DEPOSITION OF THE CAMBRIAN EAU CLAIRE FORMATION, WISCONSIN: HYDROSTRATIGRAPHIC IMPLICATIONS OF FINE-GRAINED CRATONIC SANDSTONES

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ABSTRACT

Understanding the link between the sedimentology and the hydrogeology of the Eau Claire Formation within Dane and adjacent counties in western to south-central Wisconsin is critical to fluid flow studies. The Eau Claire is a relatively fine-grained fossiliferous sandstone unit that lies between coarser-grained, highly porous, unfossiliferous sandstone of the underlying Mount Simon and the overlying Wonewoc Formations. It consists primarily of very fine- to medium-grained, variably feldspathic, glauconitic, and dolomitic sandstone locally interbedded with argillaceous siltstone and silty mudstone that has a coarsening and thickening upward succession. On the basis of sedimentary structures, lithology, and bedding characteristics, the Eau Claire is divided into five lithofacies representing different paleowater depths of an epeiric shelf environment. The Eau Claire shallowing-upward succession is subdivided into up to five depositional cycles laid down by repetitive shoreface progradation ranging from offshore–shoreface–foreshore facies bounded at the base by a marine flooding surface. In places, sharp-based shoreface facies rest directly over offshore facies attesting to lowering of sea level. The depositional cycles and the structural contour and isopach maps suggest that the Eau Claire lithofacies deposition and distribution were controlled by the substrate, including the Wisconsin Arch and syndepositional faults, and sea level. The Eau Claire depositional facies model parallels a hydrostratigraphic model in which confining properties of the Eau Claire Formation decrease from offshore to foreshore facies. The aquitard qualities increase from the Wisconsin Arch to the western outcrop belt because the formation is more heterogeneous to the west.

INTRODUCTION

Regional aquitards, extensive layers of relatively impermeable rock units, can restrict the movement of contaminants and thus protect aquifers used for municipal water supplies. The Eau Claire Formation, which consists of fine-grained sandstones, siltstones, and mudstones, is a regional aquitard that impedes the exchange of groundwater between the Mount Simon aquifer and other main overlying aquifers in Wisconsin (Bradbury and others, 1999).

Hydrogeologic studies have been hampered by a lack of understanding of the variable thickness and lithology of the Eau Claire Formation (Krohelski and others, 2000; Gotkowitz and others, 2005). Hydraulic conductivity, a parameter describing fluid flow through rock, is a function of permeability, porosity, grain size, sorting, cementation, composition, sedimentary structures, and stratification (Freeze and Cherry, 1979). Factors such as geologic origin, depositional and post-depositional processes, and lithology can result in significant heterogeneity and preferential flow pathways within aquitards. Consequently, knowledge of the depositional environment and lithofacies distribution of the Eau Claire Formation should enhance understanding of its role as an aquitard regionally and locally.

Our study focused on the link between the sedimentology and hydrogeology of the Eau Claire Formation in southern and western Wisconsin (fig. 1).

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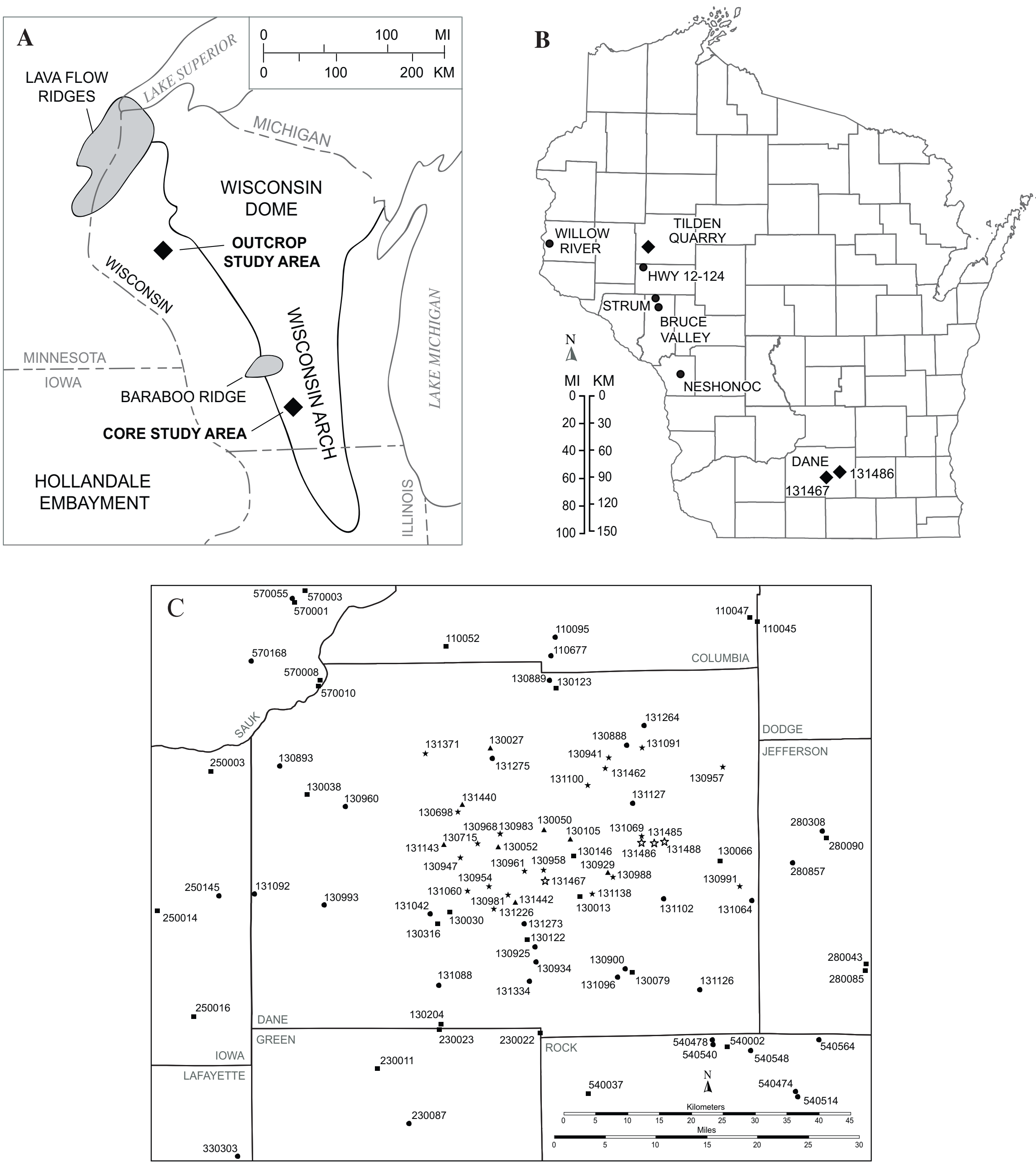


Figure 1. A. *Regional map showing early Paleozoic tectonic features and major paleotopographic highs of Precambrian rocks in the central midcontinent region. Modified from Runkel (1994).* **B.** *Core and outcrop location map. Diamonds represent the locations of the outcrop and well sections shown in figure 2.* **C.** *Locations of water wells and coreholes used in this study. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars. Well data provided by the Wisconsin Geological and Natural History Survey.*

This work may assist in predicting locations of the Eau Claire lithofacies in areas for which rock data are limited and may help explain the regional distribution of porosity and permeability, the major controls on fluid flow.

METHODOLOGY

We compiled outcrop and subsurface data within the Upper Mississippi Valley for our study. The subsurface data come primarily from Dane County in south-central Wisconsin; the outcrop information, from western Wisconsin (fig. 1). We used lithostratigraphic and sedimentologic data from outcrops, cores, cuttings, and borehole geophysical logs. Stratigraphic sections were measured and logged using a handheld natural spectral gamma-ray detector (Exploranium spectrometer, GR-320 enviSPEC). Weathered parts of outcrop faces were scraped before being measured. Four cores with gamma-ray borehole logs (Mount Sopris Instruments gamma-ray probe, 2PGA-1000) were also described. With gamma ray tools, total gamma and the amount of potassium, uranium, and thorium were measured in counts per second (cps). We studied 36 thin sections from cores and outcrops that are representative of the upper parts of the Mount Simon and Eau Claire Formations and the lower part of the Wonewoc Formation to determine mineral composition and grain size at 400 equally spaced points on each slide. In addition to the sedimentologic study, porosity and permeability of 15 samples from Tilden Quarry, West Tilden roadcut, and Willow River outcrop were measured at 400 pounds per square inch confining stress by conventional core-analysis techniques (using a Core Laboratories CMS-300 instrument) to investigate hydrostratigraphic trends.

We used subsurface data to generate structural contour and isopach maps. We reexamined 96 lithologic logs derived from cuttings that had been previously studied by Wisconsin Geological and Natural History Survey staff. We developed a continuum of reliability of well information. The most reliable information came from those wells that had cuttings with detailed descriptions supported by gamma-ray borehole logs; less reliable were wells that had detailed descriptions, but no gamma-ray measurements; next in reliability were wells that had gamma-ray logs, but poor descriptions; the least reliable were wells that had poor descriptions and no gamma-ray measurements.

EAU CLAIRE FORMATION

The Eau Claire Formation overlies the Mount Simon Formation and underlies the Wonewoc Formation. The Eau Claire Formation was deposited in a cratonic environment that included intracratonic basins and scattered arches and domes (Ostrom, 1978). During the Cambrian, the seafloor in what is now northern Wisconsin was near the Wisconsin Dome. Our core data came from Dane County, which is on the southwestern side of the Wisconsin Arch, a southeast–trending extension of the Wisconsin Dome; our outcrop data came from west of the dome (fig. 1).

The Eau Claire Formation is part of the Marjuman (*Cedaria* and *Crepicephalus* trilobite zone) to Steptoean (*Aphelaspis* trilobite zone) Stage of the Upper Cambrian Croixian Series and is predominantly very fine- to medium-grained, moderately to well sorted, variably feldspathic, glauconitic, and dolomitic sandstone with variable amounts of siltstone and mudstone. It has a distinctive gamma-ray signature that has a sharp base and up to five peaks of high gamma-ray values that decrease in magnitude up-section (fig. 2). Correlation of the gamma ray values and the lithology of the Eau Claire showed that the peaks represent greater potassium feldspar content in the very fine sand and silt than in the coarser-grained sand.

On the basis of petrographic analysis, we found two major differences between Eau Claire core and outcrop samples (fig. 3): 1) sand grains of core samples are much coarser than those of outcrop samples, and 2) potassium feldspar is a major component in outcrop samples, but almost absent in cores. These differences support the feldspar and grain-size relationship proposed by Odom (1975), who suggested that, in the Upper Cambrian rocks, feldspar is concentrated in sediments finer than 0.125 mm. We determined that the differences between cores and outcrops were influenced by the proximity to the shoreline, resulting in differences in the energy and the depth of deposition. In Dane County (core area), the Eau Claire was deposited closer to the shoreline within shallower water and higher energy conditions, so it is less feldspathic and has coarser sediments.

EAU CLAIRE LITHOFACIES

The Eau Claire Formation was first divided into lithofacies on the basis of bedding type and mudstone content by Morrison (1968) and Huber (1975) in geographically restricted investigations in west-central

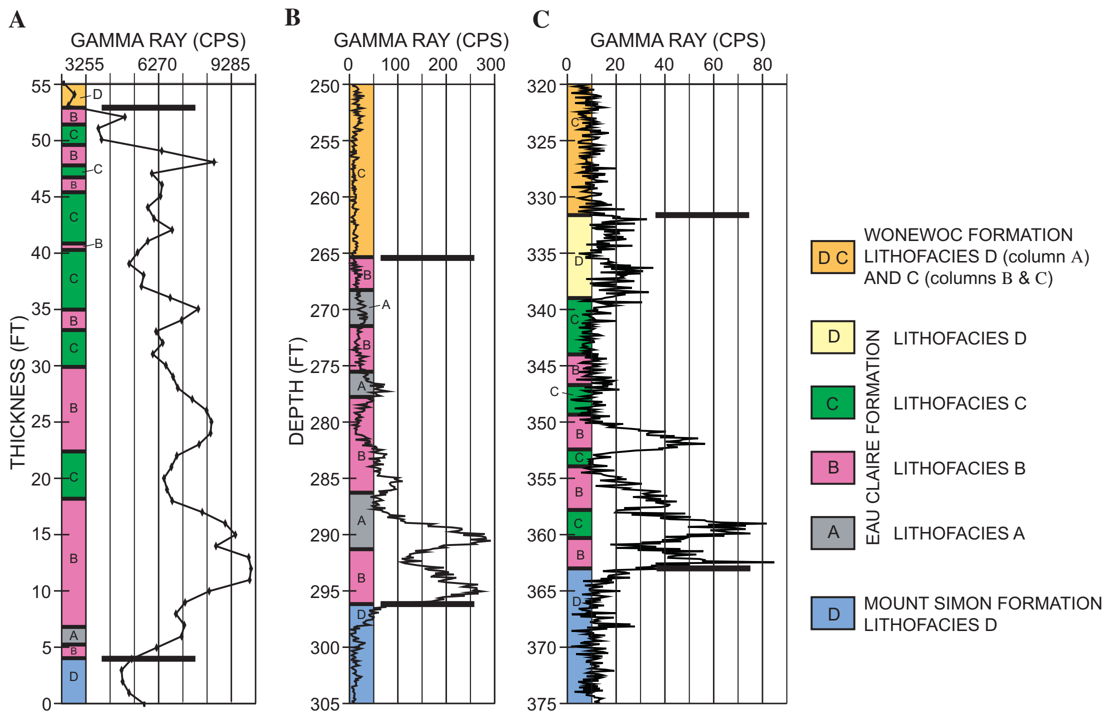


Figure 2. *Gamma-ray characteristic of the Eau Claire Formation, from outcrop:* **A.** *Tilden composite section; and from core:* **B.** *Well 131467 (Nine Springs) and* **C.** *Well 131486 (Cottage Grove MP6). See figure 1 for locations of outcrop and wells.*

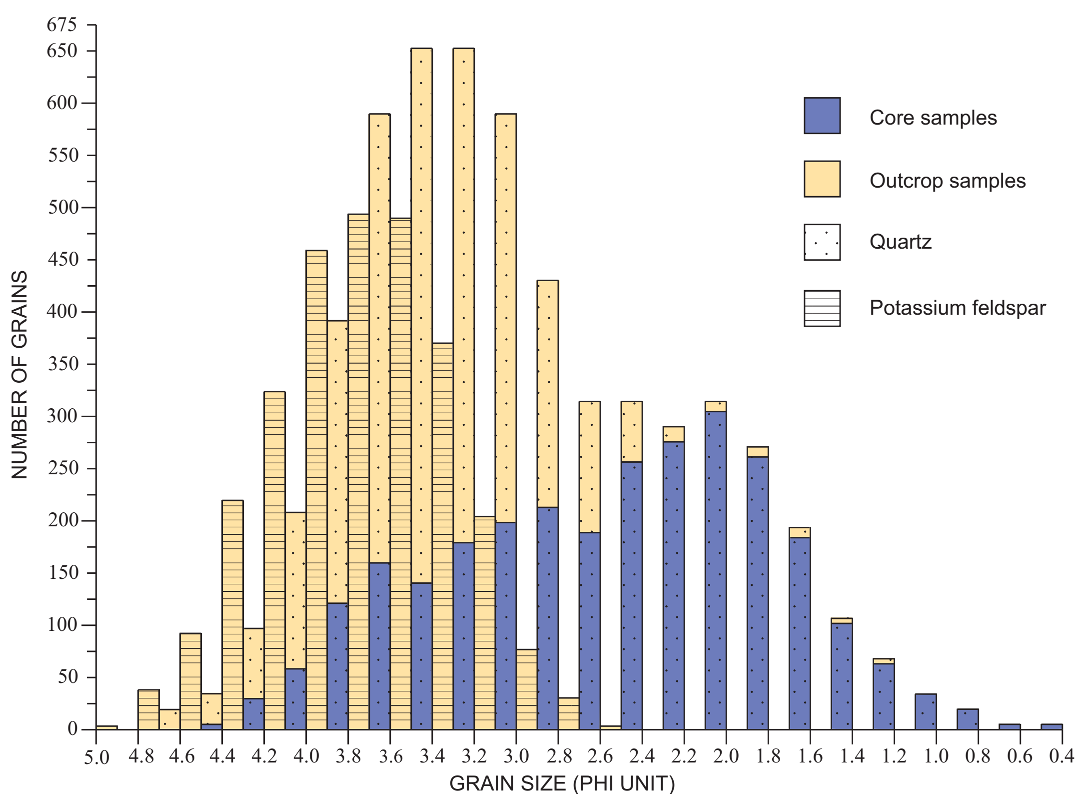


Table 1. *Eau Claire lithofacies A–E. HCS = hummocky cross-stratification; SCS = swaley cross-stratification; TCS = trough cross-stratification; FWWB = fair-weather wave base. Ichnofacies and ichnofabric index are described in Pemberton and others (1992) and Droser and Bottjer (1986), respectively.*

Lithofacies	Bedding characteristics	Sedimentary structure	Ichnofacies	Body fossil	Ichnofabric index	Contact relation with underlying lithofacies	Depositional environment
A: Mudstone and siltstone with minor sandstone	At least 1-ft interval of very thin- to thin-bedded mudstone and siltstone; very thin-bedded sandstone also present	Soft sediment deformation with loaded sandstone	*Cruziana*	Brachiopod fragments	3–4	Gradational, with litho-facies B, sharp with others	Offshore below storm wave base
B: Thin-bedded, micro-HCS sandstone with siltstone and mudstone	Sandstone beds are generally less than 2 in. thick; very thin-bedded siltstone and mudstone less than 0.1 in. thick	Microhummocky cross-stratification and ripple bed form		Brachiopod fragments	3	Gradational, with change in bedding characteristics	Offshore transition zone between storm and FWWB
C: Thick- to very thick-bedded HCS to SCS and low-angle to planar-laminated sandstone with minor siltstone and mudstone (divided into 4 sub-lithofacies: Ca, Cb, Cc, Cd)	Sandstone beds are generally thicker than 2 ft; siltstone and mudstone laminae less than 0.04 in. thick	Ripple bed forms, plus Ca: hummocky cross-stratification; Cb: hummocky cross-stratification, gutter casts and planar lamination; Cc: swaley cross-stratification; Cd: planar to low-angle lamination	*Skolithos*	Brachiopod fragments throughout; hyolithid and trilobite casts in Cb	2	Gradational and sharp-based; sharp jump in bedding style	Lower shoreface Ca: just below FWWB Cb: at FWWB Cc: just above FWWB Cd: above FWWB
D: Thick- to very thick-bedded TCS sandstone	Sandstones appear to be massive without internal breaks	Trough cross-bedding		Brachiopod fragments	1–2	Gradational	Upper shoreface below low tide
E: Very thick-bedded, planar-laminated sandstone	Massive sandstone without parting surfaces	Planar lamination		Brachiopod fragments	1	Gradational	Foreshore within intertidal zone

Wisconsin. The most recent regional study related to the Eau Claire Formation was completed by Runkel and others (1998). They divided the Eau Claire into three units on the basis of the Upper Cambrian trilobite zones, showing that the formation is a distal facies of the overlying Wonewoc Formation (*Crepicephalus* and *Aphelaspis* trilobite zones) and the underlying Mount Simon Formation (*Cedaria* trilobite zone).

◀ **Figure 3.** *Frequency diagram, showing grain-size distribution of quartz and potassium feldspar in core and outcrop samples.*

We have divided the Eau Claire Formation into five lithofacies on the basis of sedimentary structures, lithology, and bedding characteristics (table 1). Interbedding of the thin- and thick-bedded lithofacies within the formation delineates sandier-upward succes-

Figure 4. *Interbedding of thin- and thick-bedded lithofacies of the Eau Claire Formation at Tilden Quarry.*

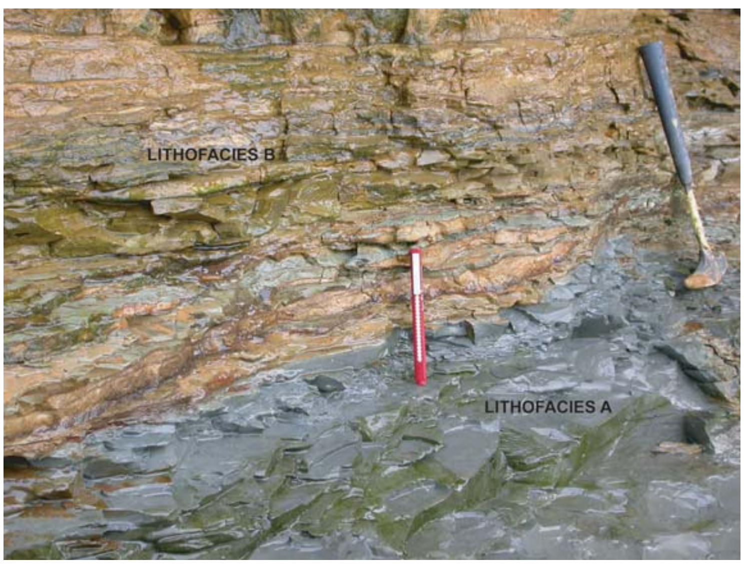


Figure 5. *Very thin- to thin-bedded silty mudstone and argillaceous siltstone of lithofacies A overlain by lithofacies B at Neshonoc Lake.*

sions (fig. 4). Because sedimentary structures are difficult to define in cores, our Eau Claire lithofacies description is mostly based on outcrop observation.

Lithofacies A is composed of 1.0- to 6.4-ft intervals of very thin to thin-bedded, relatively well cemented, silty mudstone, argillaceous siltstone, and sandy siltstone (fig. 5). Very thin-bedded, very fine-grained (fine grained in core) sandstone is common (fig. 6). The siltstone and mudstone are green to dark gray in outcrop; in core, the color ranges from green to gray, pink to maroon, and buff. The sandstone is very light gray to yellowish brown in outcrop; the sandstone in core is gray, pink, dark green, and buff. This lithofacies is locally glauconitic, dolomitic, and micaceous. Sedimentary structures are not well preserved, possibly because of the intense bioturbation.

Lithofacies B consists of 0.5- to 11.6-ft intervals of thin-bedded, very fine- to fine-grained (to medium-grained in core), variably glauconitic sandstone intercalated with substantial argillaceous siltstone and mudstone (figs. 5 and 7). The sandstone is light gray, light tan, yellowish brown, and dark green; the siltstone and mudstone are green to dark gray. In core, this lithofacies is also pink to maroon and buff. Outcrop samples are feldspathic and micaceous; cores are dolomitic. Sandstone beds pinch and swell laterally and are locally lenticular (fig. 8). They commonly display sharp, scoured bases. Mudstone and argillaceous siltstone are found in discontinuous drapes and very thin, laterally continuous beds.

The microhumocky cross-stratification is characterized by glauconite concentration and very thin-bedded siltstone and mudstone. It contains thin hummocks and swales that have wavelengths of 1.5 to 2.5 ft. Sets of laminae intersect at low angles. Low-angle to wavy lamination could be associated with the microhummocky cross-stratification. The upper surface of the sandstone beds commonly has oscillation ripples. Bioturbation obscures the original bedding in places.

Lithofacies C consists of less than 1.0-ft to 15.0-ft intervals of thick to very thick-bedded, very fine- to fine-grained (medium-grained at the top of the formation in outcrop and throughout the formation in cores), variably glauconitic sandstone intercalated with green siltstone and mudstone laminae or drapes (fig. 9). The laminae are rare compared to

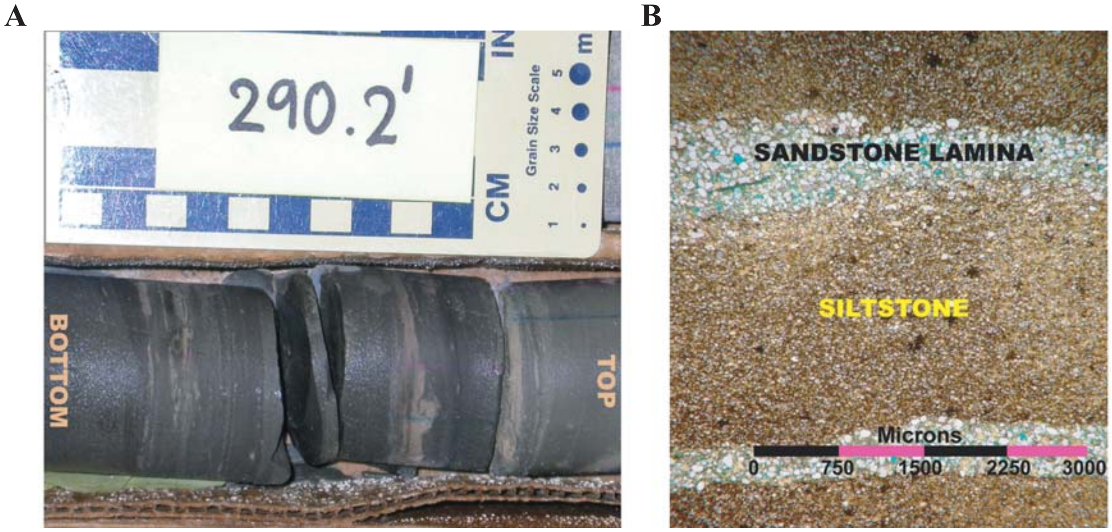


Figure 6. A. *Lithofacies A of Nine Springs core, showing presence of very thin-bedded, very fine-grained sandstone within more prominent siltstone and mudstone.* **B.** *Photomicrograph taken from sample 131467-289.8 with plane-polarized light.*

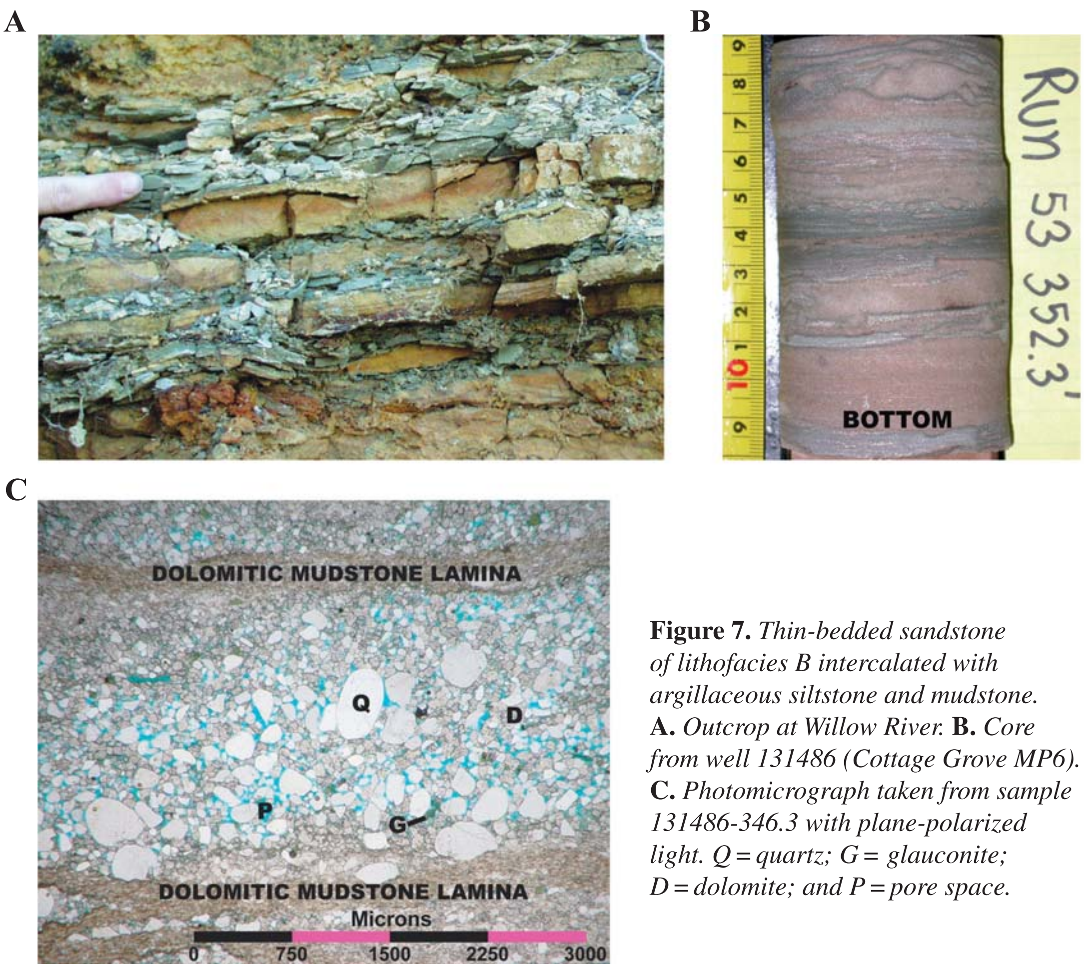


Figure 7. *Thin-bedded sandstone of lithofacies B intercalated with argillaceous siltstone and mudstone.* **A.** *Outcrop at Willow River.* **B.** *Core from well 131486 (Cottage Grove MP6).* **C.** *Photomicrograph taken from sample 131486-346.3 with plane-polarized light. Q = quartz; G = glauconite; D = dolomite; and P = pore space.*

Figure 8. *Bedding style of lithofacies B at Tilden Quarry. Sandstone beds pinch and swell laterally and locally lenticular.*

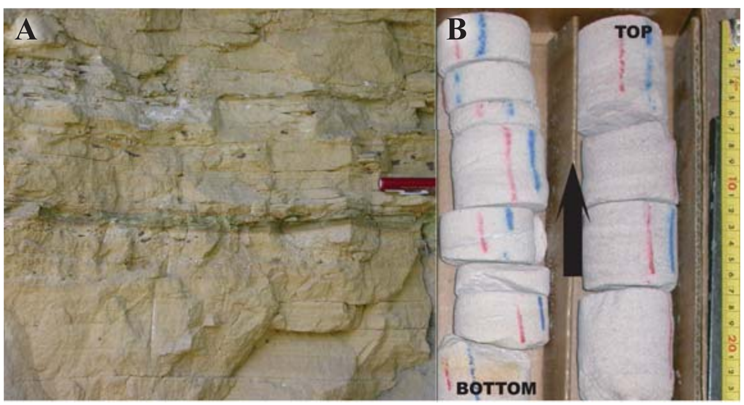


Figure 9. *Thick- to very thick-bedded sandstone of lithofacies C intercalated with siltstone and mudstone laminae.* **A.** *Outcrop at Tilden Quarry.* **B.** *Core from well 131486. The outcrop also shows amalgamated thin bedded, planar-laminated sandstone.*

those in lithofacies B. Thick sandstone beds locally compose amalgamated thin-bedded, plane parallel-laminated sandstone. Color ranges from very light gray to light tan to pink. This lithofacies is feldspathic and micaceous in outcrop and dolomitic in core.

The variation of sedimentary structures in lithofacies C in outcrop can be used to separate it into four sublithofacies. Sublithofacies Ca consists of hummocky cross-stratification; its low-angle, gently undulating laminae are formed by broad convex-upward hummocks and concave-upward swales with wavelengths of 3.0 to 5.0 ft. Sublithofacies Cb has planar lamination and less-prominent hummocky cross-stratification. Sublithofacies Cc contains swaley cross-stratification with broad, very low-angle concave-upward laminae that have some planar to low-angle internal truncation surfaces. Although the swales rarely pass laterally into hummocks, the presence of some convex-upward laminae in a swaley sandbody indicates a genetic similarity to hummocky cross-stratification. Sublithofacies Cd is dominated by planar to low-angle lamination that has a trace of swaley cross-stratification. All four sublithofacies locally display preserved asymmetric and symmetric ripple forms on top of sandstone beds.

In core, we separated lithofacies C into two sublithofacies: C1 and C2. Sublithofacies C1 is similar to sublithofacies Ca, Cb, and Cc; sublithofacies C2 is comparable to sublithofacies Cd. Sublithofacies C1 can be recognized by high- to low-angle cross-lamination and wavy lamination, which are likely to be associated with hummocky to swaley cross-stratification. Sublithofacies C2 can be defined by low-angle to planar lamination and lack of clear sedimentary structures as is sublithofacies Cd.

Lithofacies D is entirely sandstone, typified by 1.6- to 8.0-ft intervals of thick- to very thick-bedded successions of very fine- to fine-grained (up to lower medium in cores), trough cross-stratified, variably glauconitic sandstone (fig. 10). Color ranges from light tan to rusty tan, plus white to light pink in cores. Rip-up clasts of sandstone and dolomite are present. Well organized cross-sets are typically 0.3 to 1.0 ft thick. They are commonly superimposed on one another to form thick, amalgamated successions.

Lithofacies E is entirely sandstone, characterized by a 5.0-ft interval of very thick-bedded, very fine- to fine-grained, light tan to rusty tan, planar-laminated sandstone (fig. 11). Laminations dip very gently from each other.

LITHOFACIES INTERPRETATION AND DEPOSITIONAL ENVIRONMENT

Our study indicated that the lithofacies and accompanying sedimentary structures of the Eau Claire were deposited in an epeiric shelf environment ranging from offshore to foreshore facies (fig. 12). We interpreted lithofacies A to have been deposited in a quiet-water environment below the storm-wave base representing an offshore facies (Howell and Flint, 2003). Lithofacies B represents an offshore transition facies deposited by storm-generated oscillatory waves below the fair-weather-wave base, but above the storm-wave base (Dott and Bourgeois, 1982; Leckie and Walker, 1982; Duke, 1985). During storms, sands were eroded from the shoreward zone and redeposited in a microhummocky, cross-stratified sheet-like blanket across the shelf. During fair-weather periods, clays and silts were deposited from suspension and covered the sheet of sand laid down during the storms. We interpreted lithofacies C to represent lower shoreface facies deposited by storms in water depths close to the fair-weather-wave base, where the seabed was constantly agitated and clays and silts were rarely deposited (Howell and Flint, 2003). The sublithofacies Ca–Cd indicate slightly different settings: from a deeper and lower energy environment of sublithofacies Ca to a shallower and higher energy environment of sublithofacies Cd (Leckie and Walker, 1982; Walker, 1985; Duke, 1990). We interpreted the trough cross-bedded sandstone, lithofacies D, and planar-laminated sandstone, lithofacies E, to be upper shoreface and foreshore facies, respectively. The sedimentary structures and the lack of mica suggested conditions of high flow velocity and shallow water depth (Collinson and Thompson, 1989). Lithofacies D and E are rare in the Eau Claire, but common in the Wonewoc and Mount Simon Formations. This is consistent with flooding of the shoreline (Mount Simon–Eau Claire contact), followed by shallowing upward and progradation of the Wonewoc over the deeper-water Eau Claire.

Lithofacies D and E were deposited within an energetic nearshore environment, close to the arch, in a

Figure 10. *Thick- to very thick-bedded, trough cross-stratified sandstone of lithofacies D at Willow River. The broomstick is marked every 6 in.*

Figure 11. *Very thick-bedded, planar-laminated sandstone of lithofacies E at Willow River. The broomstick is marked every 6 in.*

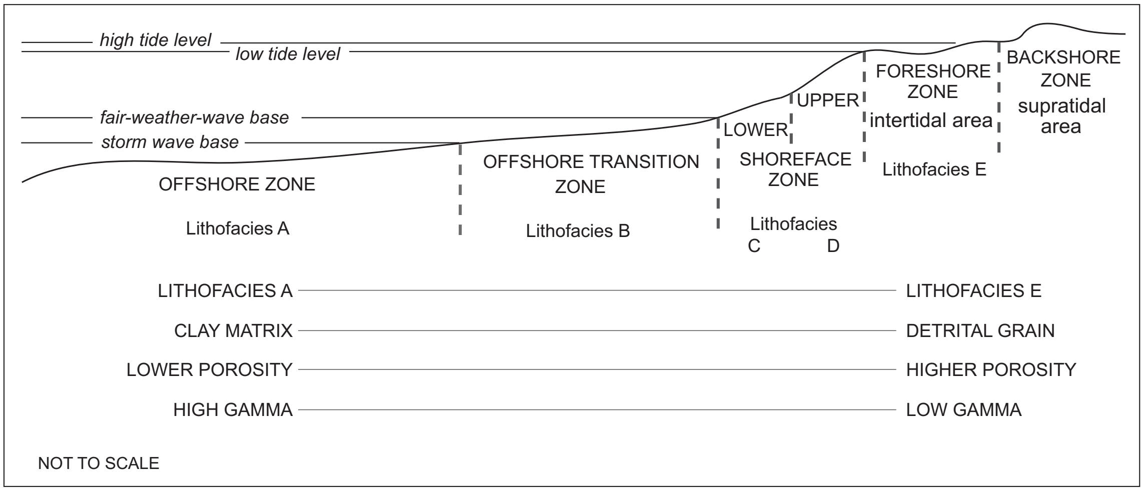


Figure 12. *Shallow marine profile, showing the typical succession of the Eau Claire Formation. (Modified from Coe and Church, 2003.)*

storm-dominated shoreface and in an intertidal zone, respectively. The lower shoreface sediment (lithofacies C) was transported by storm-enhanced currents—along the shore by longshore currents and away from the shore by rip currents (Runkel, 1994; Byers and Dott, 1995; Runkel and others, 1998) following topographic differences on the seafloor. Immediately seaward, lithofacies B sediment was buried during storms and graded basinward to the mudstone of lithofacies A.

The lithofacies of the Eau Claire Formation are also distinctly expressed in the relationship between the Eau Claire sediments and the total gamma of these sediments as measured in outcrop and in the subsurface. The total gamma-ray measurements of the Wonewoc and Mount Simon Formations (table 2) are for the base and the top, respectively. Figure 2 and table 2 show that the gamma decreases from lithofacies A to lithofacies D. On the basis of the subsurface data, the Eau Claire lithofacies of some intervals can be identified with the total gamma. The highest total gamma mostly corresponds to the lithofacies A (>100 cps) or B (<100 cps) of the second depositional cycle from the base of the formation. If the highest gamma represents lithofacies A, the peak of the bottom depositional cycle can be interpreted as representing shallower-water facies because the highest gamma-ray values of each depositional cycle decrease in magnitude up-section. If the highest total gamma of the bottom cycle is more than 200 cps, this interval consists of lithofacies B. If it is less than 200 cps, then lithofacies C composes this interval. Notably, lithofacies D and E never corresponded to the peaks of any cycles, except the uppermost cycle of the Cottage Grove MP6 core (well 131486).

STRATIGRAPHIC SUCCESSIONS AND CYCLICITY OF THE EAU CLAIRE

Correlation of a composite section based on outcrops in Chippewa County and the descriptions of two cores in Dane County demonstrates cyclicity and lithofacies repetitions within the Eau Claire stratigraphic successions (fig. 13). Note that the two cores show more proximal facies than the Tilden section, which represents more distal deposits.

The overall vertical stacking of the Eau Claire lithofacies represents shallowing-upward successions and internally can be subdivided into depositional cycles characterized by repetitions of lithofacies. The cycles are defined by deeper-water facies overlying shallower-water lithofacies. In outcrop it is possible to recognize up to eight lithofacies repetitions; the cores show no more than six lithofacies repetitions. With respect to subsurface correlations based on total gamma ray measurement, each Eau Claire depositional cycle is bounded at its base by a relatively high gamma count; we interpreted this to be a marine flooding surface, which is marked by an abrupt change from shallow- to deeper-water facies. We interpreted the intervals that have lower gamma counts to be grading into a shallowing-upward succession. The outcrop shows at least five cycles, but the cores show only four cycles. It is important to note that the cores and outcrop

Table 2. *Total gamma-ray measurements showing geophysical trends within the Eau Claire Formation. The difference between core and outcrop measurements is due to the different tools used in the study. W = Wonewoc Formation; MS = Mount Simon Formation.*

Lithofacies/ formation	Outcrop		Core	
	Total gamma (cps)	Average total gamma (cps)	Total gamma (cps)	Average total gamma (cps)
W	1,431–2,587	2,182	1.7–14.0	8.4
E	2,121–2,991	2,724	—	—
D	3,187–3,617	3,407	4.2–14.1	8.7
C	3,259–6,833	4,972	1.7–196.3	26.5
B	3,909–10,101	6,565	1.6–273.2	57.3
A	4,125–9,738	7,259	12.1–289.4	105.7
MS	2,973–5,784	4,638	7.2–37.4	20.4

are separated by approximately 150 miles and that part of this variability can be explained by changes in lithology and stacking along depositional strike. On the other hand, the cores are separated by only 12 miles; the variability between them may be a result of deposition at different locations in relation to the Wisconsin Arch.

Generally, the contacts between lithofacies are gradational, with two exceptions. The basal contact of each cycle reflects an abrupt change from shallow- to deeper-water facies that we interpreted as marine flooding. Cementation and faunal lags are common at these surfaces. In some places, sharp-based shoreface sandstone (lithofacies C and D) rests directly over lithofacies B (Willow River section), interpreted by Walker and Plint (1992) to be the result of progradation due to a relative sea level fall. In other places, the microhummocky cross-stratified sandstone of lithofacies B is overlain by hummocky cross-stratified sandstone of sublithofacies Cb; the contact is marked by gutter casts (Bruce Valley Quarry), which Aswasereelert (2005) interpreted as being formed by wave scour on the bed. Lithofacies Cc and Cd are present only in the sharp-based successions; we interpreted local wave-base erosion during regression to have led to sharp and, in some locations, erosive contacts between the offshore transition microhummocky strata and the shoreface sandstones.

Morrison (1968), Ostrom (1970), DiStefano (1973), and Huber (1975) suggested that erosive contacts and sudden changes in lithology between the Eau Claire and the Wonewoc Formations may be associated with a significant unconformity. However, Havholm (1998) and Runkel and others (1998) described the Eau Claire–Wonewoc contact as gradational and becoming younger to the west, which would likely be the result of the nearshore marine Wonewoc prograding across the Eau Claire sediment. Our outcrop investigation showed that local wave-base erosion resulted in sharp contacts between offshore transition strata and shoreface sandstones and in turn could be responsible for the thickness variability of the Eau Claire Formation. Therefore, we concluded that the unconformity-like feature between the Eau Claire and the Wonewoc Formations was due to local wave-base erosion and facies changes, not to any significant period of nondeposition or extensive erosion of previously deposited sediment.

REGIONAL CONTROLS ON EAU CLAIRE DISTRIBUTION

The amount of data from outcrops and cores (high-quality data) was insufficient to allow us to adequately define the regional distribution of the Eau Claire Formation; therefore, we used subsurface logs derived from cuttings (generally lower quality or more interpretive data) from the Wisconsin Geological and Natural History Survey to interpolate between high-quality data points.

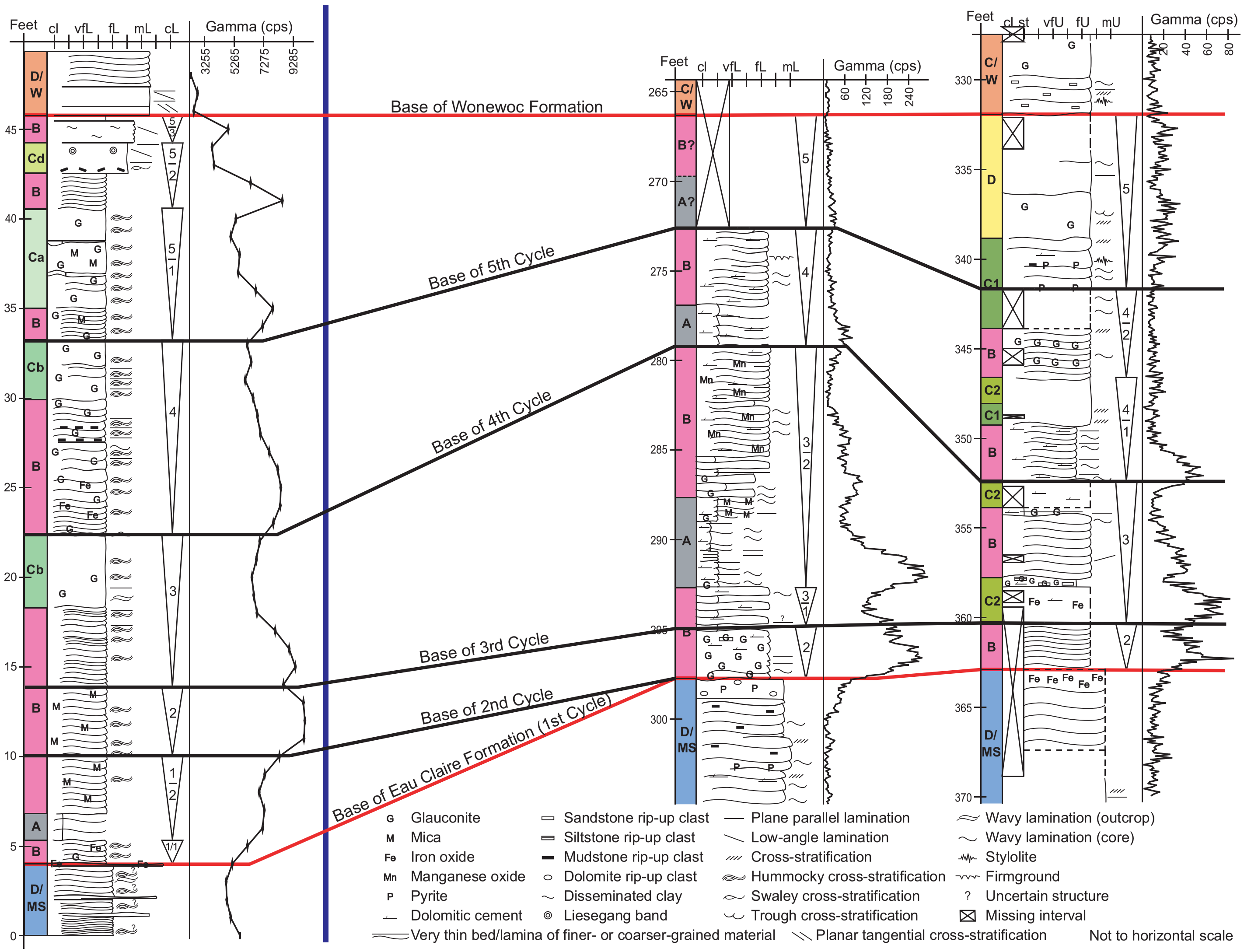


Figure 13. *Outcrop–core correlation and comparison. Notice that the Eau Claire Formation in Tilden outcrop composite section (left) is thicker and represents more shallowing-upward successions than in well 131467 (middle) and well 131486 (right); see figure 1 for locations of outcrop and wells.*

We used the relative amounts of sandstone and mudstone to define the Eau Claire lithofacies in the cuttings. Cuttings composed of shale and siltstone were interpreted to represent lithofacies A. When sandstone dominated, depending on the amount of shale and siltstone present, that interval could be lithofacies B (large amounts of clay- to silt-sized sediments), C (trace amount of clay- to silt-sized sediments), or D and E (no sediments finer than sand were present).

The structural contour map of the Precambrian basement in Dane County shows a north–south trending high and three east–west trending faults (fig. 14A). The high and the faults are also reflected in the structural contour maps of the base of the Eau Claire Formation and the Tunnel City Group (fig. 14B and 14C). The isopach maps of the Eau Claire and the combined Eau Claire–Wonewoc (fig. 14D and 14E) reflect the fact that the Eau Claire Formation progressively thins from 110 ft in southwestern Dane County to 40 ft in central Dane County; it is absent in northeastern Dane County. This is consistent with the interpretations of Twenhofel and others (1935), Odom (1975), and Runkel and others (1998), who suggested that the Eau Claire is thinned by virtue of its upper and lower parts grading laterally into the progressively thicker Mount Simon and Wonewoc Formations toward the Wisconsin Arch.

The Eau Claire and the combined Eau Claire–Wonewoc isopach maps (fig. 14D and 14E) demonstrate that faulting is a major control on the thickness variation and the stratigraphic boundaries of the Eau Claire Formation (fig. 14D and 14E). The faults were identified in areas where the contour lines were close to each other or where the elevations of the Eau Claire structural contour map and the thickness of the Eau Claire isopach map changed so abruptly that it could be evidence of displacement. The thickness contours of the Eau Claire Formation are substantially influenced by the faults; the faults have relatively less effect on the combined Eau Claire–Wonewoc thickness. Cross sections on the regional surface at the base of the Tunnel City Group show that the Wonewoc Formation (fig. 15) thins across faults corresponding to abrupt changes in the Eau Claire–Wonewoc boundary elevations, and the elevations change abruptly at the base of the Eau Claire across the faults. Consequently, we interpreted the faults to be active during the deposition of the Eau Claire and the Wonewoc.

The structural contour and isopach maps show a north–south trending structural high (fig. 14). This high is evidence that the Eau Claire deposition was also influenced by the north–south trending positive feature of the Precambrian substrate associated with the Wisconsin Arch, which modified the paleocurrents and sediment distribution. These maps indicate the shape of the north–south trending high was modified by syndepositional faults. In addition to the influence of the bedrock substrate varying over time, the cyclicity within the Eau Claire Formation can be reasonably attributed to relative sea-level fluctuations that forced shorelines to move seaward and landward.

HYDROSTRATIGRAPHIC IMPLICATIONS

The permeability contrast between lithofacies and between depositional cycles, the vertical and lateral trends in porosity and permeability, and the amount, thickness, and continuity of mudstones are particularly important to fluid flow through the Eau Claire Formation. The Eau Claire is a heterogeneous and anisotropic aquitard due to the discontinuity and vertical stacking pattern of the lithofacies within the formation. The aquitard nature of the Eau Claire Formation is defined primarily by two components: low permeability mudstone and siltstone and higher permeability sandstone.

Some of the best evidence for the Eau Claire being an aquitard comes from test well 131467 at the Nine Springs site, where a packer slug test was used to measure horizontal hydraulic conductivity (Kh) and static head of the Eau Claire (Bradbury and others, 2006; fig. 16). A significant drop in hydraulic head—approximately 30 ft across the Eau Claire–Mount Simon contact—shows that the Eau Claire Formation acts as a major aquitard. The Kh values for the Eau Claire fall into the clay–silt category, even though the sandstone dominates lithofacies B; this is consistent with our outcrop investigation, which showed that the mudstone and siltstone strata of this lithofacies are generally more laterally continuous than the sandstone beds (Aswasereelert, 2005). This continuity along with the thickness of the mudstone and siltstone is likely to be significant to fluid flow through the aquitard. The vertical hydraulic conductivity is very difficult to measure directly; we inferred it to be low because the aquitard holds up about 30 ft of hydraulic head.

The mudstone and siltstone of the Eau Claire For-

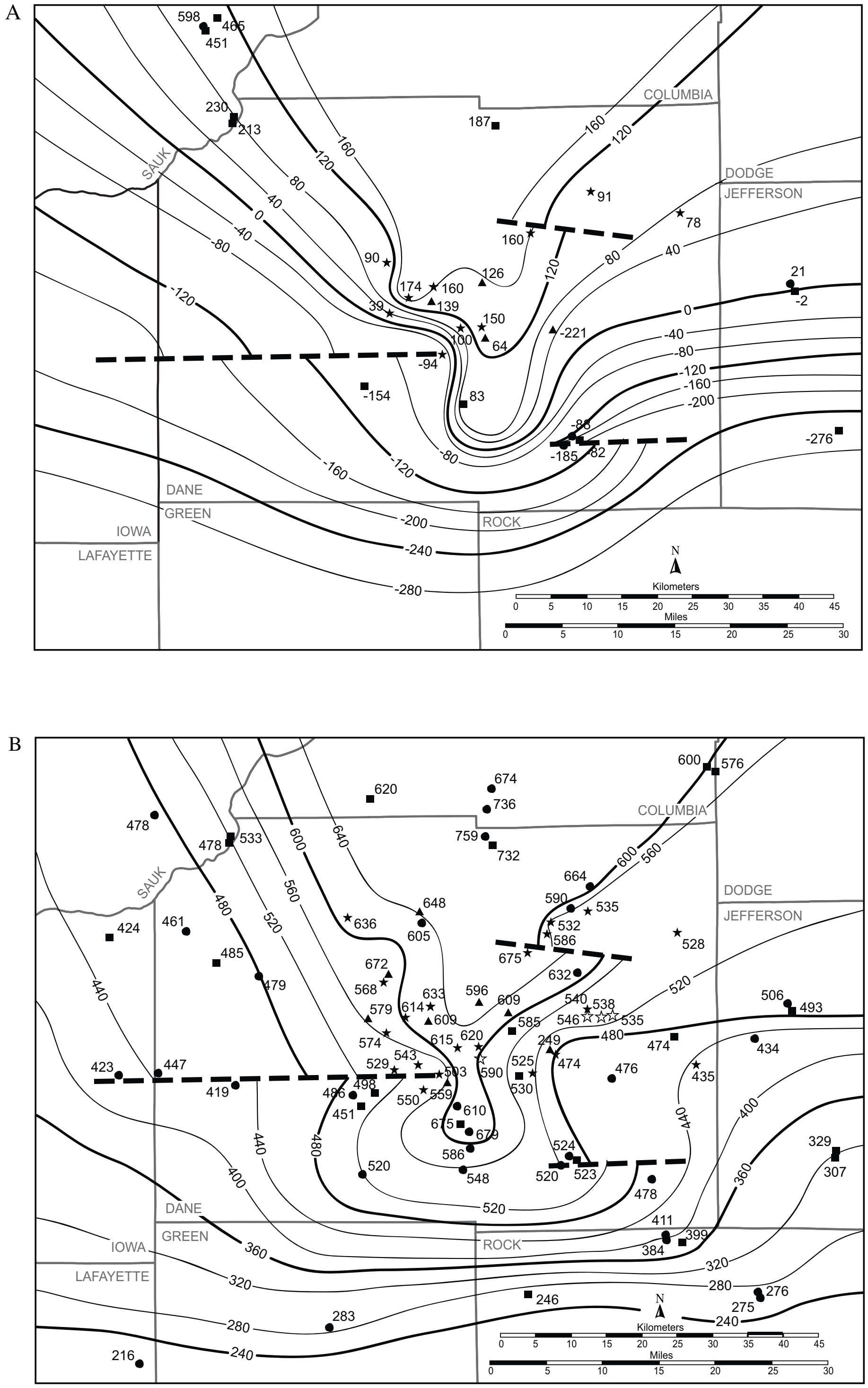
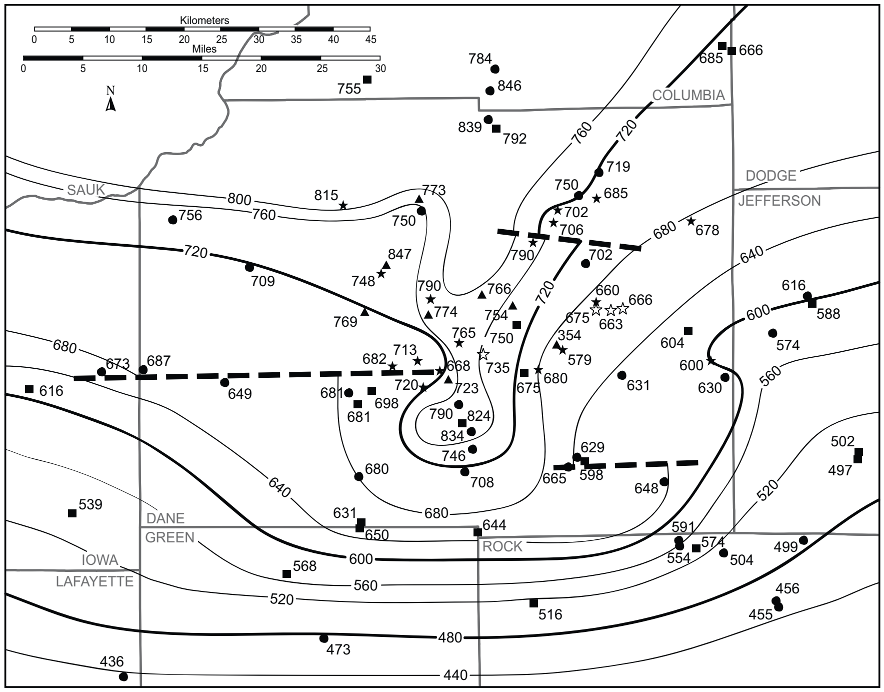


Figure 14. *Structural contour maps:* **A.** *Precambrian basement;* **B.** *Base of the Eau Claire Formation. Faults (dashed line) based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars.*

C



D

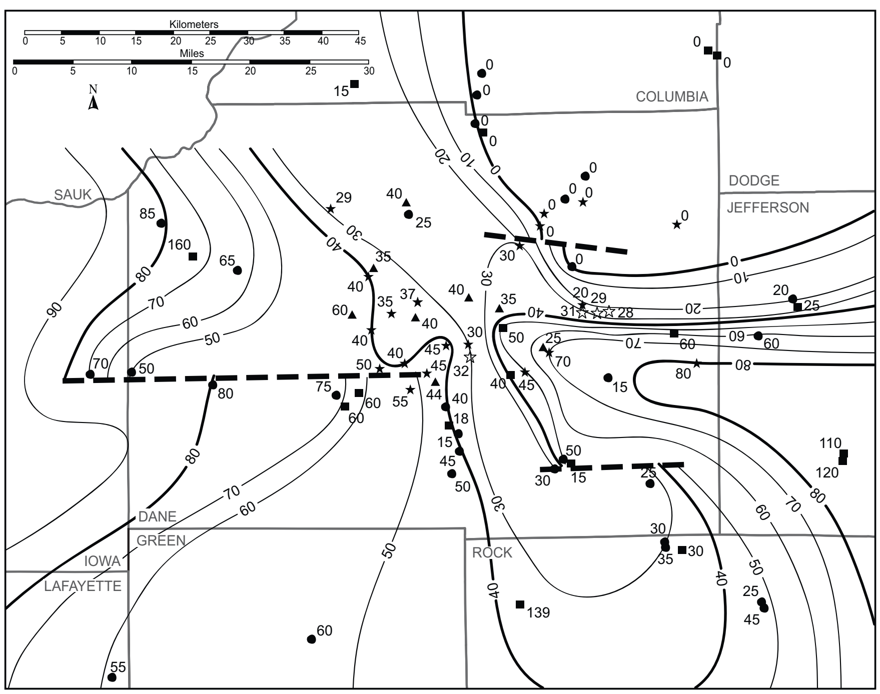


Figure 14 (continued). **C.** *Base of the Tunnel City Group. Isopach maps:* **D.** *Eau Claire Formation. Faults (dashed line) based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars.*

E

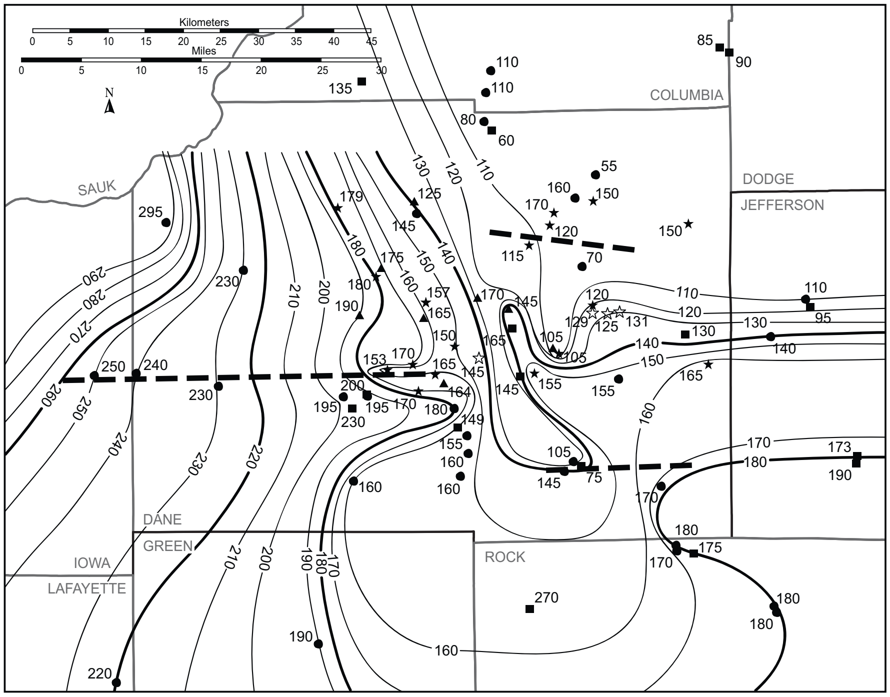


Figure 14 (continued). **E.** *Combined Eau Claire and Wonewoc Formations. Faults (dashed line) present in all maps based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Faults (dashed line) based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars.*

mation, which are interpreted to act as a major barrier to fluid flow, dominate lithofacies A and lithofacies B. On the basis of Kh values (Bradbury and others, 2006) and lithofacies distribution, the amount, thickness, and continuity of mudstone and siltstone are particularly important to fluid flow through the Eau Claire aquitard. The thickness of the least permeable strata, lithofacies A, can vary from approximately 2 ft up to 25 ft. The distribution of lithofacies A shows the most irregularity: It can be present in one well, but absent in another less than 10 miles away. Lithofacies A might have been preserved as either extensive strata or discontinuous patches; lithofacies B, which is present in all the wells (fig. 15), comprises much of the Eau Claire Formation.

The stacking pattern of the Eau Claire succession is also significant to fluid flow. The Eau Claire depositional cycles, bounded above and below by flooding surfaces, represent the building block of the Eau Claire aquitard being separated by a surface of high permeability contrast between the offshore (lithofacies A) or offshore transition (lithofacies B) facies and the various shoreface facies (lithofacies C, D, and E) of the underlying strata. The difference in facies above and below the cycle boundaries can result in flow-unit boundaries that have significant permeability differences. For instance, the permeability and porosity of the Tilden Quarry sandstones studied in outcrop in Chippewa County increase from 328.3 millidarcies (md) and 28.1 percent (lithofacies B) to 811.1 md and 29.4 percent (lithofacies C); the samples are only 3 ft apart (fig. 17).

The most porous and permeable strata are the relatively high depositional energy lower and upper shoreface and foreshore sandstones (lithofacies C, D, and E; fig. 12). The increase in porosity and permeability can be tied to an increase in depositional energy, which resulted in 1) better grain sorting and an associated decrease in the amount of fine-grained sediment within pore spaces; 2) fewer and thinner mudstone layers; and 3) a decrease in cementing materials. As a result, porosity and permeability are lower from upper

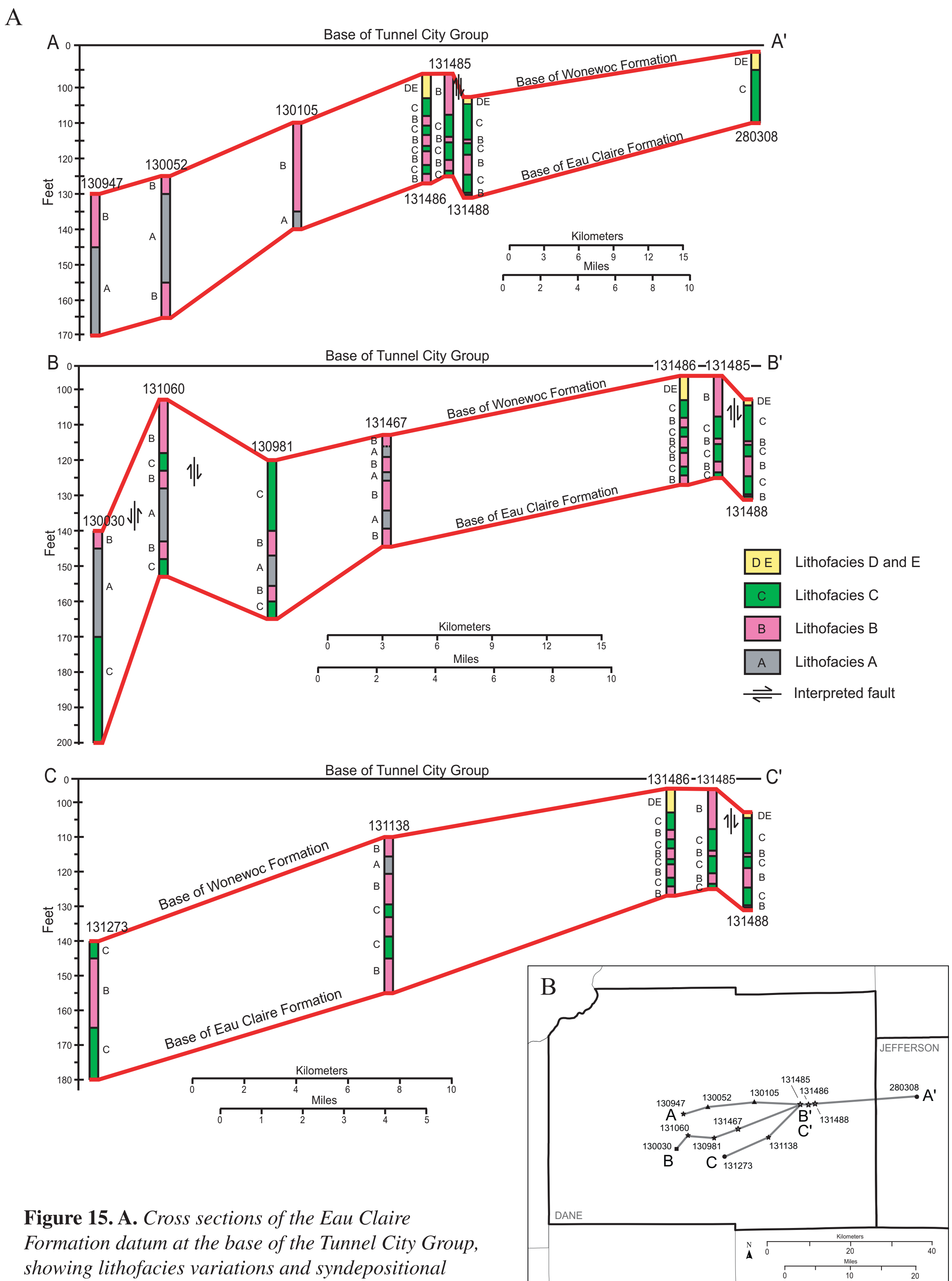


Figure 15. A. *Cross sections of the Eau Claire Formation datum at the base of the Tunnel City Group, showing lithofacies variations and syndepositional faults.* **B.** *Lines of cross sections.*

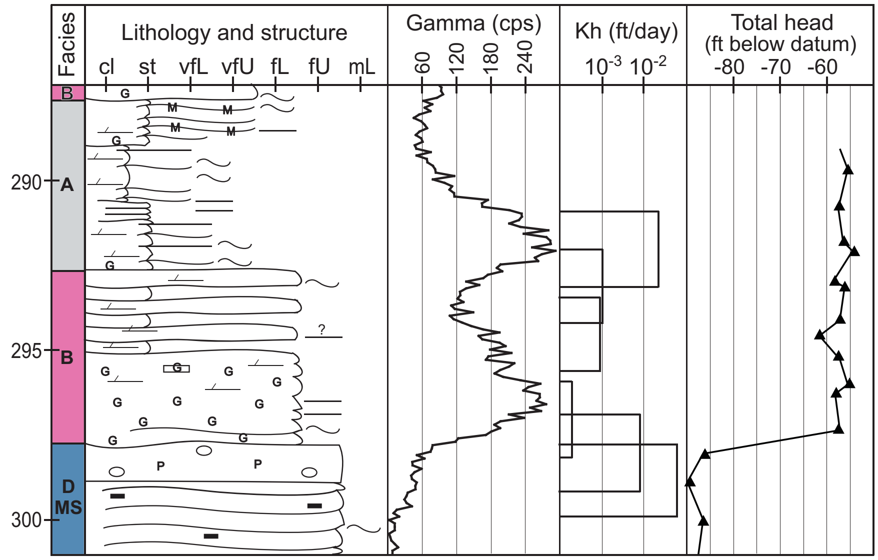


Figure 16. *Stratigraphic section of an Eau Claire interval, showing results from a packer-slug test at the Nine Springs site (well 131467). Bars show horizontal hydraulic conductivity (K_h) derived from slug test using inflatable straddle packers to isolate various sections of the borehole. Width of bars represents width of packed intervals. Hydraulic heads were measured using pressure transducers; K_h and hydraulic head data from Bradbury and others (2006). MS = Mount Simon Formation.*

shoreface sandstones to offshore mudstones. This corresponds to the previously mentioned increase in gamma-ray values from lithofacies D to lithofacies A. We concluded that the greater the permeability, the lower the gamma-ray values and the higher the depositional energy.

The relationships among the various lithofacies imply that the hydraulic properties of the aquitard are directly related to the geometry and distribution of lithofacies, which are a function of the depositional environment. Therefore, it should be possible to relate trends in the distribution of hydraulic properties to the distribution of lithofacies in the aquitard system. Regionally, more depositional cycles and more shallowing-upward successions are present along the western outcrop belt than in the area near the Wisconsin Arch. As a consequence, the Eau Claire Formation becomes more of a barrier to fluid flow from the Wisconsin Arch to the west.

SUMMARY

We have divided the Eau Claire Formation into five lithofacies based on sedimentary structures, lithology and bedding characteristics representing a shallow marine depositional shelf deposit ranging from offshore-shoreface-foreshore facies. In general, the formation thickens to the south and the west. The number of vertical stackings, potassium feldspar grains and sediments finer than fine sand increase from eastern Dane County to the western outcrop belt due to the proximity to the shoreline or the Wisconsin Arch. The structural contour and isopach maps and the cyclicity of the Eau Claire Formation suggest that the Precambrian substrate (Wisconsin Dome and Arch), syndepositional faulting, and sea level fluctuation are major controls on the Eau Claire lithofacies deposition and distribution. The Eau Claire aquitard is likely to retard fluid flow to the west from the arch to the western outcrop belt.

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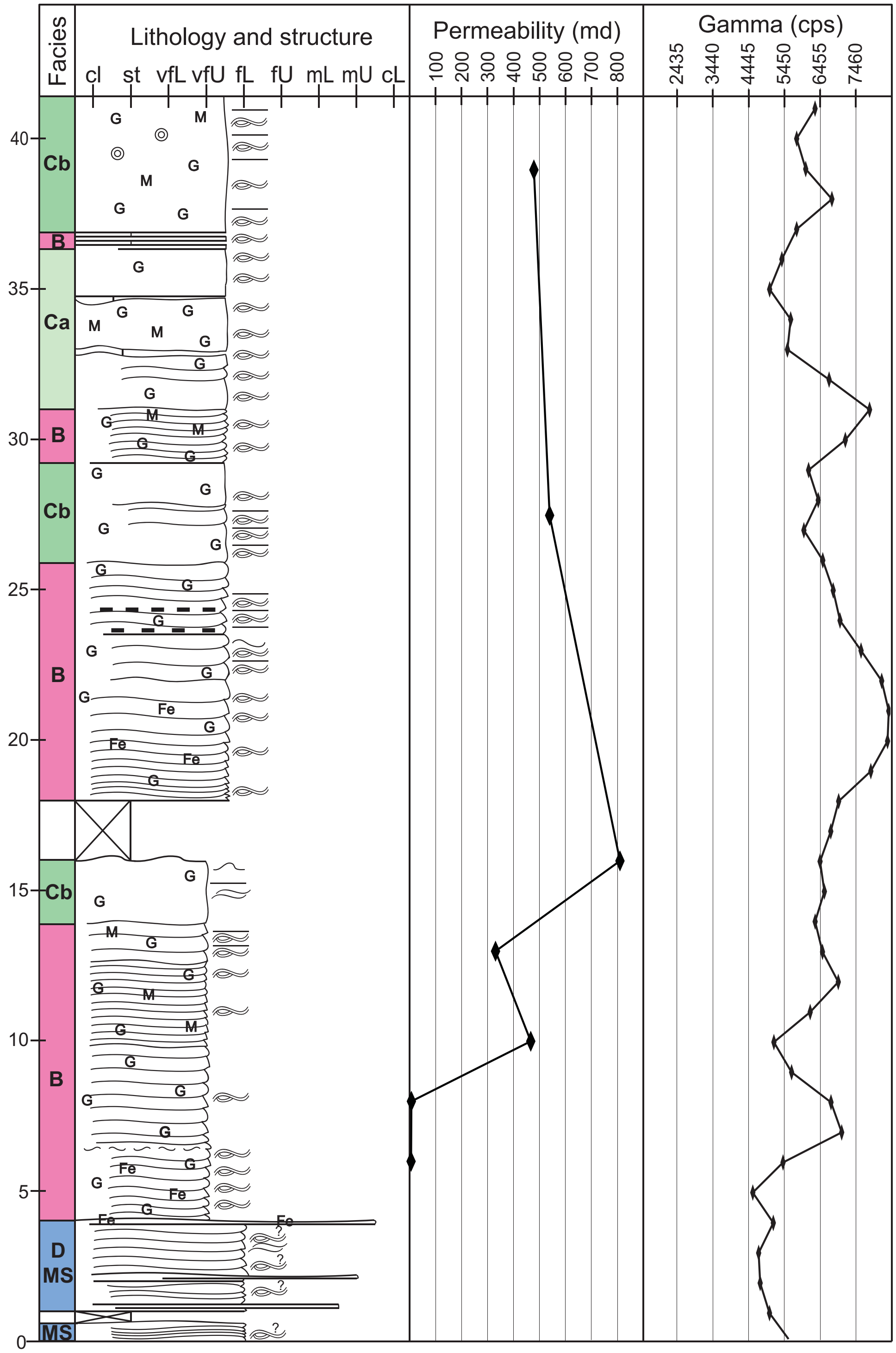

Figure 17. *Stratigraphic section at the Tilden Quarry (location 90516), showing the relationship between the Eau Claire lithofacies, total gamma, and permeability. Permeability was measured by conventional core analysis techniques, using Core Laboratories CMS-300 instrument. MS = Mount Simon Formation.*

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LITHOFACIES, K-BENTONITE GEOCHEMISTRY, AND SEQUENCE STRATIGRAPHY OF THE ORDOVICIAN (MOHAWKIAN–CINCINNATIAN) GALENA GROUP, NORTHEASTERN IOWA

Steve R. Beyer[1, 2], J.A. (Toni) Simo[1, 3], and Charles W. Byers[1]

ABSTRACT

The Ordovician (Mohawkian–Cincinnatian Series) Galena Group, a mixed carbonate–siliciclastic unit, was deposited in a near-equatorial epeiric sea that covered most of the North American craton. The Galena Group is widely distributed in the Upper Mississippi Valley and is non-dolomitized and well preserved in northeastern Iowa.

Generally, the Galena Group is composed of bioturbated wackestones and packstones that preserve abundant and diverse, predominantly benthic fauna. We recognized four lithofacies groups on the basis of subtle lithologic and ichnofaunal variations in the northeastern Iowa outcrop belt. Lithofacies group stacking patterns are broadly cyclic and define depositional cycles on the scale of 1 to 15 m.

We correlated broadly cyclic depositional cycles of the Galena Group along an approximately 100 km northwest–southeast transect in northeastern Iowa in a sequence stratigraphic framework. Our correlations were aided by the chemical fingerprinting of single primary apatite phenocrysts separated from the prominent and widespread Calmar K-bentonite bed. The Dunleith, Wise Lake, and Dubuque Formations of the Galena Group form one composite sequence that contains five high frequency sequences, which are composed of subordinate cycles. Vertical and lateral facies variations are a result of changes in eustatic sea level and terrigenous sediment supply. We interpreted the Galena Group to have been deposited on a subtidal, low energy, storm-dominated epeiric ramp.

INTRODUCTION

In the Upper Mississippi Valley (UMV), USA, an epeiric sea flooded Laurentia during a period of high global sea level in the Middle to Late Ordovician. This sea was bounded by the active Taconic Island Arc to the south and east (modern azimuth directions), Laurentian continental highlands to the north, and the Trans-Continental Arch to the west (fig. 1A) (Witzke, 1980). The Hollandale Embayment, an early Paleozoic tectonic depression, was an active depocenter within the UMV epeiric sea (fig. 1).

Our study focused on the predominantly carbonate, Middle to Late Ordovician (Mohawkian–Cincinnatian Series) Galena Group (Templeton and Willman, 1963) that is widely distributed in the UMV (fig. 1B). In the northeastern Iowa outcrop belt, the Galena Group is 75 to 85 m thick and consists of shaly to shale-free, bioturbated, fossiliferous limestone. Galena Group strata in northeastern Iowa are well preserved: they escaped the pervasive dolomitization that masks fauna and depositional fabrics in most of the lower Paleozoic carbonates of the UMV. The Galena Group contains thin, laterally extensive, altered volcanic ash beds termed K-bentonite beds. Each K-bentonite bed represents a geologically instantaneous ashfall event and has value as a timeline for stratigraphic correlation. Stratigraphic correlation is especially desirable in the northeastern Iowa Galena Group belt, where shale and shaly limestone facies to the northwest and rela-

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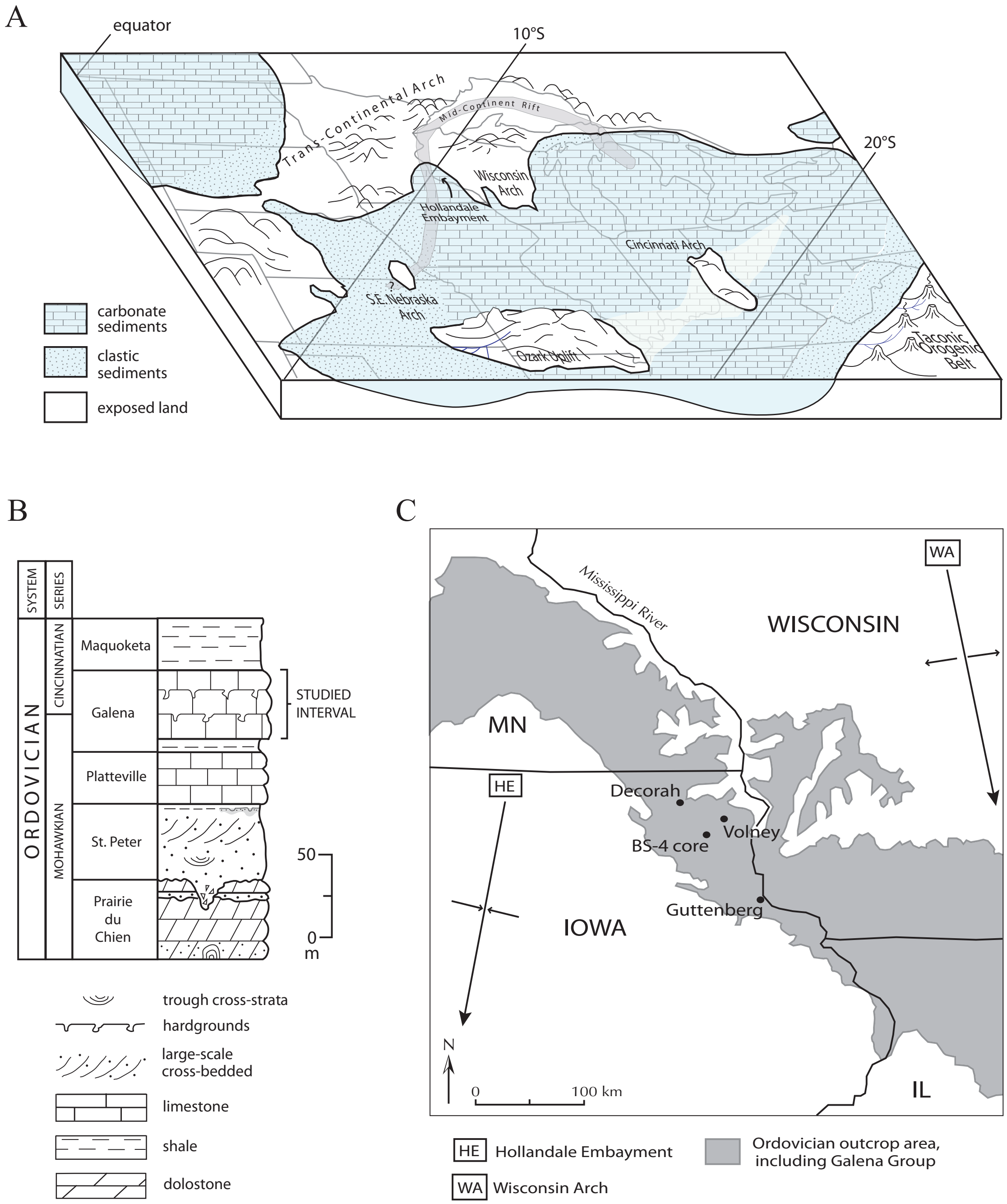


Figure 1. A. *Paleogeographic reconstruction of the north-central United States during the Middle to Late Ordovician. The Galena Group, the focus of this study, was deposited in the Hollandale Embayment, an early Paleozoic depocenter. The Hollandale Embayment was part of a larger epeiric sea that covered much of the present-day eastern United States. Modified from Witzke (1980).* **B.** *Idealized stratigraphic column for Ordovician sedimentary rocks of the UMV. Modified from Byers and Dott (1995).* **C.** *Location of study area. Stratigraphic sections were measured at Decorah, Volney, and Guttenberg, Iowa. One section was measured using core BS-4. Ordovician outcrop area includes the Galena Group. Trends of two structural features, the Wisconsin Arch and the Hollandale Embayment, are shown. Modified from Kolata and others (1996).*

tively shale-free limestone and dolomite facies to the southeast are transitional and complicate stratigraphic relationships.

Our research built upon the studies of Emerson (2002) and Simo and others (2003), which focused on the basal Decorah Formation of the Galena Group, and complements previous studies of the Galena Group in the Wisconsin outcrop belt (Choi, 1995, 1998; Choi and others, 1999). Our research contributes higher stratigraphic resolution on a local scale to previous regional-scale stratigraphic interpretations of the Galena Group (Witzke and Ludvigson, 2005; Witzke and Bunker, 1996; Witzke and Kolata, 1988) and provides a more comprehensive geologic interpretation to previous lithostratigraphic studies of the Galena Group in northeastern Iowa (Levorson and Gerk, 1972a, 1972b, 1975, 1983; unpublished data, 1972).

We had three objectives for this paper: 1) document the lithostratigraphy and lithofacies of the Galena Group in the northeast Iowa outcrop belt, where comparatively fewer studies have been performed; 2) identify a prominent K-bentonite bed, present at three localities across the study area, by primary apatite phenocryst chemistry; 3) elucidate sedimentary processes in epeiric seas. In our study we interpreted observed facies stacking patterns and lateral facies relationships in sequence stratigraphic terms, based on K-bentonite correlation of Galena Group strata within a complex facies transition. We have placed the facies of the northeastern Iowa Galena Group outcrop belt in the context of a regional-scale depositional model. For our proposed model, we drew upon research in more geologically recent epeiric sea settings to help interpret facies distribution in Ordovician UMV epeiric seas.

Previous work

Hall (1851) defined the Galena lithostratigraphic unit, and Calvin (1906), Ulrich (1911), and Kay (1935) provided additional lithostratigraphic framework. Further lithostratigraphic splitting and current nomenclature for the Galena Group was provided by Templeton and Willman (1963) and Willman and Kolata (1978).

Levorson and Gerk (1972a, 1972b, 1975, 1983; unpublished data, 1972) synthesized the results of an exhaustive lithostratigraphic study of the Galena Group in northeastern Iowa and adjacent parts of Wisconsin and Minnesota. They measured hundreds of stratigraphic sections to provide a framework for a fossil-cataloging project and were subsequently awarded the Strimple Medal for amateur paleontology by the Paleontological Society in 1987. Their works are a voluminous paleontological, stratigraphic, and sedimentological resource for those studying the Galena Group in the UMV.

Witzke and Bunker (1996) proposed a sequence stratigraphic interpretation for lower Paleozoic strata in Iowa, and identified two higher-ordered and five subordinate lower-ordered transgressive-regressive cycles for the Galena Group in Iowa. Their cycles were represented by shallowing-upward patterns bounded by hardground surfaces and/or phosphatic lags.

Emerson (2002) and Simo and others (2003) proposed a K-bentonite-aided sequence stratigraphic correlation of the basal Decorah Subgroup of the Galena Group. Some important results of this work are that 1) geochemical “fingerprinting” of K-bentonite beds via single apatite phenocryst analysis is successful and valuable for intraregional K-bentonite correlation, and 2) sediment supply and oceanic mixing were the predominant controls on sedimentation.

METHODS

We measured detailed stratigraphic sections at 14 locations near Decorah, Volney, and Guttenberg in Winneshiek, Allamakee, and Clayton Counties, respectively, northeastern Iowa (fig. 1C; see appendix: Locality register). Exposures included bluff faces, quarries, and roadcuts; we studied one previously drilled core. Sixty-six rock samples were cut into standard 30 μm thin sections and/or hand-polished slabs and studied using standard petrographic methods. A composite stratigraphic column of the Galena Group near Decorah is shown in figure 2.

Additional stratigraphic control was established using gamma ray spectrometry. Measured sections were analyzed with an Exploranium GR-320 portable spectrometer. Measurements were obtained every 0.5 m vertically, using 100-second count times. Variations in gamma response versus stratigraphic thickness were found to be consistent among sections and provided a reliable correlation tool. The potassium and to a lesser extent thorium spectrums displayed the most clear signal and were used instead of the uranium spectrum. The uranium spectrum was highly variable and produced a noisy signal for unknown reasons. A composite potassium gamma curve for the Galena Group near Decorah is shown in figure 2.

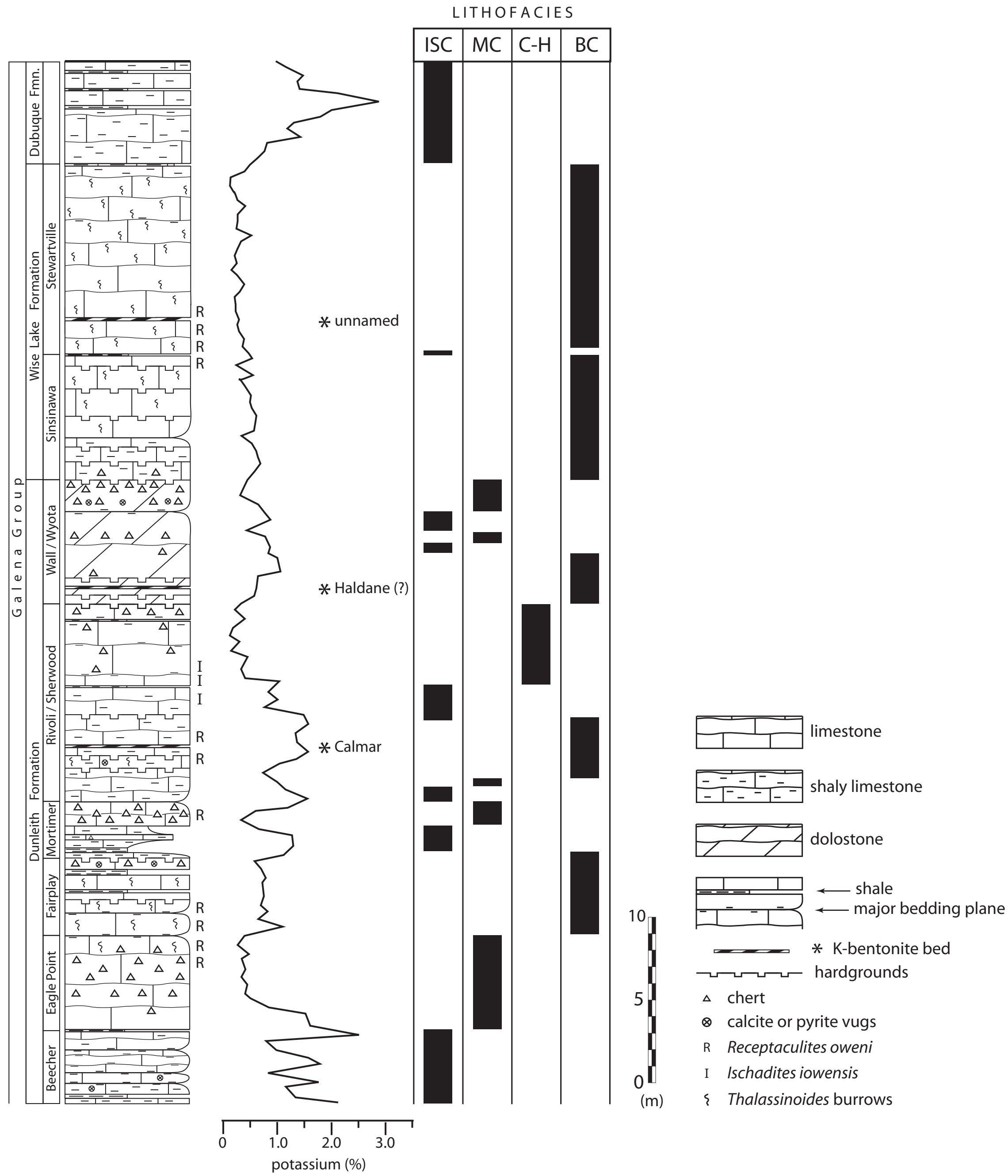


Figure 2. *Composite stratigraphic column for the Galena Group studied near Decorah, Iowa, with potassium gamma ray curve and distribution of facies groups within the Galena Group. Potassium gamma ray curve is a proxy for shale content. ISC = interbedded carbonate-shale; MC = massive carbonate; C-H =* Chondrites*-hardground carbonate; BC = bedded carbonate.*

Table 1. *Summary of the lithostratigraphic characteristics of the Galena Group (Dunleith, Wise Lake, and Dubuque Formations).*

LITHOSTRATIGRAPHIC UNIT	THICKNESS	LITHOLOGY	CONTACTS	KEY FAUNA
Dubuque Formation	6.3 m (20.7 ft) NW	Decimeter-scale bedded, gray, mud-rich, bioturbated crinoidal wackestone to packstone, regularly interbedded with 1 to 5 cm thick gray shale and thin-bedded dark brown calcareous shale toward the top	Top: Depauperate zone	*Isotelus* sp. at top
Wise Lake Formation				
Stewartville Member	11.0 m (36 ft) NW	Relatively shale-free and dolomite-mottled mud-rich to grain-rich wackestones and minor packstones; hardgrounds, nodular chert absent in exposures studied; upper half contains at least three prominent and relatively thick (5–15 cm) skeletal grainstone beds; meter-scale bedded at base, to decimeter-scale bedded at top	Top: 6 cm thick, prominent, widespread, and recessive bed plane; "marker bed" of Levorson and Gerk (1975)	*Receptaculites,* basal 4 m; *Maclurites* sp., middle 1/3; *Paleosynapta flaccida,* upper 2 m
Sinsinawa Member	7.0 m (23 ft) NW	Decimeter- to meter-scale bedded, shaly (at base) to shale-free mud-rich to grain-rich wackestone punctuated by discontinuous grainstone beds; common hardgrounds; scattered chert at base	Top: widespread and prominent shaly bed plane	*Receptaculites,* upper 1 m (approximately)
Dunleith Formation				
Wall–Wyota Members	7.5 m (24.6 ft) NW	Decimeter- to meter-scale bedded, dolomitic grain-rich wackestones, packstones, and grainstones; rare to abundant nodular chert; Haldane (?) K-bentonite present 0.5–1.0 m above the base	Top: prominent hardground, locally replaced by a prominent bedding plane	none
Rivoli–Sherwood Members	approximately 12 m (approximately 40 ft) NW	Interbedded shaly packstones and wackestones at base, grading to relatively shale-free wackestones and packstones at top; prominent hardgrounds, common *Chondrites* burrows, and common nodular chert bands in upper half; Calmar K-bentonite present approximately 2 m (NW) to 4 m (SE) above the base	Top: prominent hardground surface	*Ischadites iowensis* above Calmar K-bentonite
Mortimer Member	3.3 m (10.8 ft) NW – 4.1 m (13.5 ft) SE	Basal interbedded shale and thinly bedded shaly wacke- to packstone and shaly grain-rich wackestone; upper mudstone to wackestone with several conspicuous chert bands	Top: widespread and prominent shaly bed plane	*Receptaculites,* in cherty unit
Fairplay Member	4.4 m (14.4 ft) NW – 7.9 m (25.9 ft) SE	Decimeter- to meter-scale bedded, in many cases *Thalassinoides* burrowed wackestones and packstones punctuated by several thin (3–7 cm) grainstones with common hardgrounds; nodular chert common near top	Top: prominent and widespread hardground surface	*Receptaculites,* lower half
Eagle Point Member	5.7 m (18.7 ft) NW – 5.2 m (16.9 ft) SE	Pervasively bioturbated, nearly massive-bedded, mud-rich to grain-rich wackestones with nodular chert bands increasing to SE; more conspicuously bedded near base and top	Top: Widespread shaly bed plane that becomes thicker to SE	*Receptaculites,* upper 2 m (approximately)
Beecher Member	4.4 m (14.4 ft) NW – 3.1 m (10.1 ft) SE	Upper: decimeter-scale bedded, grain-rich wackestones. Middle: thin-bedded wackestones to grainstones Base: mud-rich to grain-rich wackestone interbedded with shale and shaly nodular grainstones and packstones	Top: Widespread shaly bed plane Base: top of *Prasopora* epibole	*Prasopora* sp. at base

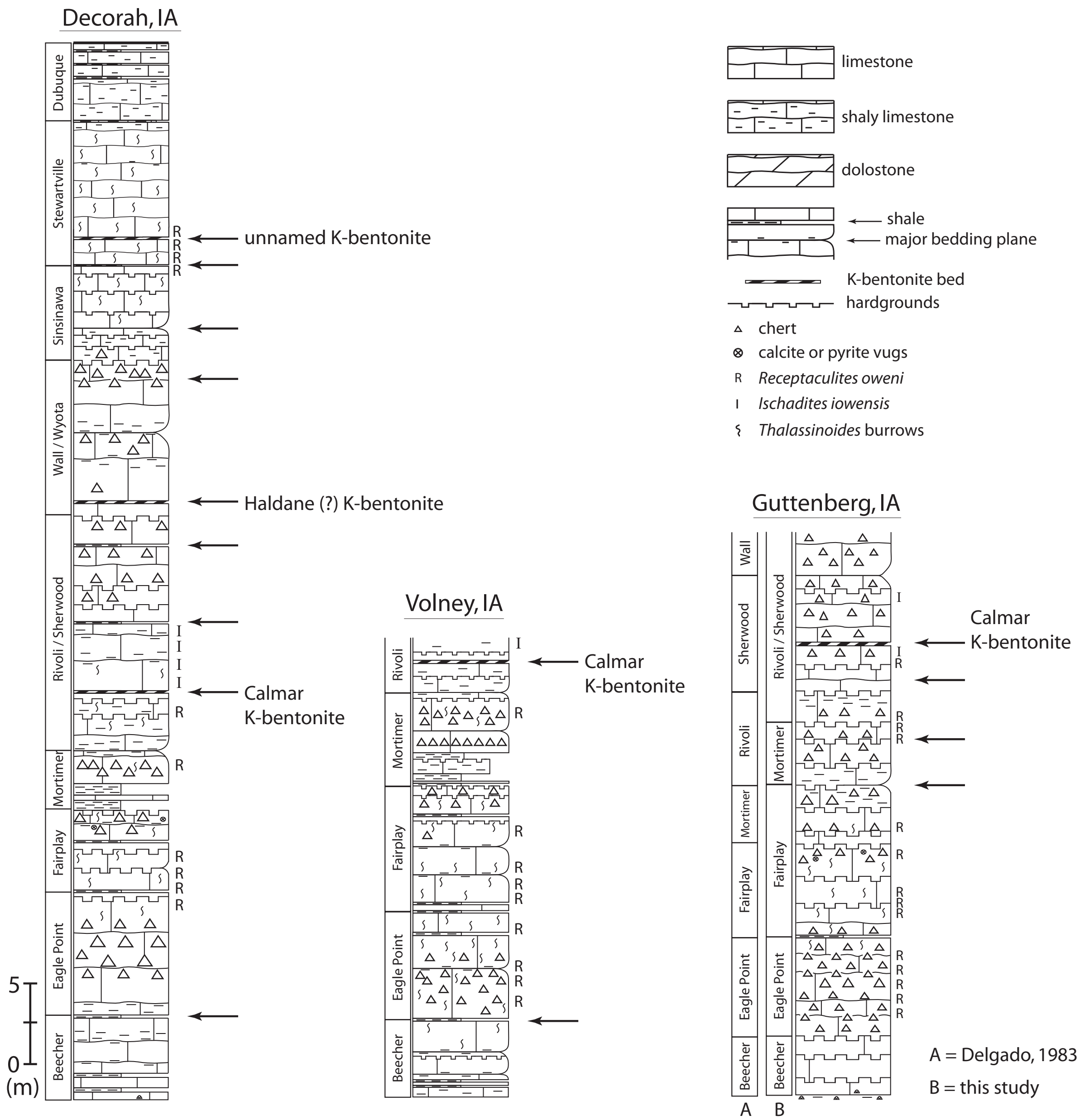


Figure 3. *Stratigraphic columns of sampled beds at Decorah, Volney, and Guttenberg, Iowa (indicated by arrows). Arrows point to K-bentonite beds (Calmar, Haldane (?), and unnamed); samples yielded abundant euhedral apatite and zircon phenocrysts. Unlabeled arrows indicate a detrital mineral assemblage and are not considered to be K-bentonite beds.*

Seventeen clay-rich and recessive beds, indicative of K-bentonite, were sampled at seven localities (see locality register) and processed to separate primary apatite phenocrysts from the bulk sample using procedures detailed in Beyer (2003), Emerson (2002), and Mange and Maurer (1992). Beds that yielded samples abundant in euhedral apatite and zircon phenocrysts were considered K-bentonite beds (fig. 3). Sampled beds not considered to be K-bentonites yielded organic apatite (conodonts), quartz, calcite, dolomite, abraded zircons, and rare potassium feldspar. Potassium feldspar in these beds yield Proterozoic $^{40}Ar/^{39}Ar$ ages

(Chetel, 2004; Chetel and others, 2005) and suggested a detrital, nonvolcanic origin. From each of the K-bentonite samples, 15 to 20 grains were analyzed by electron microprobe using five points per grain. Elements analyzed were P, Ca, F, Cl, Y, La, Ce, Fe, Mg, and Mn. Electron microprobe analysis was performed with a Cameca SX51 microprobe in the Eugene Cameron Electron Microprobe Lab, Department of Geology and Geophysics, University of Wisconsin–Madison.

LITHOSTRATIGRAPHY

Table 1 provides a summary of the lithostratigraphic characteristics of the Dunleith, Wise Lake, and Dubuque Formations of the Galena Group in northeastern Iowa. We adopted the lithostratigraphic classification of Levorson and Gerk (1972a, 1972b, 1975, 1983; unpublished data, 1972), which directly applied the classification of Templeton and Willman (1963) and Willman and Kolata (1978) to Galena Group strata in northeastern Iowa. However, differentiation between the Rivoli and Sherwood Members and between the Wall and Wyota Members was not possible at the measured sections due to similarities in lithology and bedding style and lack of clear contact criteria. Therefore, the Rivoli and Sherwood Members and the Wall and Wyota Members are herein referred to as the Rivoli–Sherwood Members and the Wall–Wyota Members, respectively. In addition, the Frankville, Luana, and Littleport Beds of the Dubuque Formation (Levorson and Gerk, 1983) were not differentiated for this study.

FACIES DESCRIPTION AND INTERPRETATION

Most of the Galena Group studied in northeastern Iowa is non-dolomitized and very well preserved. Strata preserve fauna, ichnofauna, and primary depositional fabrics that suggest sedimentation took place during periods of cyclic sea-level change in storm-dominated epeiric seas.

The Galena Group comprises four lithofacies groups: 1) interbedded shale-carbonate, 2) massive carbonate, 3) bedded carbonate, and 4) *Chondrites*-hardground carbonate. The distribution of these groups within the Galena Group is shown in figure 2.

Interbedded shale-carbonate facies group

Description

The interbedded shale-carbonate facies group includes all the interbedded and shaly carbonate lithologies of the Galena Group that we studied. This group can be recognized in outcrop by its resistant shaly carbonate beds intercalated with recessive shale-rich beds.

The recessive shale-rich beds are 1 to 20 cm thick and generally consist of greenish-gray, poorly indurated, non-fissile calcareous shales intercalated with grain-rich carbonate. One to three centimeter thick beds of carbonate-free greenish-gray or brown shales are rare. Gray-weathered, *Chondrites*-burrowed, dark brown fissile calcareous shale is a unique lithology and is restricted to the upper Dubuque Formation. In general, recessive shale-rich strata of the interbedded shale-carbonate facies group decrease in abundance to the southeast.

Carbonate lithologies belonging to the interbedded shale-carbonate facies group are predominantly tan to light gray, centimeter- to decimeter-scale bedded, grain-rich, shaly wackestones and packstones. Shale is present as 0.5 to 3.0 cm thick zones of anastomosing hairline shale drapes. Beds display pervasive *Planolites* burrowing to the extent that all primary depositional features have been destroyed. Two less predominant carbonate lithologies are 1) nodular carbonate consisting of medium to light gray (fresh and weathered) mudstone to grain-rich wackestone nodules separated by 1 to 30 mm thick undulatory to irregular gray shale beds, and 2) centimeter-scale bedded bioturbated grainstones that may be graded and separated by shale drapes.

Chert nodules are absent and hardground surfaces are rare but prominent where observed. This group displays the most diverse fauna of the four Galena Group facies groups and includes brachiopods, gastropods, bryozoans (including *Prasopora* sp.), crinoids, and solitary corals.

The group composes the entire Beecher Member, the lower half of the Mortimer Member, two parts of the lower Rivoli–Sherwood Members, the middle part of the Wall–Wyota Members, and the entire Dubuque Formation in the northwest study area. Shale content decreases to the southeast, and this facies group is restricted to the basal Mortimer Member at Guttenberg, Iowa.

Interpretation

Sediment of the interbedded shale-carbonate facies group does not display intraclasts, wave or current cross stratification, or any other fair-weather wave indicators. Strata display variable degrees of storm-wave reworking, and we interpreted them to have been deposited above the storm-wave base (SWB). Shale-rich strata are intimately associated with packstones and grainstones, suggesting deposition in a more landward position closer to a siliciclastic source and in a more frequently wave-reworked environment. Carbonate-rich strata have decreased siliciclastic content and wackestone to packstone textures, which suggests deposition farther offshore in a less frequently wave-reworked environment. The diverse faunal assemblage and pervasive bioturbation indicate deposition in normal marine conditions. However, *Chondrites*-burrowed dark brown fissile calcareous shale beds of the Dubuque Formation may indicate deposition in an oxygen-deficient environment.

Massive carbonate facies group

Description

The massive carbonate facies group includes all relatively shale-free, nearly massive-bedded carbonates with rare to absent hardground surfaces. This facies group is recognized in outcrop by its lack of prominent shale beds, homogeneous texture, and common nodular chert bands.

The most predominant lithology is light tan to light gray, decimeter- to meter-scale bedded, pervasively bioturbated, relatively shale-free, mud-rich to grain-rich wackestones. The predominant ichnogenus is *Planolites* with subordinate *Thalassinoides*. Intense *Planolites* burrowing homogenized the sediments to the extent that no primary depositional features are present. A less common but significant lithology is tan or gray, weakly to nonbioturbated, laminated, very fine-grained skeletal grainstone.

Nodular chert bands are common within the massive carbonate facies group, and they may be associated with laminated, very fine-grained grainstones. Chert content increases significantly to the southeast. Hardgrounds are rare in the northwestern study area and increase in abundance to the southeast. Predominant fauna in the massive carbonate facies group are brachiopods, gastropods, *Receptaculites*, and solitary corals.

The massive carbonate facies group comprises the entire Eagle Point Member, the upper half of the Mortimer Member, and the upper 2 to 3 m of the Wall–Wyota Members.

Interpretation

Sediments of the massive carbonate facies group display bioturbated mud-rich to grain-rich wackestone textures and lack wave- or current-generated sedimentary structures. We interpreted laminated very fine-grained grainstones to be the distal parts of tempestites that may have been deposited at or just below the SWB. The massive carbonate facies group and *Chondrites*-hardground carbonate facies group display the lowest siliciclastic content of the Galena Group that we studied; they represent deposition farthest from a terrigenous sediment source and probably at the greatest relative depth. The origin of the chert within this facies group is unclear. Previous studies have invoked siliceous sponge spicules (Korpel, 1983; Delgado, 1983) and K-bentonites (Mossler and Hayes, 1966; Levorson and Gerk, 1972a) as the source of silica for nodular chert. Samples and exposures studied did not corroborate these explanations.

The abundance of skeletal grains and pervasive bioturbation suggest deposition under normal marine conditions.

Bedded carbonate facies group

Description

The bedded carbonate facies group includes all conspicuously bedded, commonly dolomitized carbonate lithologies containing common hardground surfaces and *Thalassinoides* burrowing. It is recognized in outcrop by decimeter- to meter-scale, hardground-bearing carbonate beds separated by prominent and laterally continuous shaly bed planes. The presence of abundant hardgrounds, *Thalassinoides* burrows, and common dolostone distinguishes this facies group from the interbedded shale-carbonate facies group, which also appears well bedded in outcrop.

The bedded carbonate facies group consists of gray to tan, decimeter- to meter-scale bedded, pervasively bioturbated mud-rich to grain-rich wackestones and packstones. One to three centimeter thick, laterally discontinuous grainstone beds are rare to common. Several medium to coarse-grained, prominent, and laterally continuous, 8 to 15 cm thick grainstone beds that display imbrication of clasts and burrowed tops are present in the upper half of the Stewartville Member.

Strata display weak to moderate dolomitization, with dolomite content increasing to the southeast. Dolostone is unique to this facies group.

Carbonate beds are bounded by shaly bed planes, rare shale beds, and/or prominent hardground surfaces. Shale is also present within the beds as rare to abundant 2 to 20 mm thick zones of anastomosing hairline drapes.

Thalassinoides is the predominant ichnogenus of this facies group and imparts a distinct appearance to exposures: Fresh exposures are mottled and display dark-colored burrows that contrast with light-colored host sediments; weathered exposures display a pock-marked to vuggy appearance due to preferential weathering of dolomite burrow fill; highly weathered exposures can display complete removal of the dolomite burrow fill, displaying casts of the three-dimensional geometry of *Thalassinoides* burrow networks and imparting a Swiss cheese appearance to the rock. *Thalassinoides* burrowing is either pervasive or cyclic. Cycles are decimeters to meters thick and consist of a shaly limestone base, overlain by *Thalassinoides* burrowed wackestones and a hardground surface.

Hardground surfaces are abundant, weakly to moderately mineralized, closely spaced (3–30 cm); they have been scoured to notably planar surfaces. Nodular chert bands are rare to common. Common fauna include *Receptaculites*, gastropods, solitary corals, and bryozoans (including *Prasopora* sp.).

The bedded carbonate facies group comprises the entire Fairplay Member, the basal Rivoli–Sherwood Members, most of the Wall–Wyota Members, the entire Sinsinawa Member, and the upper seven-eighths of the Stewartville Member.

Interpretation

Sediments of the bedded carbonate facies group do not display fair-weather wave sedimentary structures. The presence of discontinuous to continuous centimeter-scale grainstone beds, scoured hardgrounds, and grain-rich wackestone to packstone textures indicate reworking and erosion by storm currents above the SWB. Scouring of hardgrounds may have been aided by more frequent impingement of storm-generated currents and storm wave action on the seafloor at shallower depths. Increased siliciclastic content, including conspicuous shaly bed planes, represent deposition in a more landward position when compared to the massive carbonate facies group. We interpreted *Thalassinoides*-related cycles to represent an upward decrease in net sediment accumulation. Shaly cycle bases represent high siliciclastic input and relatively high net sediment accumulation. Siliciclastic input decreases into the middle part of the cycles as indicated by relatively shale-free and *Thalassinoides*-burrowed carbonates: Burrowing organisms were probably able to colonize seafloor sediments during periods of low net sediment accumulation. Cycle-terminating hardground surfaces represent a halt in sedimentation and seafloor cementation.

The presence of diverse and plentiful fauna and abundant bioturbation suggest deposition under normal marine conditions. The presence of pyrite-cemented hardground surfaces may indicate periods of nondeposition under oxygen-poor conditions.

***Chondrites*-hardground carbonate facies group**

Description

The *Chondrites*-hardground carbonate facies group includes all relatively shale-free carbonates that display abundant *Chondrites* burrows and prominent, strongly mineralized hardground surfaces. These features, plus common nodular chert bands, characterize this facies group in outcrop.

The most predominant lithology of this facies group is dark to light gray to tan, centimeter- to decimeter-scale bedded, thoroughly bioturbated mud-rich to grain-rich wackestones and packstones. Zones of 1 to 40 mm thick, anastomosing dark brown, dark gray, or black very fine-grained drapes that contain *Chondrites* burrows are common. The drapes preserve graptolites at some locations. Beds are punctuated by several conspicuous, 3 to 7 cm thick laterally continuous grainstone beds. Grainstone beds are very fine to medium-grained and weakly to nonbioturbated. Rarely, the grainstone beds display the “sand wave” geometry described by Delgado (1983), in which grainstone thickness varies due to the presence of an undulatory top. Very fine-grained grainstones are in many instances laminated.

Hardground surfaces are prominent and abundant in the *Chondrites*-hardground carbonate facies group. Pairs or trios of hardgrounds may be vertically evenly spaced at intervals of 0.5 to 1.5 m. Hardgrounds are strongly cemented by micro- to macro-crystalline pyrite, which imparts a stark black color to the surface at relatively fresh exposures and a rusty brown or red-brown color at weathered exposures. Relief of hardground surfaces ranges from 0.0 to 5.0 cm. Those hardgrounds that have no relief are exceptionally planar surfaces that may display *Trypanites* borings, truncation of burrows, and micro- and macro-scale truncation of fossils. Hardground "clasts," or centimeter-scale, *Trypanites*-bored hardground rip-ups are present within 1 dm above or below prominent hardgrounds. Blackened, sulfide-mineralized skeletal grains are also abundant above and below hardgrounds.

Nodular chert bands are common within this facies group, but are relatively less abundant than in parts of the massive carbonate facies group. Common fauna include brachiopods, crinoids, and *Ischadites iowensis*.

The *Chondrites*-hardground carbonate facies group is restricted to the upper Rivoli–Sherwood Members and approximately the basal meter of the Wall–Wyota Members in the northwest study area. This facies group is not present at measured sections to the southeast.

Interpretation

Sediments of the *Chondrites*-hardground carbonate facies group do not display fair-weather wave sedimentary structures. The presence of centimeter-scale grainstone beds, scoured hardgrounds, and hardground "clasts" indicate reworking by storm currents above the SWB. However, the presence of nonbioturbated, laminated, very fine-grained grainstones and non-scoured hardgrounds may suggest deposition just below the SWB. Relatively shale-free, predominantly wackestone textures indicate deposition far removed from a siliciclastic sediment source.

The bioclastic-rich and bioturbated wackestones and packstones that compose much of this facies group indicate deposition under normal marine conditions. However, the presence of strongly mineralized hardground surfaces and *Chondrites*-burrowed dark-colored shale drapes throughout the lithofacies suggests periods of deposition under oxygen-poor conditions.

K-BENTONITE GEOCHEMISTRY

Potassic-altered volcanic ash beds—K-bentonite beds—are present in Ordovician strata throughout eastern North America, including northeastern Iowa (Sardeson, 1924; Allen, 1929; Allen, 1932; Templeton and Willman, 1963; Mossler and Hayes, 1966; Willman and Kolata, 1978; Kolata and others, 1996). The K-bentonite beds serve as marker horizons and provide correlation among sections in the facies transition zone. The beds have been positively identified via chemical fingerprinting. The fingerprint was provided by electron microprobe analysis (EMPA) of single primary apatite phenocrysts, which quantifies trace elemental abundances of the phenocryst population. Apatite phenocrysts are abundant and are most likely unaffected by alteration of the parent ash, and thus preserve primary magmatic chemistry (Samson and others, 1988). Bi-elemental scatter plots of relatively abundant trace elements such as Mg and Mn provide separate "clusters" for individual K-bentonites (Emerson, 2002; Simo and others, 2003). Clusters show little to no variability among localities, allowing individual K-bentonites to be identified and used for regional stratigraphic correlation (Samson, 1986; Samson and others, 1988; Emerson, 2002; Simo and others, 2003; Shaw, 2003).

Seventeen clay-rich and recessive beds were sampled within the Dunleith and Wise Lake Formations in northeastern Iowa (see appendix) and processed to separate primary phenocrysts (see Methods section). On the basis of phenocryst mineralogy, we recognize the Calmar and Haldane K-bentonites of Willman and Kolata (1978) and an unnamed K-bentonite within the Stewartville Member (fig. 3).

Calmar K-bentonite bed

(Willman and Kolata, 1978)

The Calmar K-bentonite bed is widespread in northeastern Iowa and is stratigraphically located 2.0 to 3.5 m above the base of the Rivoli–Sherwood Members of the Dunleith Formation. The bed is 2 to 6 cm thick and consists of orange-gray to olive green plastic clay.

Prominent K-bentonite beds at Volney, Iowa (locality 12), and Guttenberg, Iowa (locality 13), have been identified as the Conover K-bentonite (Levorson and Gerk, unpublished data, 1972) and the Nasset K-bentonite (Delgado, 1983; Samson, 1986; Sloan and others, 1987; Kolata and others, 1996), respectively. Our EMPA of apatite phenocrysts from these beds plus the Calmar K-bentonite (Levorson and Gerk, 1983) at Decorah, Iowa (locality 5), yielded a single cluster on a Mg vs. Mn bi-elemental plot (fig.

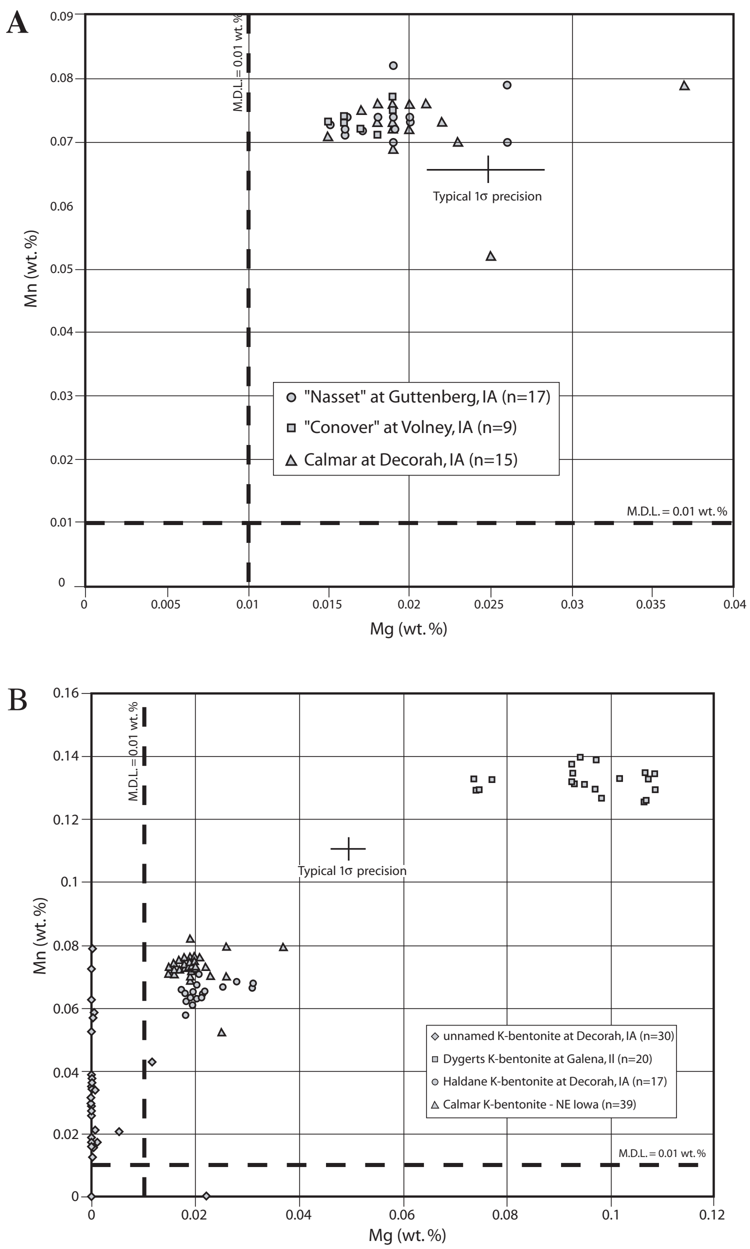


Figure 4. A. *Mg vs. Mn plot for apatite phenocrysts from the Calmar K-bentonite (Levorson and Gerk, 1983) at Decorah, Iowa (locality 5), the "Conover" K-bentonite (Levorson and Gerk, unpublished data, 1972) at Volney, Iowa (locality 12), and the "Nasset" K-bentonite (Delgado, 1983; Samson, 1986; Sloan and others 1987; Kolata and others 1996) at Guttenberg, Iowa (locality 13). Apatites from all three beds yielded a single cluster and are therefore a single K-bentonite rather than three separate K-bentonites.* **B.** *Mg vs. Mn plots for all K-bentonites studied. The Dygerts K-bentonite was collected at the type section of Willman and Kolata (1978) and was not present at studied exposures in northeast Iowa. Data for the Haldane K-bentonite are from Leslie (2002).*

4A). These data suggested that the sampled beds are the same K-bentonite, not three separate K-bentonites. On the basis of stratigraphic position, specifically constrained by an overlying and unique zone of *Ischadites iowensis*, we determined that the three sampled beds are the Calmar K-bentonite. The Conover and Nasset K-bentonite beds were not present at sections measured during this study.

The presence of the Calmar K-bentonite at three locations across the study area makes the bed a valuable stratigraphic marker and a candidate for further K-bentonite correlation study.

Haldane (?) K-bentonite bed

(Willman and Kolata, 1978)

The Haldane K-bentonite bed is present at two locations in Decorah, Iowa, and is not widespread in the study area. Where observed, the bed is stratigraphically located 0.6 to 1.0 m above the base of the Wall–Wyota Members and consists of orange-gray to olive green plastic clay. The bed is in stratigraphic proximity to the Haldane K-bentonite of Willman and Kolata (1978). However, the Haldane K-bentonite was not sampled at the type section for comparison. Due to the uncertainty in correlation, the Haldane K-bentonite studied in northeastern Iowa is herein referred to as the Haldane (?) K-bentonite.

Apatite phenocrysts separated from the Haldane (?) K-bentonite were analyzed by Leslie (2002) at locality 2, Decorah, Iowa. A bed at the same stratigraphic position was sampled at locality 1, Decorah, Iowa, during this study, but yielded an authigenic assemblage of minerals, including abundant barite and ubiquitous, unweathered euhedral pyrite. The presence of apatite phenocrysts at only one location precluded use of this horizon as a stratigraphic marker.

The Mg vs. Mn ratios for Haldane (?) K-bentonite apatite phenocrysts by Leslie (2002) vary only slightly from Mg vs. Mn ratios for Calmar K-bentonite apatites analyzed during this study (fig. 4B). Clear stratigraphic relationships allow differentiation of the Haldane (?) and Calmar K-bentonites at Decorah, but it is unclear whether apatite analysis could distinguish the two beds if stratigraphic relations were unknown.

Unnamed K-bentonite bed

(new)

A 1 cm thick bed plane consisting of dense, dark reddish-brown plastic clay is present throughout the Decorah, Iowa, area. It is stratigraphically located 2.0 m above the base of the Stewartville Member and approximately marks the top of the upper *Receptaculites* zone. The bed was sampled during this study at localities 7 and 8 and yielded abundant euhedral apatite and minor euhedral zircon. The phenocryst mineralogy and plastic nature of the clay suggest that the bed is a K-bentonite.

The EMPA of apatite for this bed yielded Mg vs. Mn ratios distinct from those of Calmar and Haldane (?) K-bentonite in the study area (fig. 4B). Ratios were also distinct from Dygerts K-bentonite (Willman and Kolata, 1978) Mg vs. Mn ratios from samples at the type section in northwest Illinois (fig. 4B). The Dygerts K-bentonite is not present at studied exposures in northeastern Iowa.

SEQUENCE STRATIGRAPHIC ARCHITECTURE

Figure 5 displays a correlation of Galena Group strata across the study area in a sequence stratigraphic framework. The Calmar K-bentonite was correlated along the cross section via apatite fingerprinting and serves as the datum. Additional correlation was provided by potassium gamma ray curves and recognition of key faunal zones, including the *Prasopora* epibole and *Receptaculites–Ischadites* zones. Potassium gamma ray values were assumed to be a proxy for clay content; highest potassium gamma ray values represent greatest influx of siliciclastic sediment and mark sequence, high frequency sequence, and cycle boundaries.

On the basis of interpretation and correlation of measured sections and described samples, we interpreted the Galena Group strata that we studied to form one composite, “third order” (Kerans and Tinker, 1997) sequence (fig. 6). This composite sequence is named G2 and is consecutive with the Galena Group composite sequence G1 (defined by Emerson, 2002) that represents the underlying Decorah Formation. Composite sequence G2 contains five nested high-frequency sequences and numerous nested complete and partial cycles.

Sequence boundaries

Composite sequence G2 is bounded by a lower sequence boundary (SB 2) and an upper sequence boundary (SB 3). SB 2 (defined by Emerson, 2002) is marked by the widely recognized *Prasopora* zonule. This key bed has been previously interpreted as a sequence boundary; it is laterally continuous, marks a sharp lithologic boundary, and separates two distinct brachiopod communities (Emerson, 2002; Simo and

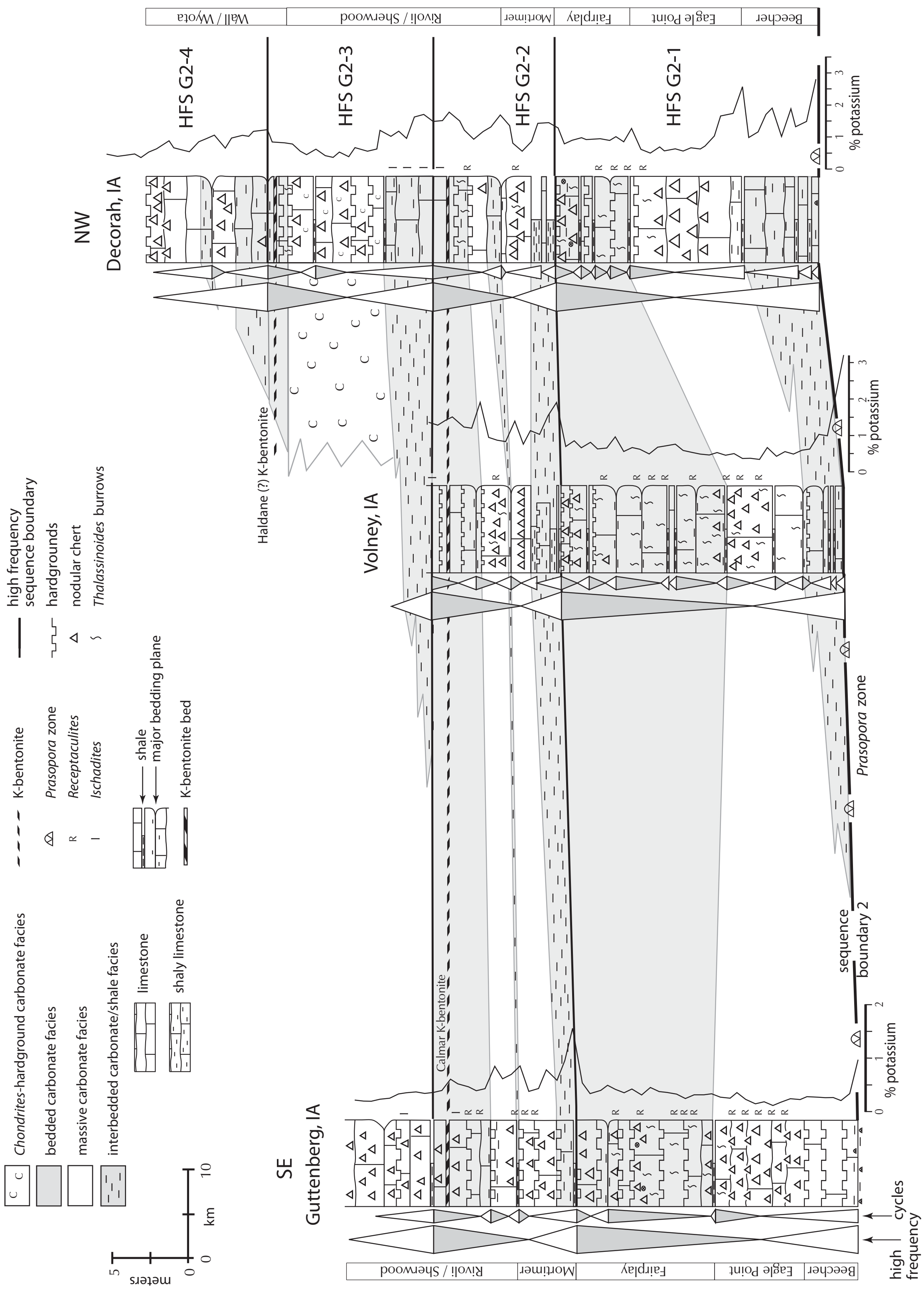


Figure 5. *Cross section for the Galena Group studied. (See fig. 1 for study locations.) Datum is the Calmar K-bentonite. Shaded triangles = regressive hemicycles.*

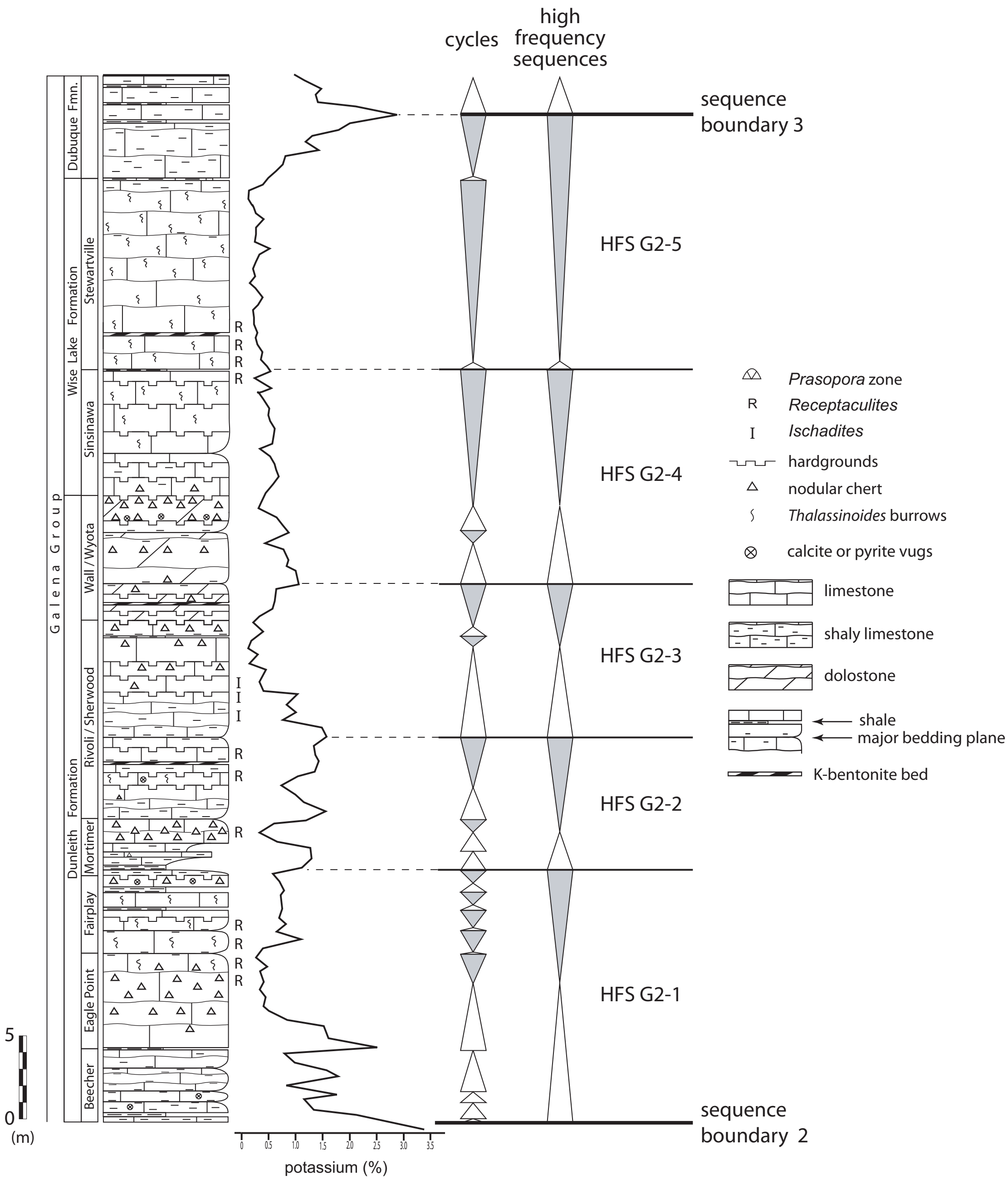


Figure 6. *Composite stratigraphic column with high frequency sequences. We interpreted the Galena Group to form one composite sequence that is bounded by a lower sequence boundary and an upper sequence boundary. The composite sequence contains a nested hierarchy of higher-ordered high frequency sequences and higher-ordered cycles. HFS = high frequency sequence; shaded triangles = regressive hemicycles. Refer to the text for composite sequence and sequence nomenclature.*

others, 2003).

Sequence boundary 3 is at the base of a locally widespread 2 dm thick bed of thin-bedded calcareous shale that lies approximately 3 m below the top of the Dubuque Formation. This boundary is marked by high gamma ray (all spectra) values and a conspicuous lithologic change. Above SB 3, green-gray calcareous shales typical of the underlying Galena Group are absent and replaced by brown, thin-bedded, calcareous organic-rich shales that preserve common *Chondrites* burrows and specimens of the trilobite *Isotelus* sp. Witzke and Bunker (1996) and Witzke and Kolata (1988) recognized the 2 dm thick bed of thin-bedded calcareous shale, but interpreted it as a marker for maximum flooding. Sequence boundary 3 may therefore be interpreted as a Type 3 sequence boundary, or drowning unconformity, described by Schlager (1999).

High-frequency sequences

Composite sequence G2 is divided into five higher-ordered packages that have been termed high-frequency sequences (HFS) (fig. 6), as defined by Kerans and Tinker (1997). The five HFS are named G2-1 to G2-5 and are consecutive with HFS described by Emerson (2002) for the underlying Decorah Formation. High-frequency sequences G2-1 to G2-5 are 8 to 15 m thick and are defined by vertical repetition of lithofacies groups.

The ideal HFS consists of an interbedded shale-carbonate base, an overlying massive carbonate middle, and a bedded carbonate top. This facies stacking pattern is recognized in HFS G2-1, G2-2, G2-4, and G2-5. The pattern is modified by the replacement of the massive carbonate facies group by the *Chondrites*-hardground carbonate facies group. This facies relationship is recognized in HFS G2-3. The upper 3 m of the Dubuque Formation above SB 3 belongs to the Dubuque–Elgin T–R subcycle of Raatz and Ludvigson (1996). We confidently correlated HFS G2-1 and G2-2 across the study area (fig. 5).

Figure 7 displays vertical trends for HFS defined in this study. The bases of the sequences are marked by high gamma ray values and are surfaces across which siliciclastic content and distribution of grain-rich lithologies abruptly increase. The transgressive hemicycle of these sequences is represented by an upward decrease in siliciclastic content and gamma ray values, an upward increase in mud–grain ratio, hardgrounds that are rare but prominent where observed, and a *Planolites*-dominated ichnofossil assemblage. The transgressive-regressive turnaround point is marked by low gamma ray values and siliciclastic content and nonbioturbated to weakly *Planolites*- or *Chondrites*-burrowed sediments. The turnaround is commonly marked also by laminated fine-grained grainstones and nodular chert. High frequency sequence G2-3 displays strongly mineralized hardgrounds and common *Chondrites* burrowing at the turnaround point. The regressive hemicycle of the HFS defined is represented by an upward increase in siliciclastic content and gamma ray values, an upward decrease in mud–grain ratio, numerous weak to prominent hardgrounds, and a *Thalassinoides*-dominated ichnofossils assemblage.

Cycles

High frequency sequences are further divided into higher-ordered packages that have been termed cycles (fig. 6), as defined by Kerans and Tinker (1997). High frequency sequences contain 2 to 5 complete cycles; partial cycles are observed in the transgressive hemicycles of HFS G2-1 and G2-2. Cycles are decimeters to meters thick and are defined by the same facies stacking patterns as HFS (fig. 7). Cycle bases are marked by higher gamma ray values and are usually shale-rich bed planes. Siliciclastic content decreases upward in the transgressive hemicycle and is reflected by lower gamma ray values. Cycle turnaround points are marked by relatively shale-free carbonate lithologies that commonly display nodular chert and mud-dominated textures. The regressive hemicycles of cycles defined display an upward increase in siliciclastic content and gamma ray values, hardgrounds, and *Thalassinoides* burrows.

Correlation of individual cycles across the study area is poor to non-correlative, and cycles were generally more difficult to define in the relatively shale-free southeast study area because of thin to absent shaly cycle bases. The decrease in siliciclastic sediment content to the southeast and the disruption of cycle features by storm processes and bioturbation are probable causes for poor decimeter- to meter-scale correlation.

DISCUSSION

Depositional model

Distribution of Galena Group strata indicate deposition over hundreds of square kilometers of the present-day upper and mid-Mississippi Valley. Strata studied are devoid of bioclastic sand shoals, barriers, reefs, or buildups. Sedimentary structures that indicate reworking by fair-weather waves or currents (that is, ripple marks, intraclasts, cross-bedding) were not observed, and no evidence for subaerial exposure was present nor has any been reported by previous workers. These

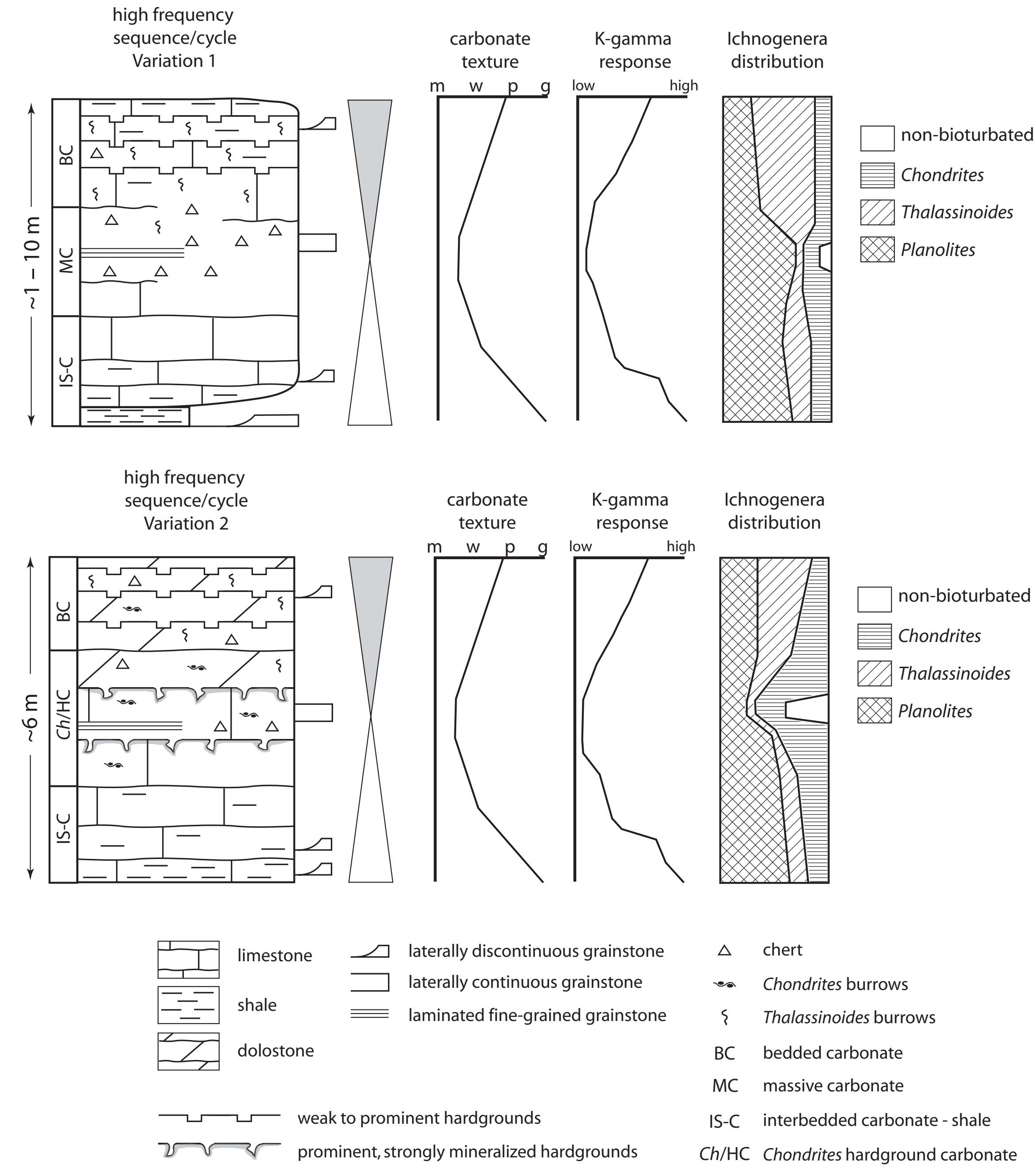


Figure 7. *Vertical trends in lithology, carbonate texture, K-gamma ray response, and ichnogenera distribution for the Galena Group studied; m = mudstone/micrite; w = wackestone; p = packstone; g = grainstone; shaded triangles = regressive hemicycles.*

observations support the interpretation that the Galena Group was deposited in a subtidal, low gradient, storm-dominated epeiric sea. Specifically, the "epeiric ramp" model named by Wright and Burchette (1998) and defined by Lukasik and others (2000) displays similar distribution of facies and hydrodynamic processes to the Galena Group studied.

We interpreted the Galena Group in our study area to represent deposition in the proximal zone of the epeiric ramp model (fig. 8A). Deposition in this

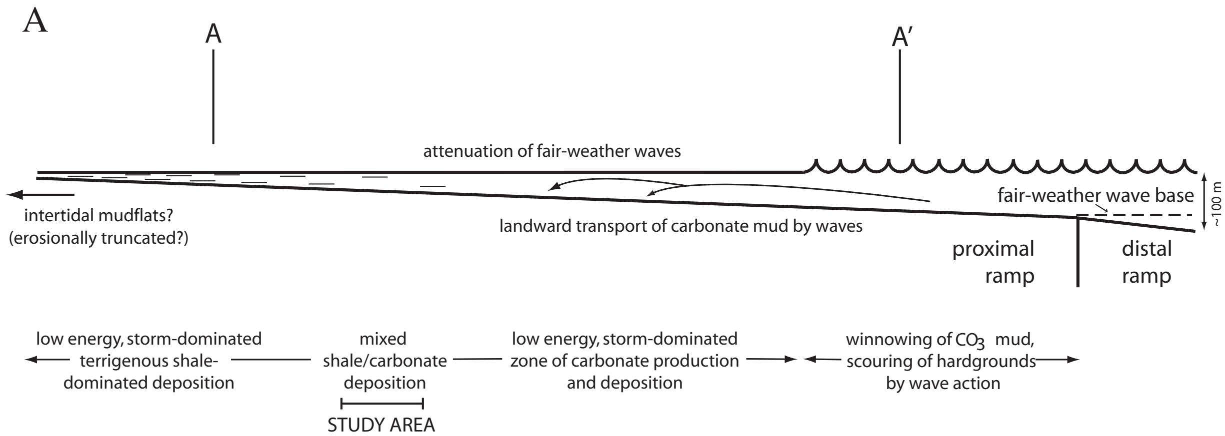
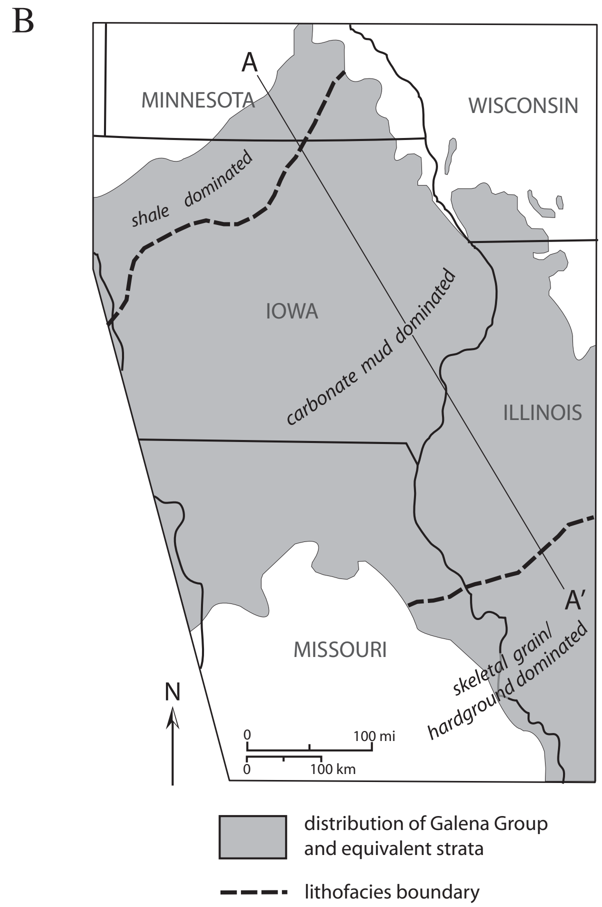


Figure 8. A. *Cross section showing epeiric ramp depositional model proposed for the Galena Group, with study area indicated. Modified from Lukasik and others (2000).* **B.** *Distribution of broadly defined facies belts of the Galena Group and equivalent strata in the Upper and Middle Mississippi Valley, with line of cross section A'. Modified from Witzke and Ludvigson (2005).*



zone is characterized by bioturbated, fossiliferous, hardground-bearing carbonate of variable texture and lacking grainy shoal or barrier facies. Bathymetry of the proximal zone is above the fair-weather-wave base, but wave energy was minimal, reduced by friction during travel over the broad and uniform expanses of the ramp. Reworking and seafloor scouring by storm-generated waves were instead the dominant hydrodynamic processes.

The epeiric ramp model predicts a gradual decrease in carbonate mud content and an increase in hardground frequency in a seaward direction as fair-weather-wave energy increases. This trend is present in the Illinois and Missouri Galena Group-equivalent outcrop belt, where strata become considerably thinner, grainier, and hardground-rich to the south (fig. 8B) (Templeton and Willman, 1963; Witzke and Kolata, 1988; Thompson, 1991; Witzke and Ludvigson, 2005). Carbonate mud winnowed from this "middle shelf" zone of Witzke and Ludvigson (2005) may have been transported by wave energy landward into the study area, a process similar to the epeiric ramp and epeiric platform (Irwin, 1965) models.

A landward zone of low energy, storm-influenced terrigenous shale deposition is present in the southern Minnesota and northern Iowa Galena Group outcrop belt and is represented by the shale subfacies of the Galena Group studied in northeastern Iowa (fig. 8A and B). This distribution is similar to that of the Murray Basin, south Australia, which is also interpreted to have been deposited on an epeiric ramp (Lukasik

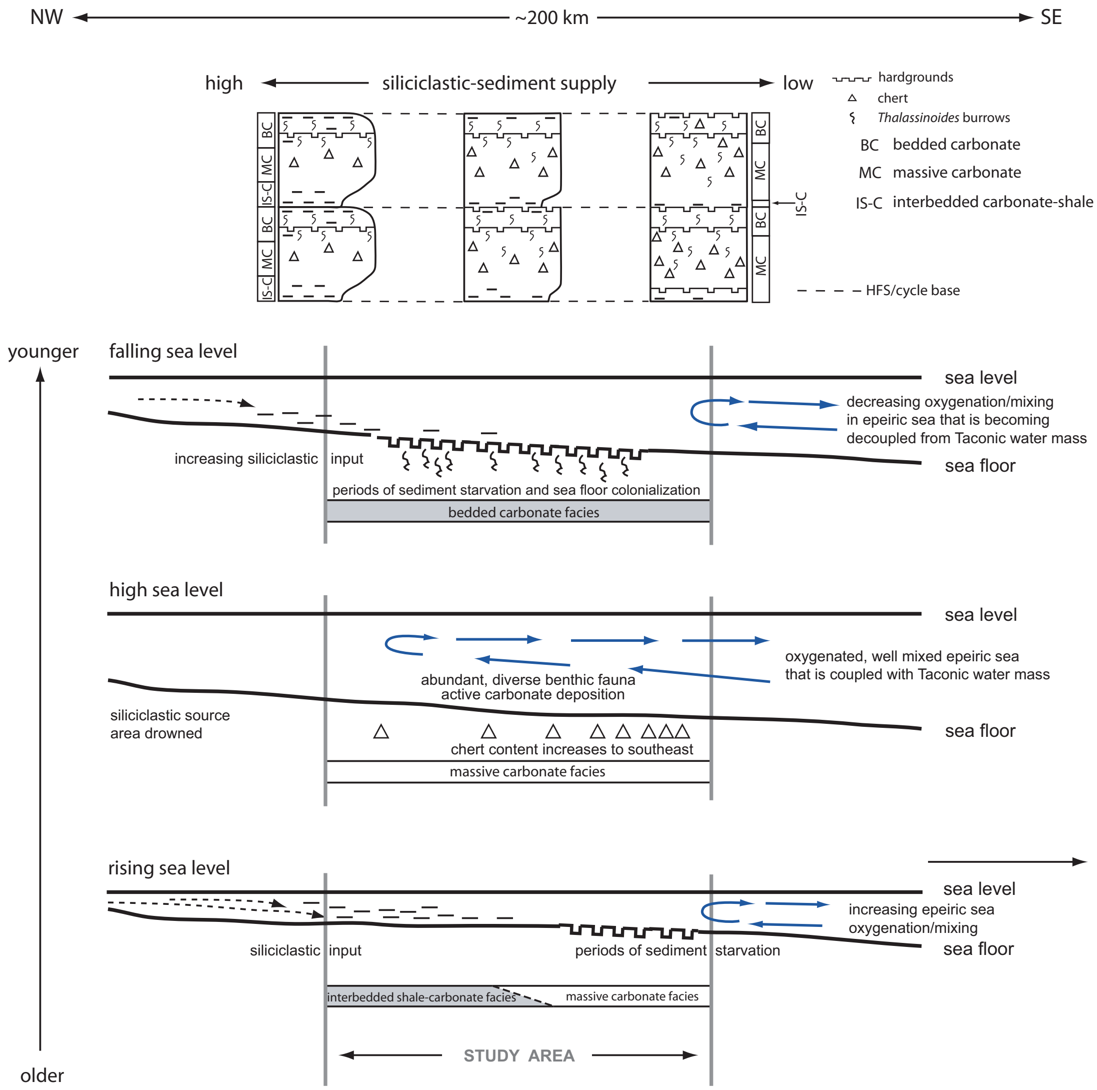


Figure 9. *Interpretation of sedimentological controls during deposition of high frequency sequences defined in this study. Columns represent the effect of siliciclastic sediment supply on Galena Group lithology, facies stacking, and outcrop expression from northwest to southeast.*

and others, 2000; Lukasik and James, 2003). Mudflat facies of the epeiric ramp model are not present in the Galena Group that we studied, but may have been present in a more landward position to the northwest and are erosionally truncated.

Controls on epeiric sea sedimentation

We interpreted the observed vertical and lateral facies variations to be primarily a product of relative sea-level change. In addition, we interpreted siliciclastic sediment supply and regional-scale oceanic circulation to be related, significant depositional controls.

We considered siliciclastic sediment supply to be a significant depositional control because it is intrinsically related to sea level in our depositional model for the Galena Group. The proposed low-gradient subtidal epeiric ramp is characterized by a lack of significant inherited topography, by a lack of high relief features such as reefs, buildups, or prominent shelf margins, and by diminished wave competency in proximal settings. In low relief settings, large absolute values of sea level rise or fall need not be invoked to produce substantial retreats or advances of the shoreline, resulting in exposure or drowning of widespread terrigenous source areas, respectively. Diminished wave competency in proximal settings may impede the basinward transfer of fine terrigenous sediment, resulting in association of shaly facies with shallow, normally high energy environments. The constraints imposed by the proposed depositional model suggest that siliciclastic sediment supply, rather than changes in absolute sea level, is a primary control of facies variation.

We determined that changes in sea level produced the following sedimentologic responses (fig. 9):

1) Increased siliciclastic content and skeletal grain-rich facies indicate lower sea levels and increased exposure and subsequent erosion of the Trans-Continental Arch to the northwest. This resulted in high runoff and basinward transport of siliciclastic sediments. Under these conditions, shaly carbonate interbedded with calcareous grain-rich shale accumulated in the northwest part of the study area proximal to the siliciclastic source area; relatively shale-free carbonates with zones of hardground surfaces accumulated more distally to the source area in the southeast part of the study area. Upward decreases in siliciclastic content and skeletal grain content indicate rising sea level and subsequent reduction of exposed source areas.

2) Carbonate mud-rich and siliciclastic-free facies suggest higher sea level and significant drowning of siliciclastic source areas. Under these conditions, the Hollandale Embayment experienced increased circulation and enhanced mixing of the local water mass with the more extensive "Taconic Sea" to the southeast. Diverse and abundant benthic communities thrived in the well mixed and siliciclastic-free water mass and resulted in accumulation of hardground-free, relatively shale-free, and nodular chert-prone carbonate across the study area. Deposition of laterally continuous, laminated fine-grained grainstones and the most shale-free carbonates accompanied maximum sea-level rise. The presence of prominent and strongly mineralized hardground surfaces and abundant *Chondrites* burrows in HFS G2-3, however, indicated dissimilar maximum flooding conditions. Apparently, the Hollandale Embayment did not become well mixed during sea-level rise during deposition of HFS G2-3, resulting in periodic dysoxia–anoxia and reducing conditions. The geographic restriction of these conditions to the northwest study area suggests a modification of local conditions, although the direct cause of the modification was not determined. Local inherited topography or increased epeiric sea stratification may be possible causes.

3) Upward increases in siliciclastic and skeletal grain content indicate falling sea level and gradual reexposure of the Transcontinental Arch to the northwest. Episodic inputs of siliciclastic-rich sediments are represented by conspicuous shaly bed planes in the northwest study area. Common centimeter-scale, laterally discontinuous grainstone beds were deposited during storm events and later dissected by ensuing storm currents and/or bioturbation. Pervasive *Thalassinoides* burrow networks represent colonialization of seafloor sediments during periods of slow carbonate production and accumulation. Hardground surfaces may represent periods of sediment starvation and diminished oceanic circulation in the Hollandale Embayment during lowering of sea level. Scouring of hardground surfaces and deposition and dissection of centimeter-scale grainstone beds were achieved by more frequent impingement of storm wave base on the seafloor.

CONCLUSIONS

- Much of the Galena Group is composed of pervasively bioturbated wackestones and packstones that are punctuated by thin (1–10 cm), laterally discontinuous grainstone beds. The rocks preserve diverse and abundant, predominantly benthic invertebrate fauna. Four lithofacies groups are recognized in the subtle lithologic and ichnofaunal variations in the Galena Group of northeastern Iowa. Repetition of lithofacies groups is cyclic throughout the study area. Depositional cycles generally consist of a shale-rich base, a carbonate-rich middle, and a hardground-bearing, *Thalassinoides*-burrowed carbonate top.
- Altered volcanic ash beds, or K-bentonites, are interstratified within the Galena Group. Specifically, the Calmar and Haldane (?) K-bentonites (Willman and Kolata, 1978) and an unnamed K-bentonite were identified during this study. Electron microprobe analysis of single apatite phenocrysts provided a chemical fingerprint for individual K-bentonites. The technique allowed correlation of Galena strata within a complex facies transition. Positive identification of the Calmar K-bentonite bed at three locations in northeast-

ern Iowa corrected misidentifications by previous workers at two of these locations.

- We interpreted the Galena Group in our study area to be a third-order composite sequence (Kerans and Tinker, 1997) named G2. Composite sequence G2 is bounded by surfaces across which major sedimentological changes are evident; it contains a nested hierarchy of five lower-ordered high-frequency sequences and numerous higher-ordered cycles. High-frequency sequences and cycles display repeating facies stacking patterns; the ideal stacking pattern consists of a transgressive, interbedded carbonate-shale base overlain by maximum flooding, shale-free carbonate, and a regressive, bedded carbonate top (where bedding is provided by thin shale beds and hardground surfaces). The cyclic manner in which the facies groups are stacked is a result of changes in eustatic sea level and sediment supply during deposition.
- The Galena Group of northeastern Iowa was deposited in the proximal zone of an epeiric ramp, spatially transitional between a terrigenous-supplied siliciclastic rich zone to the northwest and a siliciclastic-free zone of active carbonate production to the southeast. Deposition occurred under conditions of low fair-weather-wave energy and strong episodic storm energy.

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APPENDIX: LOCALITY REGISTER

All thin sections and polished slabs are housed at the Department of Geology and Geophysics, Weeks Hall, University of Wisconsin–Madison and are available upon request to the senior author. Map on next page shows approximate locality locations.

1. Madison Road quarry

- Northernmost of two quarries on north side of Madison Road, approximately 0.8 km (0.5 mi) west of intersection with Highway 52, Decorah, Winneshiek County, Iowa. Owned by Wiltgen Construction Co. in 2003. Named Pavlovec West in Levorson and Gerk (unpublished data, 1972).
- Mortimer Member: 1.9 m; Rivoli–Sherwood Members: 12.1 m; Wall–Wyota Members: 1.0 m.
- Sampled beds: Haldane (?) K-bentonite at 14.7 m.
- UTM: NAD 83/15N/ 595708E/ 4795391N.

2. Stream diversion and roadcut

Stream diversion

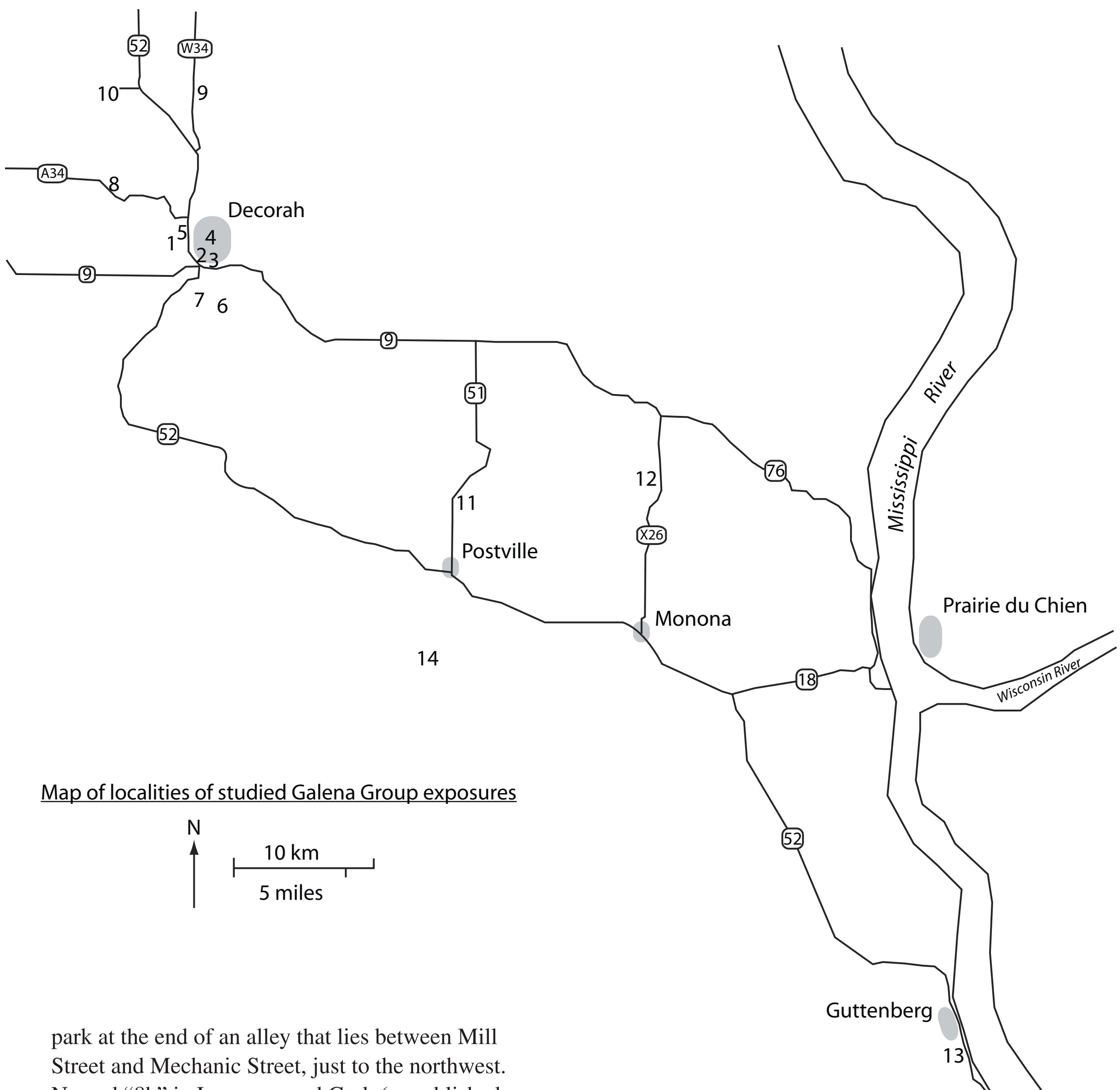
- West side of Highway 52, approximately 0.5 km (0.3 mi) north of intersection with Highway 9, Decorah, Winneshiek County, Iowa.
- Fairplay Member: 4.1 m; Mortimer Member: 2.0 m; Rivoli–Sherwood Members: 4.8 m.
- UTM: NAD 83/15N/ 596649E/ 4794311N.

Roadcut

- East side of Highway 52, 0.5 km (0.3 mi) north of intersection with Highway 9, Decorah, Winneshiek County, Iowa.
- Rivoli–Sherwood Members: 7.8 m; Wall–Wyota Members: 0.7 m.
- Sampled beds: Haldane (?) K-bentonite at 18.3 m.
- UTM: NAD 83/15N/ 596649E/ 4794311N.

3. Highway 9 roadcut

- North side of Highway 9, approximately 1.2 km (0.6 mi) east of intersection with Highway 52, Decorah, Winneshiek County, Iowa. It is convenient to



park at the end of an alley that lies between Mill Street and Mechanic Street, just to the northwest. Named "8h" in Levorson and Gerk (unpublished data, 1972).
- Rivoli–Sherwood Members: 4.8 m; Wall–Wyota Members: 7.4 m; Sinsinawa Member: 4.2 m.
- Sampled beds: recessive, clay-rich bed (non-K-bentonite) at approximately 15.2 m.
- UTM: NAD 83/15N/ 598068E/ 4793828N.

4. Ice cave

- North side of Quarry Street–Ice Cave Road, approximately 1.3 km (0.8 mi) east of intersection with College Drive, Decorah, Winneshiek County, Iowa.
- Beecher Member: 0.7 m; Eagle Point Member: 5.6 m; Fairplay Member: 4.6 m; Mortimer Member: 2.8 m; Rivoli–Sherwood Members: 3.6 m.
- UTM: NAD 83/15N/ 598803E/ 4796119N.

5. Highway 52 roadcut

- West side of Highway 52, approximately 0.7 km (0.4 mi) south of intersection with Highway W20 (also Pole Line Road), Decorah, Winneshiek County, Iowa.
- Rivoli–Sherwood Members: 12.6 m; Wall–Wyota Members: 8.2m; Sinsinawa Member: 1.0 m.
- Sampled beds: Calmar K-bentonite at 3.4 m; recessive, clay-rich bed (non-K-bentonite) at 7.1 m; recessive, clay-rich bed (non-K-bentonite) at 11.2 m; recessive, clay-rich bed (non-K-bentonite) at 18.4 m.
- UTM: NAD 83/15N/ 596114E/ 4796119N.

6. Holthaus quarry

- Two quarries located on south side of Trout Run Road, approximately 0.5 km (0.3 mi) east of intersection with Highway W38 (also Division Street, Middle Calmar Road), south of Decorah, Winneshiek County, Iowa. Owned by Roverud Const. Co. in 2003.
- Rivoli–Sherwood Members: 3.8 m.
- Sampled beds: recessive, clay-rich bed (non-K-bentonite) at 1.5 m.
- UTM: NAD 83/15N/ 598287E/ 4791908N.

7. Hovey quarry

- West side of Highway W38 (also Division Street, Middle Calmar Road), approximately 2.0 km (1.2 mi) south of underpass at Highway 9, south of Decorah, Winneshiek County, Iowa.
- Sinsinawa Member: 6.3 m; Stewartville Member: 3.9 m.
- Sampled beds: unnamed K-bentonite at 8.6 m; recessive, clay-rich bed (non-K-bentonite) at 6.3 m.
- UTM: NAD 83/15N/ 597652E/ 4791936N.

8. Pole Line Road roadcut

- Long roadcut on north side of Pole Line Road, approximately 5.8 km (3.6 mi) west of the intersection with Highway 52, northwest of Decorah, Winneshiek County, Iowa.
- Wall–Wyota Members: 0.8 m; Sinsinawa Member: 6.1 m; Stewartville Member: 9.0 m.
- Sampled beds: unnamed K-bentonite at 9.2 m.
- UTM: NAD 83/15N/ 592744E/ 4798671N.

9. Canoe Creek roadcuts and quarry

Roadcut

- West side of Highway W34 (also N. Winn Road), approximately 4.4 km (2.7 mi) north of intersection with Highway 52, north of Decorah, Winneshiek County, Iowa.
- Ion Formation: 1.3 m; Beecher Member: 2.9 m.
- UTM: NAD 83/15N/ 596477E/ 4806578N.

Roadcut

- East side of Highway W34 (also N. Winn Road), approximately 4.7 km (2.9 mi) north of intersection with Highway 52, north of Decorah, Winneshiek County, Iowa.
- Eagle Point Member: 2.7 m; Fairplay Member: 4.0 m; Mortimer Member: 1.0 m.
- UTM: NAD 83/15N/ 596334E/ 4806870N.

Quarry

- East side of Highway W34, approximately 4.9 km (3.0 mi) north of intersection with Highway 52, north of Decorah, Winneshiek County, Iowa.
- Mortimer Member: 1.8 m; Rivoli–Sherwood Members: 2.9 m.
- UTM: NAD 83/15N/ 596362E/ 4807083N.

10. Hitching Post Road roadcut

- South side of Hitching Post Road, approximately 2.4 km (1.5 mi) west of intersection with Highway 52, 1.4 km (0.9 mi) east–northeast of Bluffton, Winneshiek County, Iowa.
- Ion Formation: 0.3 m; Beecher Member: 4.4m; Eagle Point Member: 6.5 m; Fairplay Member: 4.3 m; Mortimer Member: 2.5 m.
- Sampled beds: recessive, clay-rich bed (non-K-bentonite) at 4.7 m.
- UTM: NAD 83/15N/ 589966E/ 4806840N.

11. Postville quarry

- Quarry located on north side of Quarry Road, off the east side of Highway 51, approximately 4.6 km (2.8 mi) north of intersection of Highway 51 and Highway 52 in Postville, Allamakee County, Iowa.
- Stewartville Member: 5.4 m; Dubuque Formation: 6.3 m.
- UTM: NAD 83/15N/ 616739E/ 4775886N.

12. Volney roadcut

- West side of Highway X26 (also Volney Road), approximately 6 km (3.7 mi) south of intersection with Highway 76, or approximately 11.8 km (approximately 7.3 mi) north of intersection with Highway 18–52, north of Monona, Allamakee County, Iowa.
- Ion Formation: 0.5 m; Beecher Member: 3.9 m; Eagle Point Member: 4.5 m; Fairplay Member: 7.7 m; don, Special Publications 149, p. 437–456.
- Mortimer Member: 4.1 m; Rivoli–Sherwood Members: 4.0 m.
- Sampled beds: recessive, clay-rich bed (non-K-bentonite) at 4.4 m; Calmar K-bentonite at 23.2 m.
- UTM: NAD 83/15N/ 632081E/ 4777375N.

13. Guttenberg south roadcut

- West side of Highway 52, approximately 1.9 km (approximately 1.2 mi) south of intersection with Highway C7X (also Garber Road), south of Guttenberg, Clayton County, Iowa.

- Buckhorn Member: 2.8 m; St. James Member: 2.8 m; Beecher Member: 3.1 m; Eagle Point Member: 5.1 m; Fairplay Member: 8.0 m; Mortimer Member: 3.0 m; Rivoli–Sherwood Members: 10.0 m.
- Sampled beds: recessive, clay-rich bed (non-K-bentonite) at 21.8 m; recessive, clay-rich bed (non-K-bentonite) at 23.1 m; recessive, clay-rich bed (non-K-bentonite) at 24.9 m; Calmar K-bentonite at 29.2 m.
- UTM: NAD 83/15N/ 656043E/ 4735239N.

14. BS-4 core

- Drilled in Clayton County, Iowa, on east side of Highway W62, 6.4 km (approximately 4 mi) south of Postville, Iowa. Housed at Iowa Geological Survey Bureau, Iowa City, Iowa.

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