn2–Tn3 transition, such as the Hasterian–Ivorian boundary in Western Europe and the Cherepetsky–Kizelovsky boundary in Russia.

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