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-

[1] Department of Geology and Geophysics, University of Wisconsin–Madison, 1215 West Dayton Street, Madison, Wisconsin 53706
[2] Now at Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario K7L 3N6 Canada
[3] Now at Exxon Mobil, URC GW3 980B, P.O. Box 2189, Houston, Texas 77252-2189

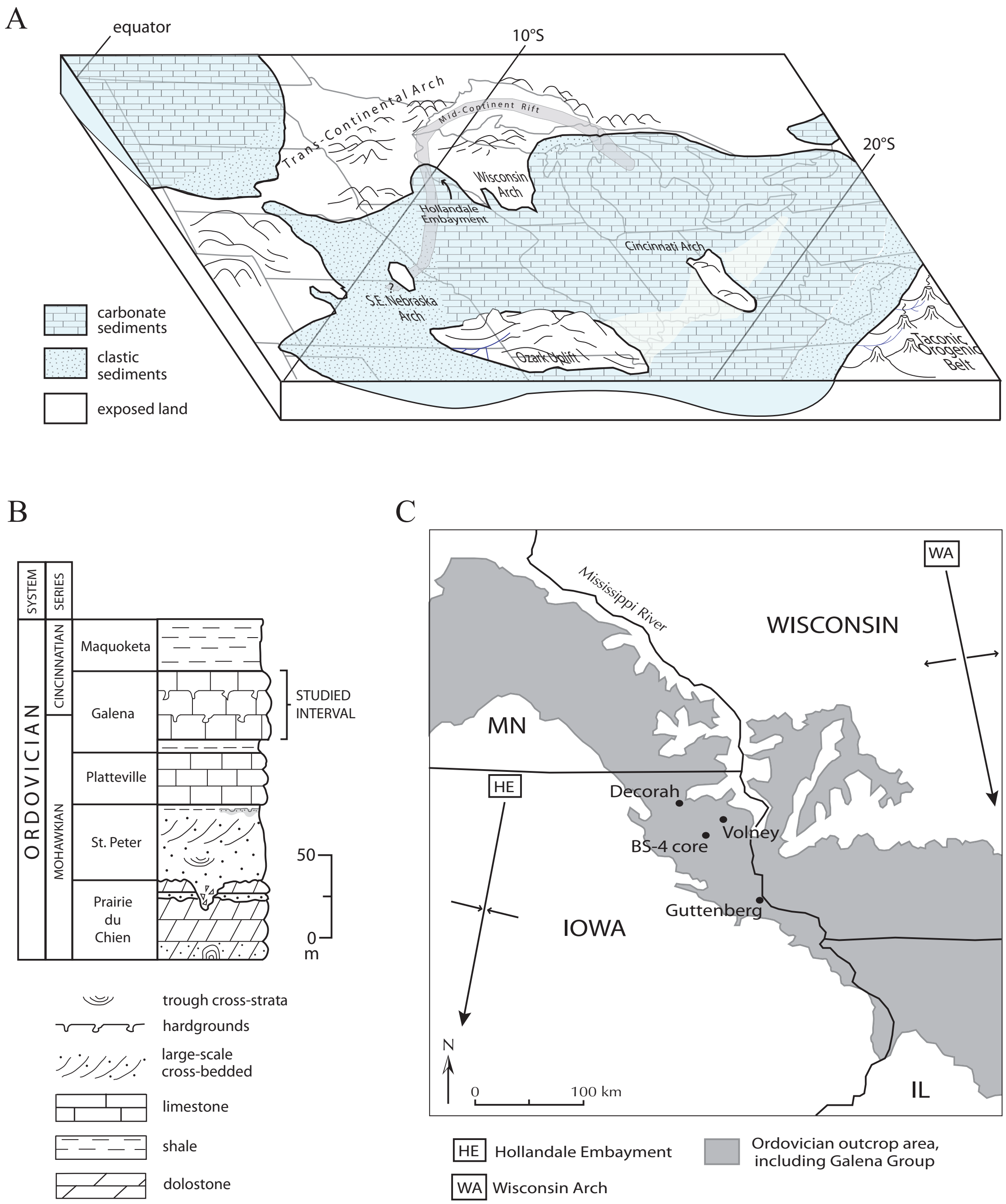


Figure 1. A. *Paleogeographic reconstruction of the north-central United States during the Middle to Late Ordovician. The Galena Group, the focus of this study, was deposited in the Hollandale Embayment, an early Paleozoic depocenter. The Hollandale Embayment was part of a larger epeiric sea that covered 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.

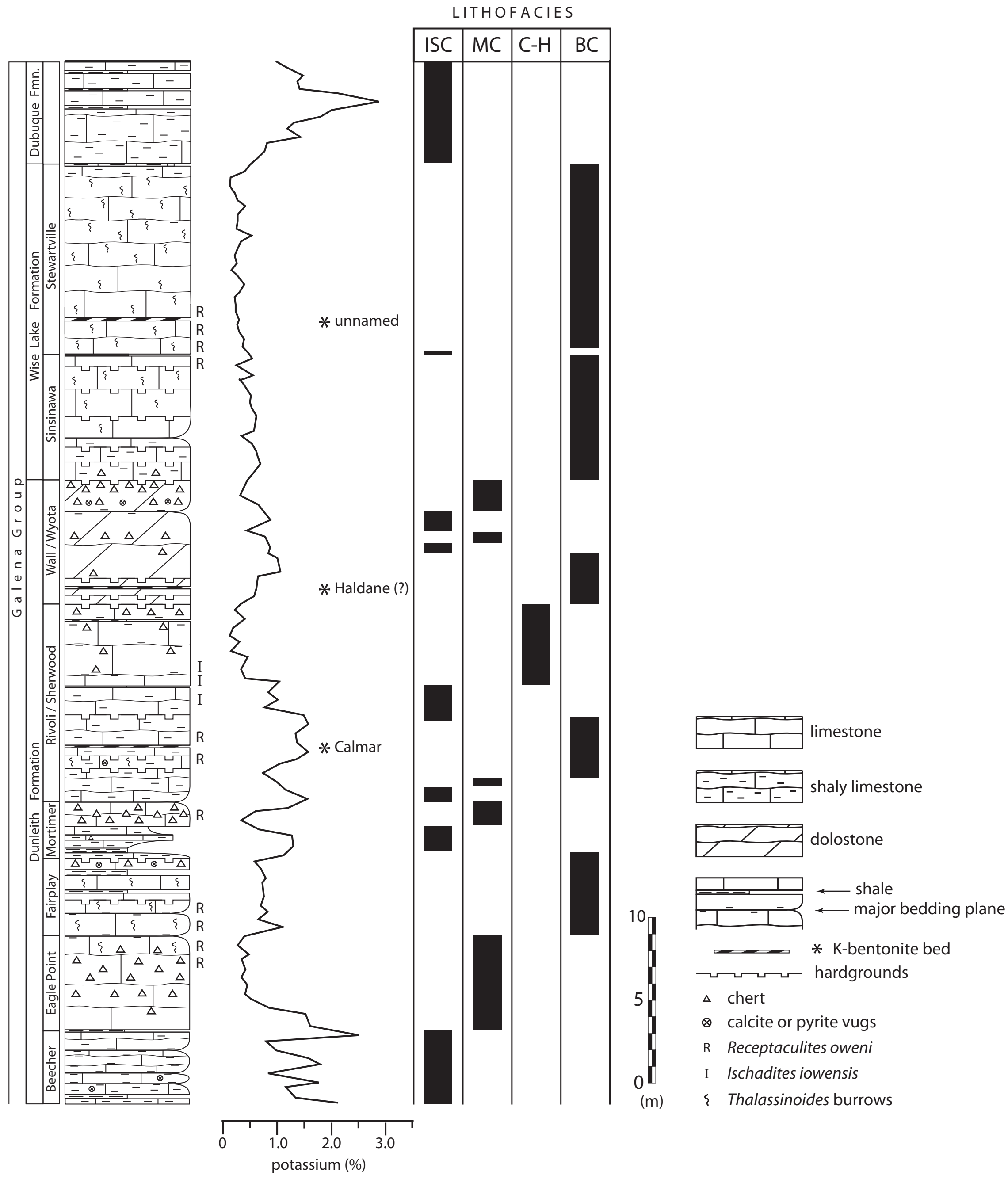


Figure 2. *Composite stratigraphic column for the Galena Group studied near Decorah, Iowa, with potassium gamma ray curve and distribution of facies groups within the Galena Group. Potassium gamma ray curve is a proxy for shale content. ISC = interbedded carbonate-shale; MC = massive carbonate; C-H =*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

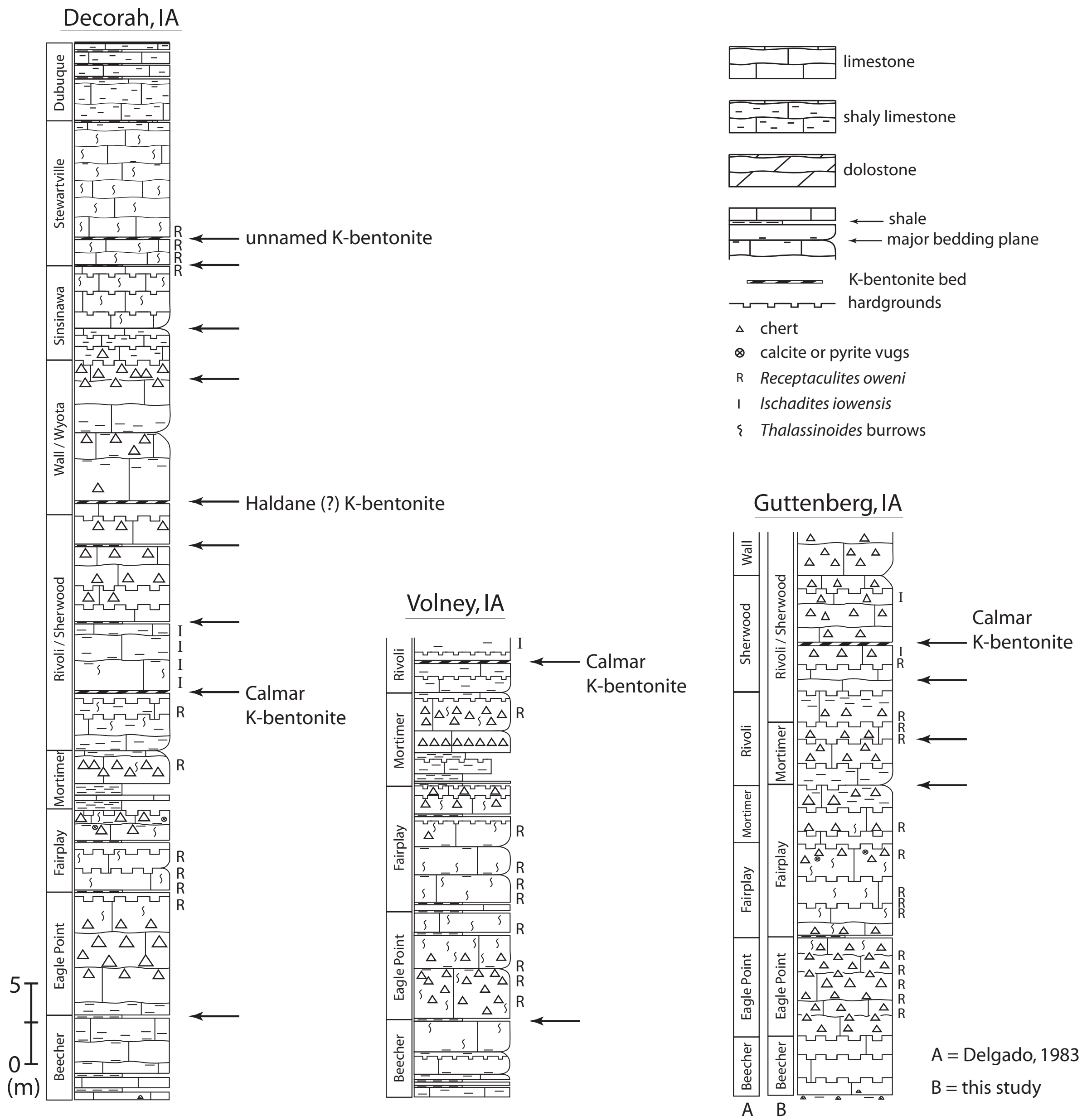


Figure 3. *Stratigraphic columns of sampled beds at Decorah, Volney, and Guttenberg, Iowa (indicated by arrows). Arrows point to K-bentonite beds (Calmar, Haldane (?), and unnamed); samples yielded abundant euhedral apatite and zircon phenocrysts. Unlabeled arrows indicate a detrital mineral assemblage 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.

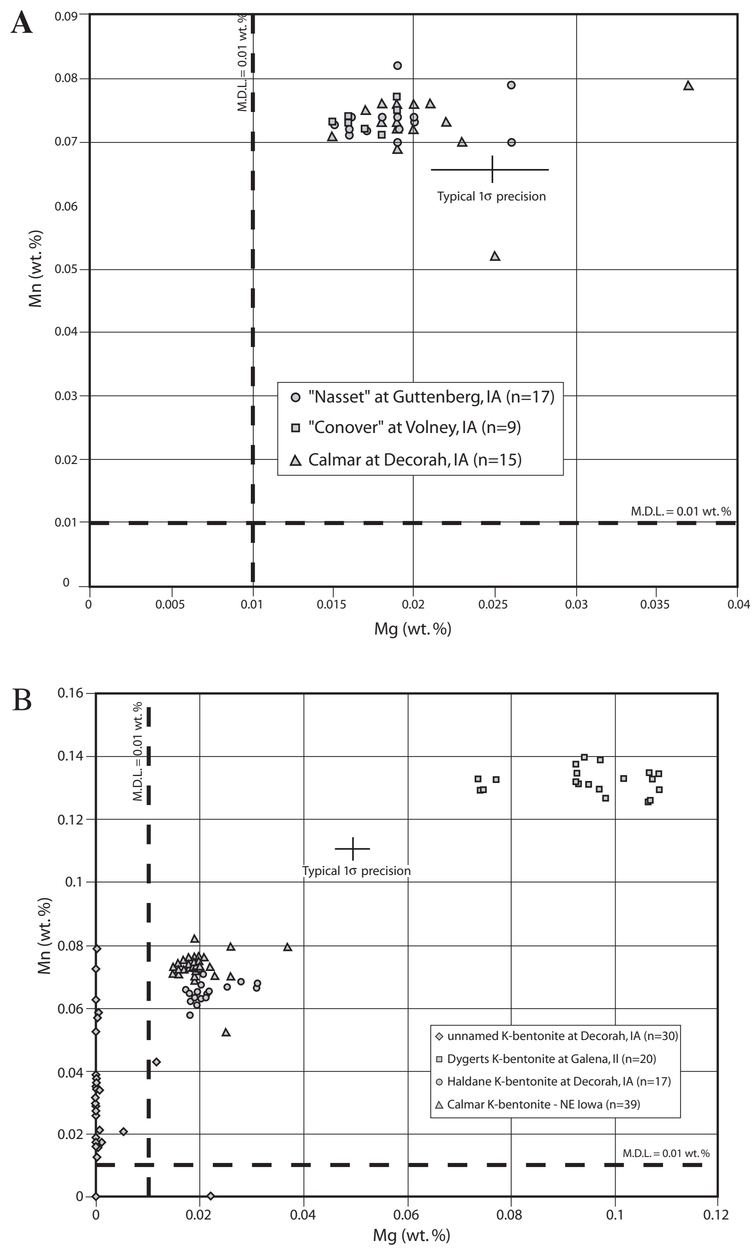


Figure 4. A. *Mg vs. Mn plot for apatite phenocrysts from the Calmar K-bentonite (Levorson and Gerk, 1983) at Decorah, Iowa (locality 5), the "Conover" K-bentonite (Levorson and Gerk, unpublished data, 1972) at Volney, Iowa (locality 12), and the "Nasset" K-bentonite (Delgado, 1983; Samson, 1986; Sloan 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

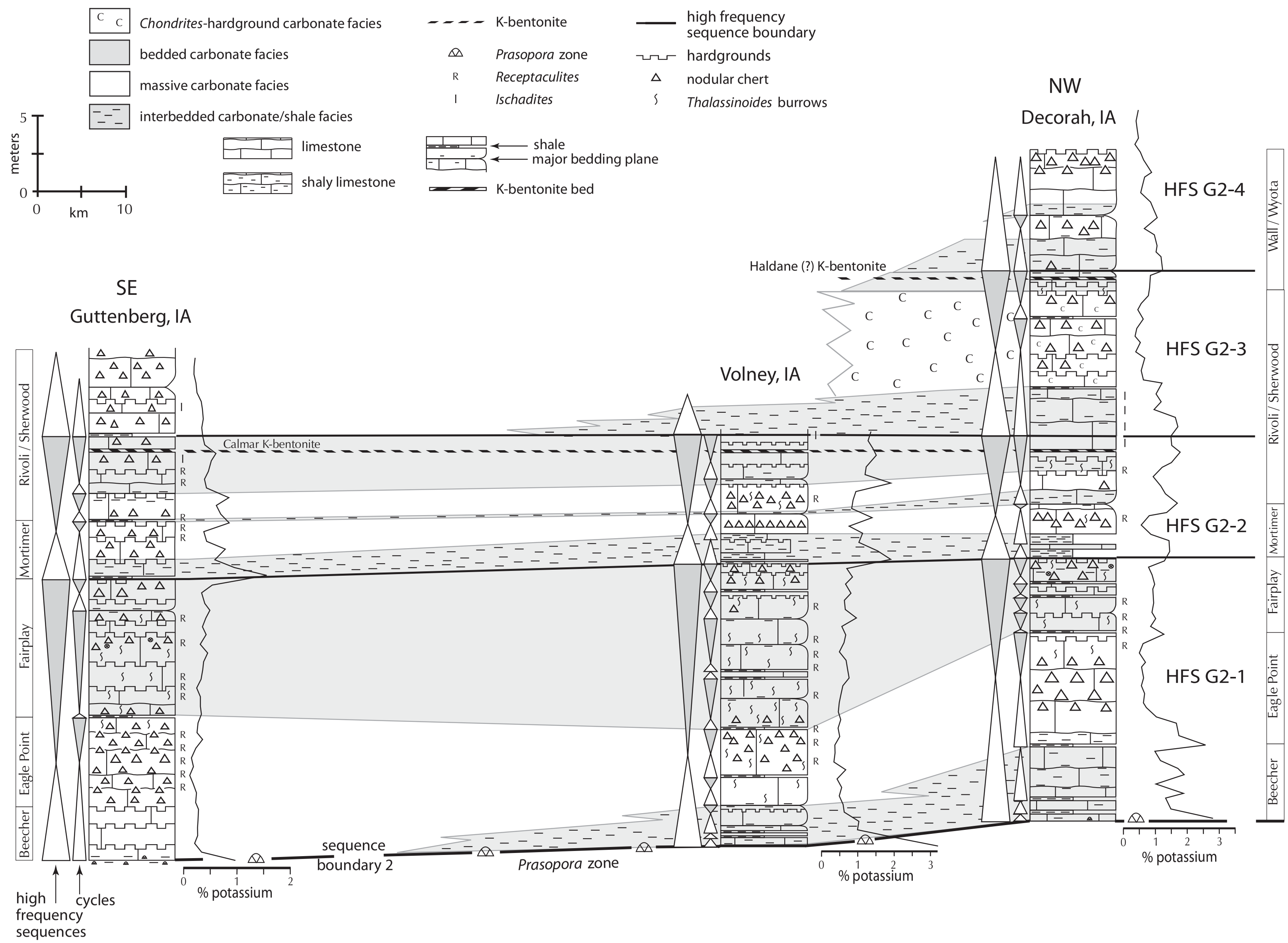


Figure 5. *Cross section for the Galena Group studied. (See fig. 1 for study locations.) Datum is the Calmar K-bentonite. Shaded triangles = regressive hemicycles.*

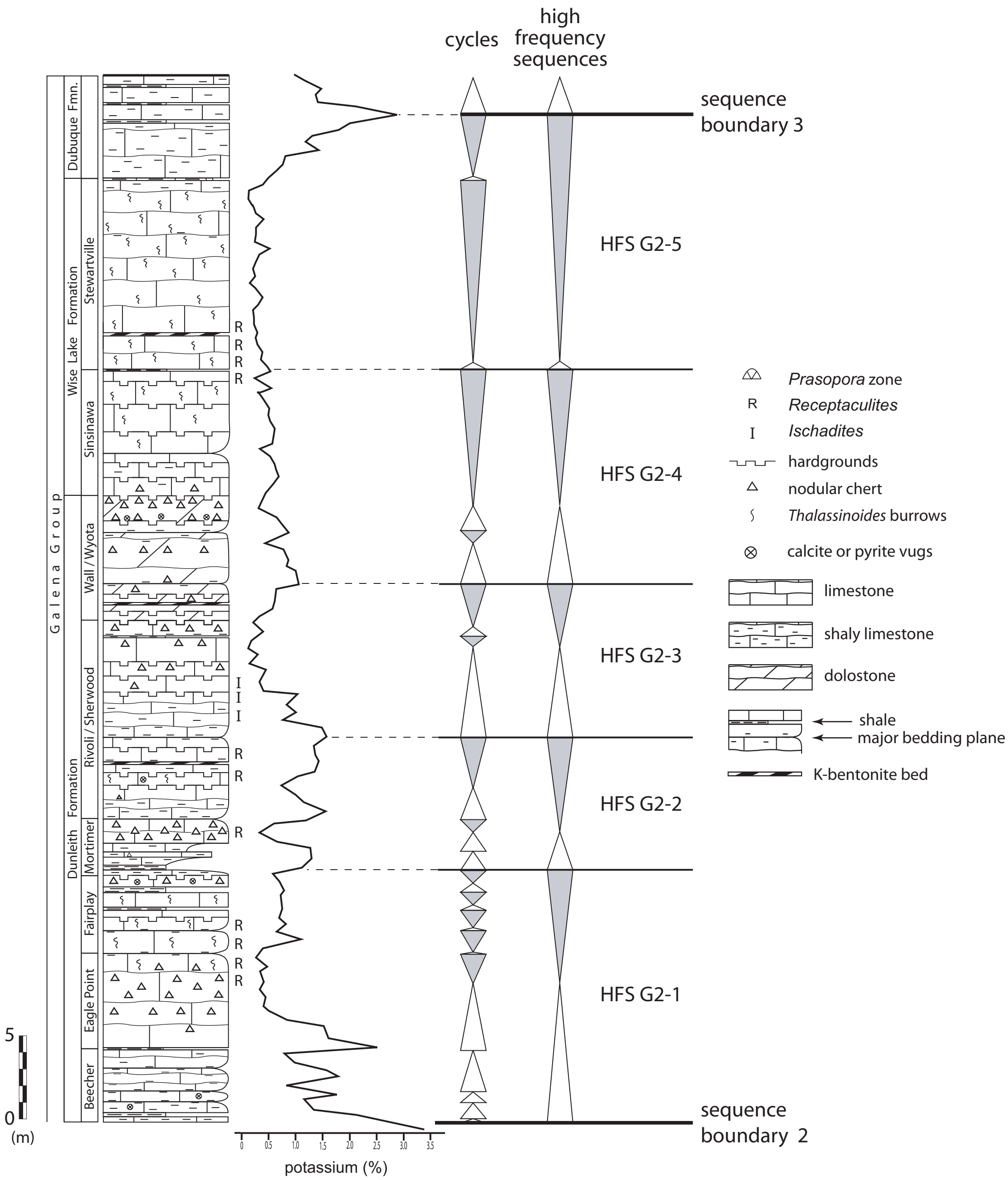


Figure 6. *Composite stratigraphic column with high frequency sequences. We interpreted the Galena Group to form one composite sequence that is bounded by a lower sequence boundary and an upper sequence boundary. The composite sequence contains a nested hierarchy of higher-ordered high frequency sequences 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

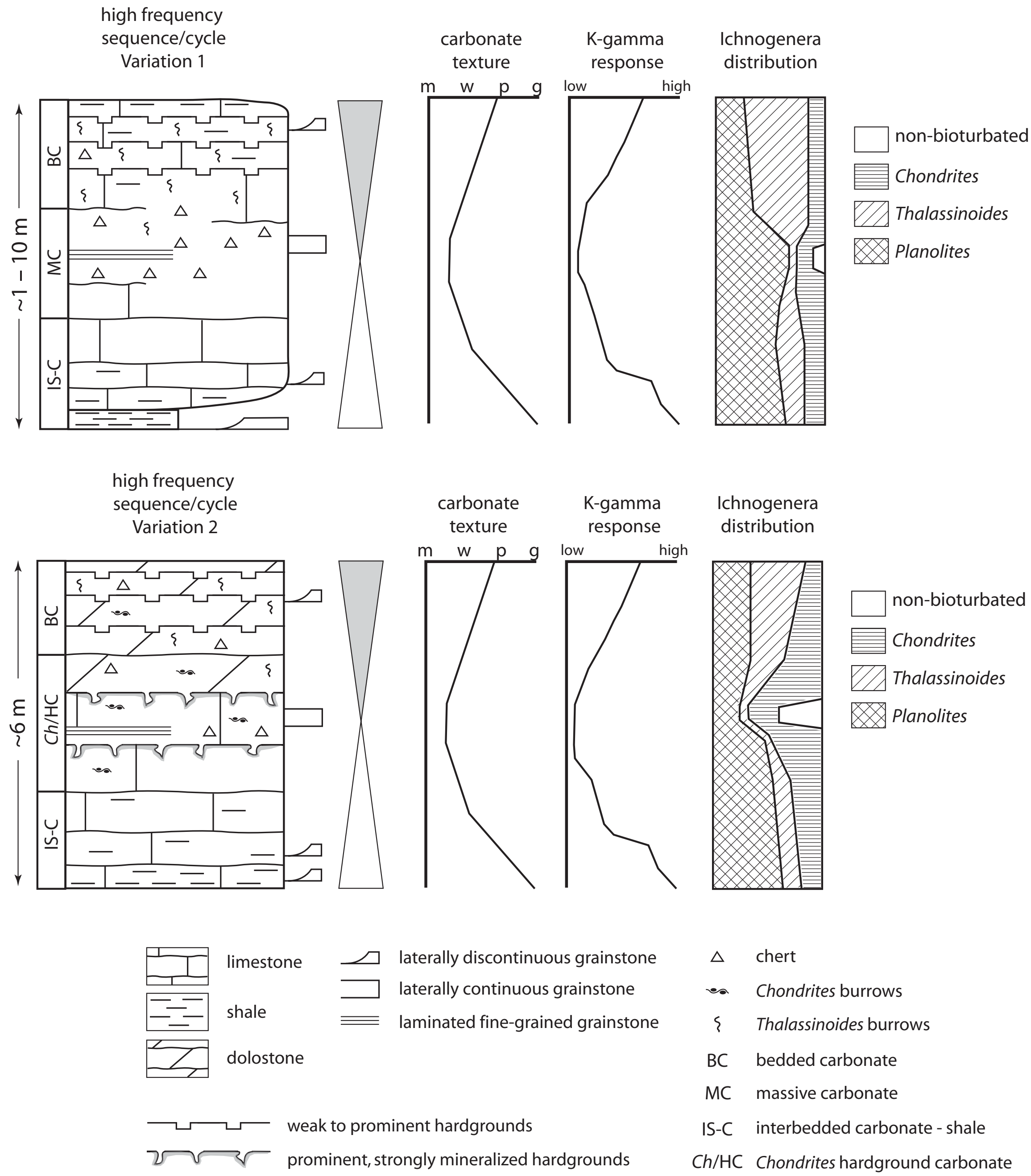


Figure 7. *Vertical trends in lithology, carbonate texture, K-gamma ray response, and ichnogenera distribution for the Galena Group studied; m = mudstone/micrite; w = wackestone; p = packstone; g = grainstone; shaded triangles = regressive hemicycles.*

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

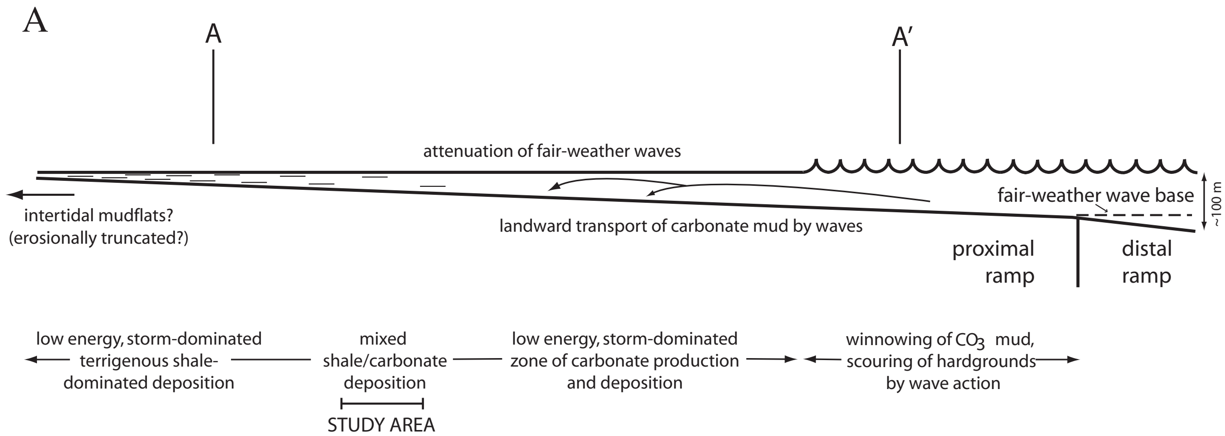
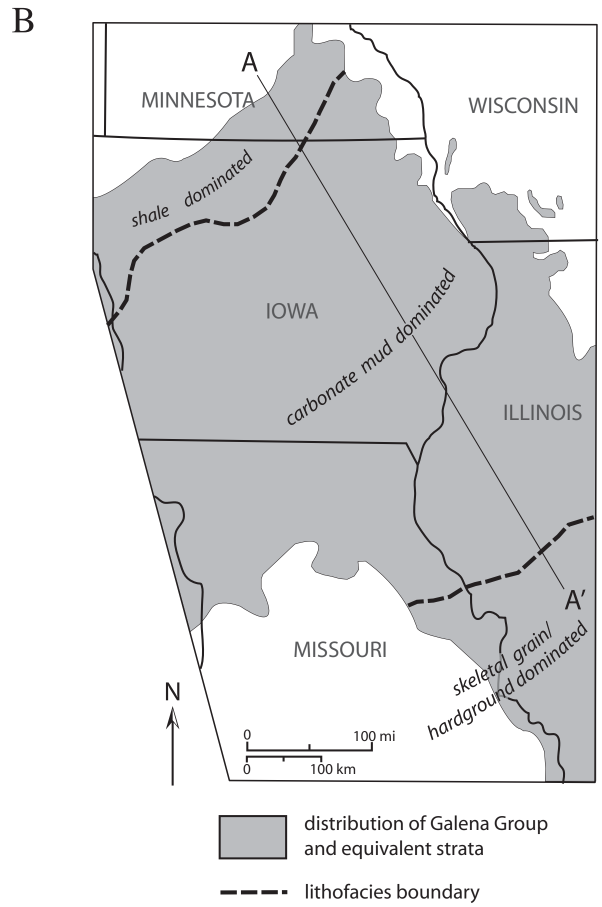


Figure 8. A. *Cross section showing epeiric ramp depositional model proposed for the Galena Group, with study area indicated. Modified from Lukasik and others (2000).* **B.** *Distribution of broadly defined facies belts of the Galena Group and equivalent strata in the Upper and Middle Mississippi Valley,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

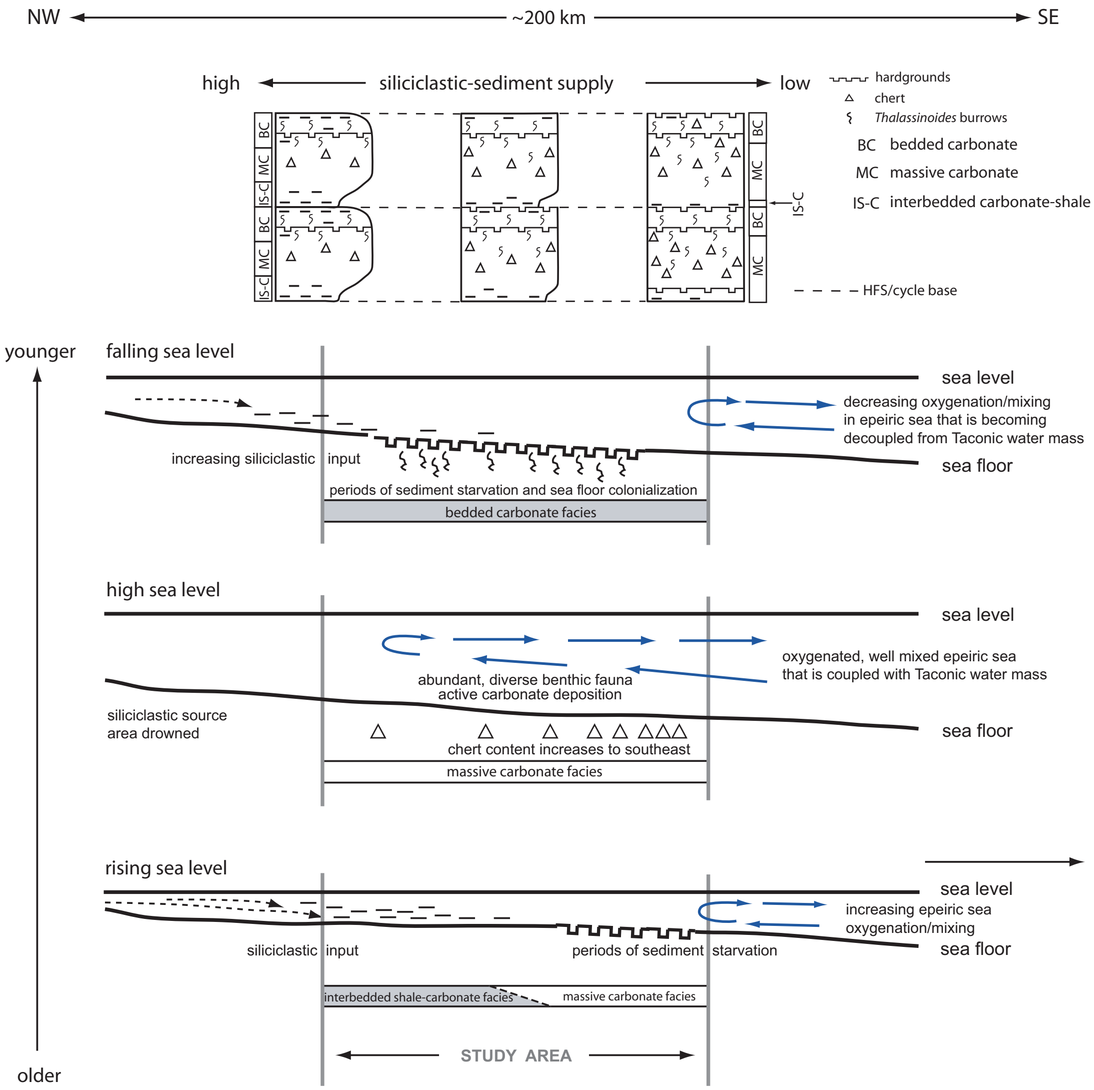


Figure 9. *Interpretation of sedimentological controls during deposition of high frequency sequences defined in this study. Columns represent the effect of siliciclastic sediment supply on Galena Group lithology, facies stacking, and outcrop expression from northwest to southeast.*

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.

ACKNOWLEDGMENTS

We acknowledge John Fournelle for microprobe analysis and thank Norlene Emerson, Lauren Chetel, and Jarad Schmitt for insightful discussion and field assistance. Financial support was provided by the Department of Geology and Geophysics, University of Wisconsin–Madison. We thank Dennis R. Kolata, John Mossler, and Bruce A. Brown for their helpful reviews of the manuscript. S.R. Beyer is grateful to C.W. Byers and J.A. Simo for supervision during his M.Sc. research of this project.

REFERENCES

Allen, V.T., 1929, Altered tuffs in the Ordovician of Minnesota: *Journal of Geology,* v. 37, p. 239–248.

Allen, V.T., 1932, Ordovician altered volcanic material in Iowa, Wisconsin, and Missouri: *Journal of Geology,* v. 40, p. 259–269.

Beyer, S.R., 2003, Stratigraphy, sedimentology, and K-bentonite geochemistry of the Galena Group, northeastern Iowa, Upper Mississippi Valley: Madison, University of Wisconsin, M.S. thesis, 304 p.

Byers, C.W., and Dott, Jr., R.H., 1995, Sedimentology and depositional sequences of the Jordan Formation (Upper Cambrian), northern Mississippi Valley: *Journal of Sedimentary Research,* v. B65, p. 289–305.

Calvin, Samuel, 1906, Geology of Winneshiek County: Iowa Geological Survey, v. 16, p. 37–146.

Chetel, L.M., 2004, $^{40}Ar/^{39}Ar$ geochronology of detrital and volcanic K-feldspar of the Upper Mississippi Valley: Implications for terrigenous provenance and the depositional and biostratigraphic history of an upper Ordovician epeiric sea: Madison, University of Wisconsin, M.S. thesis, 490 p.

Chetel, L.M., Simo, J.A., and Singer, B.S., 2005, $^{40}Ar/^{39}Ar$ geochronology and provenance of detrital K-feldspars, Ordovician, Upper Mississippi Valley: *Sedimentary Geology,* v. 182, p. 163–181.

Choi, Y.S., 1995, Stratigraphy and sedimentology of the Middle Ordovician Sinnipee Group, eastern Wisconsin: Madison, University of Wisconsin, M.S. thesis, 299 p.

Choi, Y.S., 1998, Sequence stratigraphy and sedimentology of the Middle to Upper Ordovician Ancell and Sinnipee Groups, Wisconsin: Madison, University of Wisconsin, Ph.D. thesis, 284 p.

Choi, Y.S., Simo, J.A., and Saylor, B.Z., 1999, Sedimentologic and sequence stratigraphic interpretation of a mixed carbonate-siliciclastic ramp, mid-continent epeiric sea, Middle to Upper Ordovician Decorah and Galena Formations, Wisconsin, *in* Harris, P.M., Saller, A.H., and Simo, J.A. eds., Advances in Carbonate Sequence Stratigraphy: Application to Reservoirs, Outcrops, and Models: SEPM Special Publication No. 63, p. 275–289.

Delgado, D.J., 1983, Deposition and diagenesis of the Galena Group in the Upper Mississippi Valley, *in* Delgado, D.J., ed., Ordovician Galena Group of the Upper Mississippi Valley—Deposition, diagenesis, and paleoecology: Guidebook for the 13th Annual Field Conference, Great Lakes Section SEPM, p. A1–A17.

Emerson, N.R., 2002, Sedimentology, sequence stratigraphy, and brachiopod biostratigraphy of the Ordovician (Mohawkian) Decorah Formation, Midcontinent, USA: Madison, University of Wisconsin, Ph.D. thesis, 490 p.

Hall, James, 1851, Lower Silurian System; Upper Silurian and Devonian Series, *in* Foster, J.W., and Whitney, J.D., eds., Report on the geology of the Lake Superior land district, pt. 2: U.S. 32nd Congress Special Session, Senate Executive Document 4, p. 140–166; *American Journal of Science,* 2nd series, v. 17, p. 181–194.

Irwin, M.L., 1965, General theory of epeiric clear water sedimentation: *AAPG Bulletin,* v. 49, p. 445–459.

Kay, G.M., 1935, Ordovician System in the Upper Mississippi Valley, *in* Kansas Geological Society 9th Annual Field Conference Guidebook, p. 281–295.

Kerans, C., and Tinker, S.W., 1997, Sequence stratigraphy and characterization of carbonate reservoirs: Tulsa, Society for Sedimentary Geology Short Course 40, 130 p.

Kolata, D.R., Huff, W.D., and Bergström, S.M., 1996, Ordovician K-bentonites of eastern North America: Geological Society of America Special Paper 313, 84 p.

Korpel, J.A., 1983, Depositional and diagenetic history of the middle/upper Ordovician Dunleith Formation in northeastern Iowa: Iowa City, University of Iowa, M.S. thesis, 91 p.

Leslie, E.R., 2002, Chemical fingerprinting, ^{40}Ar/^{39}Ar dating and diagenetic alteration of Ordovician K-bentonites, Upper Mississippi Valley: Madison, University of Wisconsin, M.S. thesis, 68 p.

Levorson, C.O., and Gerk, A.J., 1972a, A preliminary stratigraphic study of the Galena Group of Winneshiek County, Iowa: Iowa Academy of Science Proceedings, v. 79, no. 3–4, p. 111–122.

Levorson, C.O., and Gerk, A.J., 1972b, Revision of Galena stratigraphy: Geological Society of Iowa Field Trip Guidebook 25, 15p.

Levorson, C.O., and Gerk, A.J., 1975, Field recognition of subdivision of the Galena Group within Winneshiek County: Field Trip Guide for the Iowa, Minnesota, and Wisconsin Academies of Science, 17 p.

Levorson, C.O., and Gerk, A.J., 1983, Field recognition of stratigraphic position within the Galena Group of northeastern Iowa (limestone facies), *in* Delgado, D.J., ed., Ordovician Galena Group of the Upper Mississippi Valley—Deposition, diagenesis, and paleoecology, Guidebook for the 13th Annual Field Conference, Great Lakes SEPM, p. C1–C11.

Lukasik, J.J., and James, N.P., 2003, Deepening-upward subtidal cycles, Murray Basin, South Australia: *Journal of Sedimentary Research,* v. 73, no. 5, p. 653–671.

Lukasik, J.J., James, N.P., McGowran, B., and Bone, Y., 2000, An epeiric ramp: Low-energy, cool-water carbonate facies in a Tertiary inland sea, Murray Basin, South Australia: *Sedimentology,* v. 47, p. 851–881.

Mange, M.A., and Maurer, H.F.W., *Heavy Minerals in Colour:* New York: Chapman and Hall, 1992.

Mossler, J.H., and Hayes, J.B., 1966, Ordovician bentonites of Iowa: *Journal of Sedimentary Petrology,* v. 36, p. 414–427.

Raatz, W.D., and Ludvigson, G.A., 1996, Depositional environments and sequence stratigraphy of Upper Ordovician epicontinental deep water deposits, eastern Iowa and southern Minnesota, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, p. 307–330.

Samson, S.D., 1986, Chemistry, mineralogy, and correlation of Ordovician bentonites: Minneapolis, University of Minnesota, M.S. thesis, 128 p.

Samson, S.D., Kyle, P.R., and Alexander Jr., E.C., 1988, Correlation of North American Ordovician bentonites by using apatite chemistry: *Geology,* v.16, p. 444–447.

Sardeson, F.W., 1924, Volcanic ash in Ordovicic rocks of Minnesota: *Pan-American Geologist,* v. 42, no. 1, p. 45–52.

Schlager, W., 1999, Type 3 sequence boundaries, *in* Harris, P.M., Saller, A.H., and Simo, J.A. eds., Advances in carbonate sequence stratigraphy: Application to reservoirs, outcrops, and models: SEPM Special Publication No. 63, p. 35–45.

Shaw, G.H., 2003, Trace element chemistry of individual apatite phenocrysts as a tool for fingerprinting altered volcanic ash beds: Assessing interbed and intrabed variation at local and regional scales: *Geological Society of America Bulletin,* v. 115, no. 8, p. 933 – 942.

Simo, J.A., Emerson, N.R., Byers, C.W., and Ludvigson, G.A., 2003, Anatomy of an embayment in an Ordovician epeiric sea, Upper Mississippi Valley, USA: *Geology,* v. 31, no. 6, p. 545–548.

Sloan, R.E., Kolata, D.R., Witzke, B.J., and Ludvigson, G.A., 1987, Description of major outcrops in Minnesota and Iowa, *in* Sloan, R.E., ed., Middle and Late Ordovician Lithostratigraphy and biostratigraphy of the Upper Mississippi Valley: Minnesota Geological Survey Report of Investigations 35, p. 197–223.

Templeton, J.S., and Willman, H.B., 1963, Champlainian Series (Middle Ordovician) in Illinois: Illinois State Geological Survey Bulletin 89, 260 p.

Thompson, T.L., 1991, Paleozoic succession in Missouri, part 2: Ordovician system: Missouri Department of Natural Resources, Division of Geology and Land Survey Report of Investigations 70, 282 p.

Ulrich, E.O., 1911, Revision of the Paleozoic systems: *Geological Society of America Bulletin,* v. 22, p. 281–680.

Willman, H.B., and Kolata, D.R., 1978, The Platteville and Galena Groups in northern Illinois: Illinois State Geological Survey Bulletin 502, 75 p.

Witzke, B.J., 1980, Middle and Upper Ordovician paleogeography of the region bordering the Transcontinental Arch, *in* Fouch, T.D., and Magathan, E.R., eds., Paleozoic paleogeography of west-central United States: West-Central United States Paleogeography Symposium 1: Society of Economic Paleontologists and Mineralogists, p. 1–18.

Witzke, B.J., and Bunker, B.J., 1996, Relative sea-level changes during Middle Ordovician through Mississippian deposition in the Iowa area, North American craton, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic sequence stratigraphy: Views from the North American craton: Geological Society of America Special Paper 306, p. 307–330.

Witzke, B.J. and Ludvigson, G.A., 2005, The Ordovician Galena Group in Iowa and its regional stratigraphic relationships, *in* Ludvigson, G.A., and Bunker, B.J., eds., Facets of the Ordovician geology of the Upper Mississippi Valley region: Iowa Geological Survey Guidebook Series 24, p. 3–21.

Witzke, B.J., and Kolata, D.R., 1988, Changing structural and depositional patterns, Ordovician Champlainian and Cincinnatian series of Iowa–Illinois, *in* Ludvigson, G.A., and Bunker, B.J., eds., New perspectives on the Paleozoic history of the Upper Mississippi Valley: Iowa Department of Natural Resources, Geological Survey Bureau Guidebook 8, p. 55–77.

Wright, V.P., and Burchette, T.P., 1998, Carbonate ramps: An introduction, *in* Wright, V.P., and Burchette, T.P., eds., *Carbonate Ramps:* Geological Society, London, Special Publications 149, p. 437–456.

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

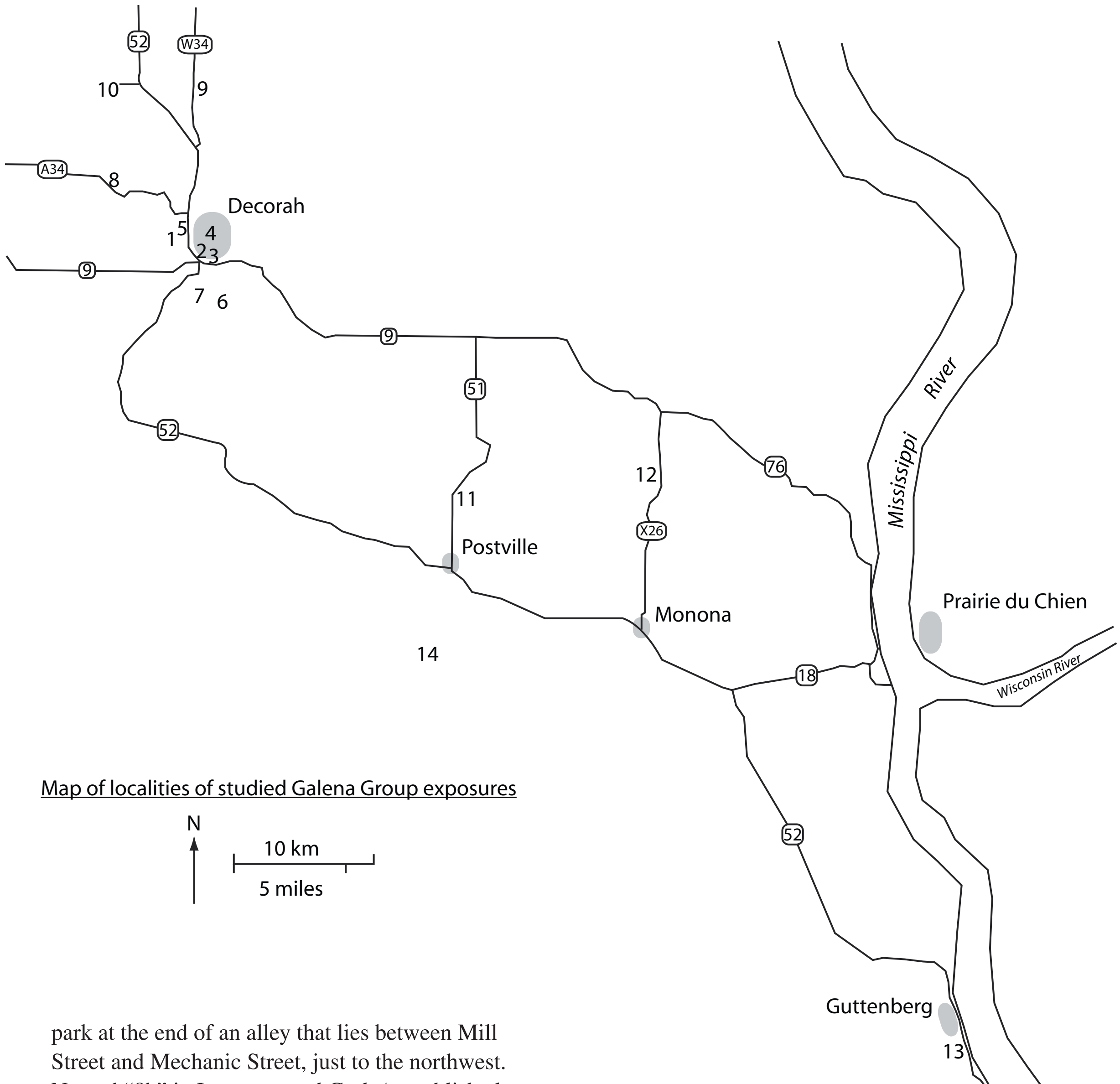
- West side of Highway 52, approximately 0.5 km (0.3 mi) north of intersection with Highway 9, Decorah, Winneshiek County, Iowa.
- Fairplay Member: 4.1 m; Mortimer Member: 2.0 m; Rivoli–Sherwood Members: 4.8 m.
- UTM: NAD 83/15N/ 596649E/ 4794311N.

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.

Published by and available from

Wisconsin Geological and Natural History Survey
3817 Mineral Point Road • Madison, Wisconsin 53705-5100
☎ 608/263.7389 FAX 608/262.8086 www.uwex.edu/wgnhs/

James M. Robertson, *Director and State Geologist*

ISSN: 0164-2049

This report is an interpretation of the data available at the time of preparation. Every reasonable effort has been made to ensure that this interpretation conforms to sound scientific principles; however, the report should not be used to guide site-specific decisions without verification. Proper use of this publication is the sole responsibility of the user.

The use of company names in this document does not imply endorsement by the Wisconsin Geological and Natural History Survey.

Issued in furtherance of Cooperative Extension work, Acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture, University of Wisconsin–Extension, Cooperative Extension. University of Wisconsin–Extension provides equal opportunities in employment and programming, including Title IX and ADA requirements. If you need this information in an alternative format, contact the Office of Equal Opportunity and Diversity Programs or the Wisconsin Geological and Natural History Survey (☎ 608/262.1705).

Mission of the Wisconsin Geological and Natural History Survey

The Survey conducts earth-science surveys, field studies, and research. We provide objective scientific information about the geology, mineral resources, water resources, soil, and biology of Wisconsin. We collect, interpret, disseminate, and archive natural resource information. We communicate the results of our activities through publications, technical talks, and responses to inquiries from the public. These activities support informed decision-making by government, industry, business, and individual citizens of Wisconsin.