Anatomy of an embayment in an Ordovician epeiric sea, Upper Mississippi Valley, USA

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ABSTRACT

The integration of stratigraphic, geochemical, and biostratigraphic data from Middle Ordovician carbonates and shales indicates that the North American epeiric sea was partitioned into shelf areas with distinct characteristics. The Upper Mississippi Valley part of the epeiric sea was appraised by using regionally traceable and geochemically "fingerprinted" K-bentonites, as well as detailed lithologic correlation. In the Midcontinent, the Decorah Formation records a time of high clastic sediment influx and abundant freshwater runoff from the Transcontinental Arch that created a salinity-stratified water column and led to episodic dysoxia. Later, relative flooding of the clastic source areas greatly reduced both the clastic sediment and freshwater runoff. As a result, the salinity stratification broke down, oxygenating the seafloor and permitting carbonates to form. Associated with this change, clarity of the water improved and the photic zone expanded, allowing seasonal blooms of *Gloeocapsomorpha prisca* to occur, resulting in increased burial of organic matter. The increase in *G. prisca* and total organic carbon coincided with, but lagged behind, a regional δ^{13}C excursion. In addition, the timing of the initiation of the isotopic anomaly is different across the studied area, suggesting that local environmental conditions influenced the isotopic record. Data presented in this study support the partitioning of distinct areas within epeiric seas and the importance of this setting in storing inorganic and organic carbon and recording environmental and biological changes.

Keywords: epeiric sea, Midcontinent, Ordovician, Decorah Formation, depositional environments.

INTRODUCTION

The Ordovician of the North American Midcontinent epeiric sea has been viewed traditionally as layer-cake stratigraphy with remarkably homogeneous and continuous stratigraphic units (Templeton and Willman, 1963; Willman and Kolata, 1978). These stratigraphic units are dominated by carbonate rocks with small amounts of shale. Recent work indicates that deposition on cratonic epeiric seas was complex; subtle changes in topography, sea level, and hydrology had profound impacts on the oceanography and resulting ocean-water chemistry, lithology, and biota.

In this paper we reevaluate the Middle Ordovician stratigraphy of the northern Midcontinent on the basis of a new K-bentonite correlation within the Hollandale Embayment (Fig. 1). We also provide a comprehensive depositional model in which inherited topography and runoff budget play important roles in the depositional history, and we review data supporting a complex oceanographic setting within the Midcontinent epeiric sea.

GEOLOGIC AND STRATIGRAPHIC SETTING

During the Middle and Late Ordovician, the North American craton was subjected to one of the largest marine floodings in Phanerozoic history (Witzke, 1980). The Middle Ordovician stratigraphy (Fig. 1) starts with a karst unconformity overlain by the St. Peter Sandstone. A shift to carbonates occurred with the deposition of the Platteville Formation. The overlying Decorah Formation is a mixed shale-carbonate unit, whereas younger formations (Dunleith, Wise Lake, and Dubuque) are composed of thin-bedded carbonates with hardgrounds and no shale. The youngest Ordovician is the Maquoketa Shale. Fossils and structures within these packages indicate normal-marine environments below wave base.

We focus our work on the Decorah Formation, a mixed carbonate-shale depositional sequence, which reflects the interplay between continental flooding and weathering of exposed land. The Decorah Formation is bounded below and above by sequence boundaries (Witzke and Bunker, 1996). The lower surface is an angular discordance, and the upper is marked by a key bed (*Prasopora epibole*) that separates two different lithologies and two brachiopod communities. Brachiopods (32 species) are very common, and 6000 specimens were collected and identified. A composite species range chart (FADs, first appearance datums; LADs, last appearance datums) shows that most species had their FADs and LADs confined within the upper and lower boundaries of the Decorah and did not have ranges that crossed formation boundaries (Emerson, 2002). FADs and LADs and multivariate *Q*-mode cluster analyses show two major brachiopod clusters reflecting shale-rich versus carbonate-rich lithologies and indicate a close link between environment and fauna.

K-BENTONITE CORRELATION

Four K-bentonite layers (Willman and Kolata, 1978) within the Decorah Formation (Fig. 1) were identified and correlated on the basis of primary apatite phenocryst chemistry contained within the altered ash. Figure 2 shows Mg versus Mn (wt%) values that separate the different K-bentonite apatite phenocrysts into four clusters. Comparison of grain analyses from various localities indicates that apatite Mg and Mn values for a single K-bentonite remain within the same cluster and do not show geographic variations, although values from a single crystal may overlap with other fields.

SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY

The integration of the K-bentonite and lithologic correlations allows for the subdivision of the Decorah sequence into two wedges, a lower shale and an upper carbonate. This correlation (Fig. 3) is different from previous interpretations in which shales and carbonates interfinger (Ludvigson et al., 1996). Our reconstruction implies that the majority of the Decorah shale in Minnesota is older than the majority of the Decorah carbonates in Iowa and Wisconsin (Fig. 3). The lower shale facies of the Decorah occurs primarily within the Hollandale Embayment and thins against the Wisconsin Dome. The overlying Decorah car-

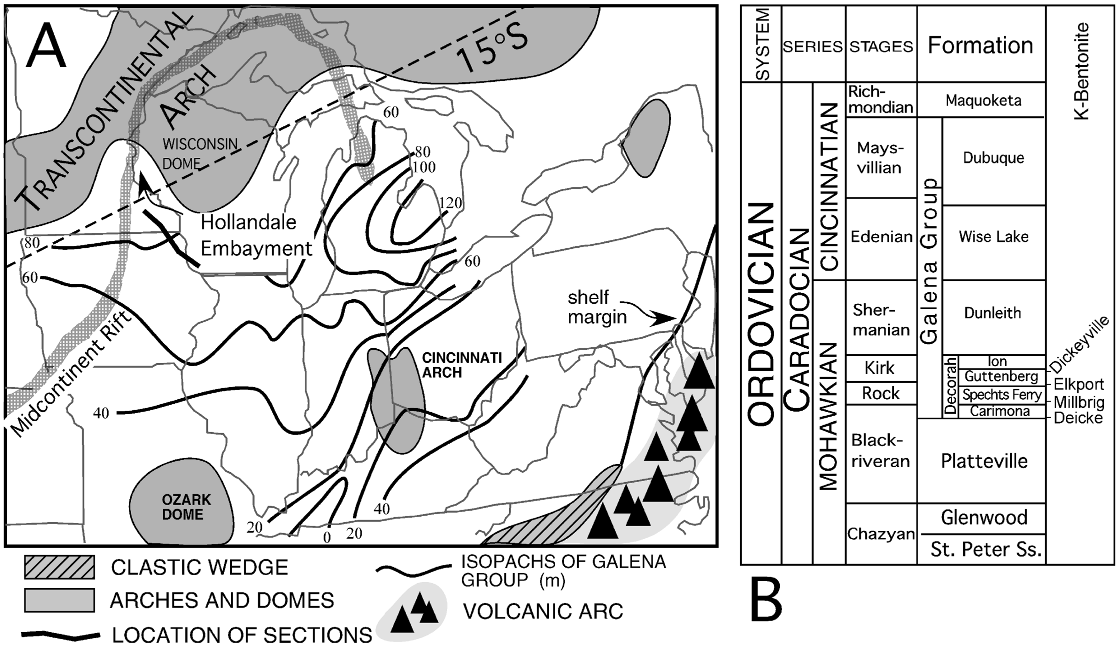

Figure 1. A: Geologic setting for Midcontinent and eastern United States. Position of lat 15°S during Ordovician is shown. Note position of Hollandale Embayment, tectonic depression, between Transcontinental Arch and Wisconsin Dome (Bunker et al., 1988). Generalized isopachs of Galena Group follow Witzke and Kolata (1988) and Kolata et al. (2001). Thicknesses suggest two different basins and possibly water masses (Holmden et al., 1998). B: Chronostratigraphy following Templeton and Willman (1963). Kirk—Kirkfieldian, Rock—Rocklandian.

bonates extend farther upramp onto the Wisconsin Dome and become thinner, less grainy, and more shale rich to the NW.

The lower Decorah shale wedge consists of shale-rich cycles defined by fossil-poor, laminated, shale bases that grade upward into interbedded shales with carbonate mudstones and shell pavements containing a nearly monospecific assemblage of disarticulated, nonabraded brachiopod valves. *Chondrite* is the dominant trace fossil. The shales have a high gammacerane ratio and homohopane index (Pancost et al., 1998). These cycles are interpreted to represent deposition in an outer ramp below storm wave base. The bases of the shale cycles were deposited in dysoxic conditions; oxygenation appears to have increased upward, owing to water mixing and wave reworking.

The upper Decorah carbonate wedge consists of carbonate-rich cycles with fossil-rich, bioturbated, calcareous shale bases that grade upward into bioturbated packstones. These cycles are interpreted to have developed within the mid-ramp, where frequent storm waves reworked bottom sediment.

Cycles at the transition from the shale to the carbonate wedges have unique characteristics, suggesting that the lithologic change was accompanied by modification in the ocean chemistry, productivity, and biota. The uppermost shale-rich cycle contains an interval rich in phosphate (Fig. 3), suggesting a period of slow sedimentation. The lowermost cycle of the carbonate wedge has very high values of total organic carbon (TOC) and *Gloeocapsomorpha prisca*, and also records a δ^{13}C excursion (Fig. 4).

DECORAH ISOTOPIC RECORD

The δ^{13}C profiles of the Decorah Formation have been developed from numerous sites in Iowa and show a positive carbon isotope excursion that appears to be correlative to an excursion found elsewhere (Ainsaar et al., 1999; Ludvigson et al., 1996; Patzkowsky et al., 1997).

The Iowa bulk stable carbon isotope values show a positive δ^{13}C excursion of ~3‰. Within our high-resolution stratigraphic framework, it is possible to show that the timing and magnitude of the isotopic excursion changes across the studied area (Fig. 4). These sections also show an interruption in the excursion with more negative δ^{13}C values within the interval containing high concentrations of phosphate granules (Fig. 4) and interpreted to reflect an influx of phosphorus and ^{12}C-rich deep basinal waters (Brasier et al., 1990; Kump and Arthur, 1999).

In sections dominated by thick carbonates (Wisconsin Dome, Fig. 3), the positive excursion postdates the Millbrig K-bentonite and the phosphate-rich interval. The profile (Fig. 4) shows that low δ^{13}C values coincide with the phosphate-rich interval and that high δ^{13}C values peak near the transition between the shale and carbonate wedges, which is geographically and stratigraphically well constrained by the Elkport K-bentonite (Fig. 4). These sections also show high TOC (to 50%), organic carbon (~8‰), and concentrations of

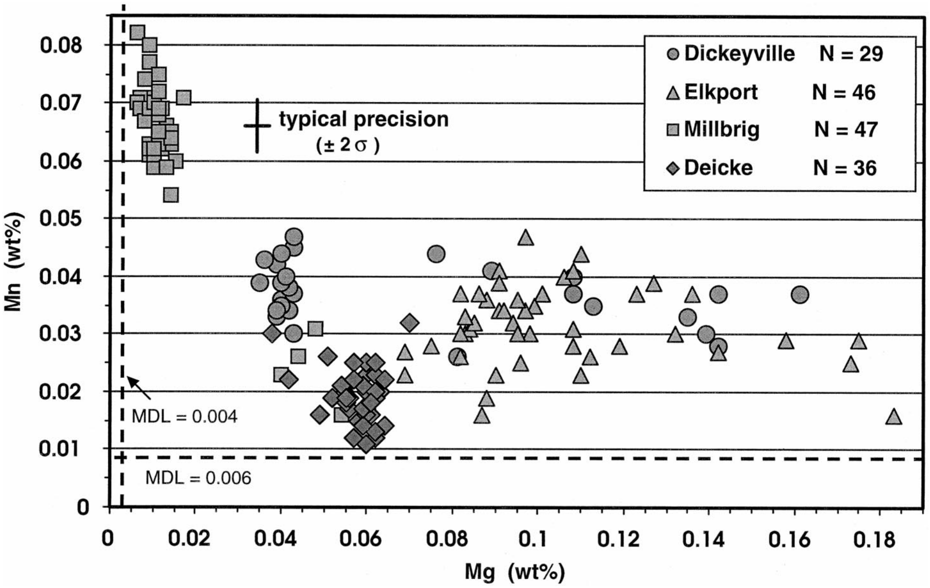

Figure 2. Plot of Mg vs. Mn (elemental wt%) of all apatite grains analyzed with electron microprobe. MDL—minimum detection limits. Each data point represents microprobe values averaged from 3 to 5 points taken from single grain. N—number of grains.

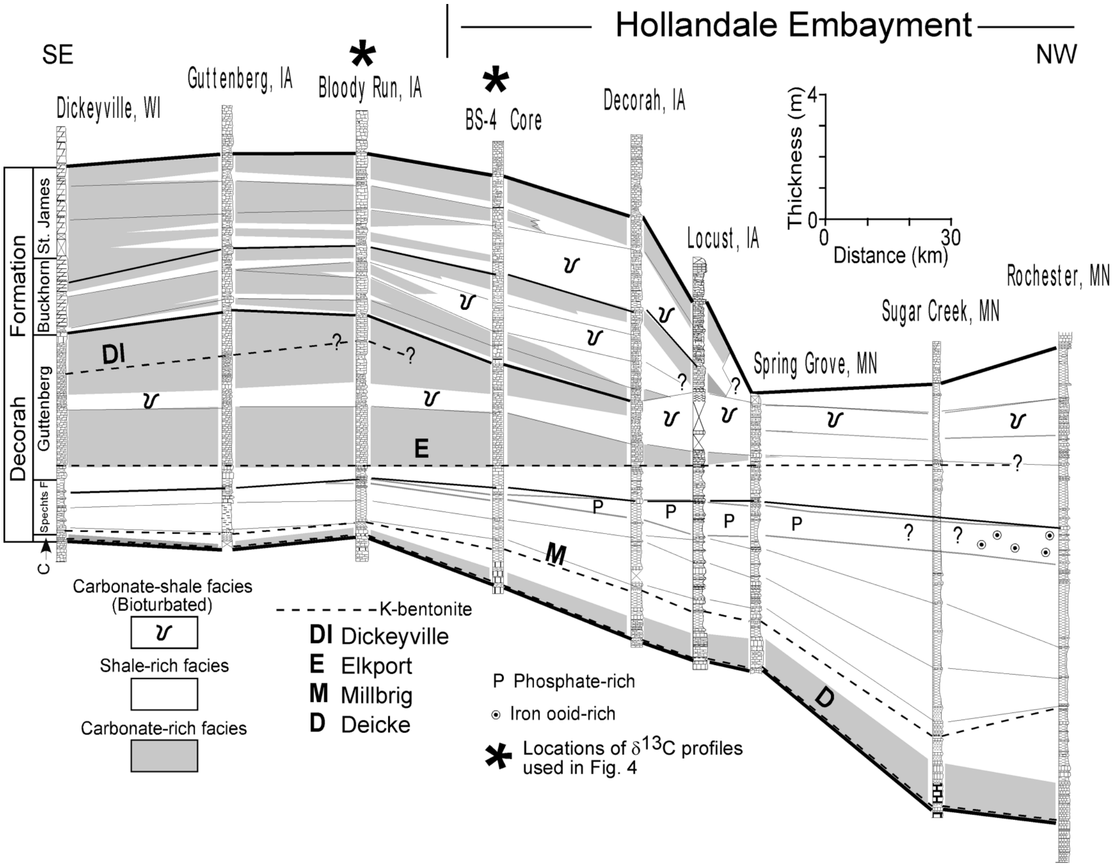

Figure 3. Cross section showing lithologic and K-bentonite correlation across research area. See Figure 1 for location. Diagram illustrates compensating relationship between lower shale-rich facies thinning to southeast, and upper carbonate-rich facies thinning to northwest. Elkport K-bentonite is datum. C—Carimona Member.

G. prisca (Pancost et al., 1998, 1999). However, these high values occur above the Elkport K-bentonite after the increase in, and in part overlapping with, the δ^{13}C excursion.

In contrast, the shale-rich sections deposited in the deeper-water Hollandale Embayment (Fig. 4) show an earlier δ^{13}C increase, between the Deicke and Millbrig K-bentonites, and the highest δ^{13}C values, near the Elkport K-bentonite. There is little or no presence of the brown shales that host the high *G. prisca* concentrations in these sections.

DECORAH DEPOSITIONAL MODEL

Deposition of the Decorah occurred in two stages. During the early stage, the Transcontinental Arch was exposed. Runoff from the land supplied clastic sediment that accumulated within the Hollandale Embayment. Our interpretation is that the freshwater runoff created a salinity-stratified water column. This stratification led to times of dysoxic conditions in the Hollandale Embayment. Organic productivity was restricted by the photic zone's shallow depth, which was due to the suspended clastic content.

At a later stage (soon after deposition of the Elkport K-bentonite), relative flooding of the Transcontinental Arch greatly diminished the supply of both clastic sediments and freshwater. The salinity stratification broke down, oxygenating the seafloor, permitting carbonates to form on the Wisconsin Dome and prograde into the Hollandale Embayment. Similarly, ^{143}Nd/^{144}Nd isotope ratios (Fanton et al., 2002) suggest high sea level and expansion of the Taconian water mass northward during deposition of the base of the Decorah's upper wedge.

We hypothesize that the improved water clarity expanded the photic zone and increased primary productivity, allowing for the anomalous organic content and increased *G. prisca* deposition. These oxic conditions on the seafloor coincided with the high organic carbon content and the positive carbon isotope spike recorded within the basal Guttenberg Member. The anomalous organic content cannot simply be the result of enhanced preservation; it must record an actual increase in phytoplankton productivity.

In the modern tropical ocean, the chlorophyll maximum (the maximum concentration of phytoplankton) is not at the surface where available light is greatest, but is tens of meters down in the water column. The plankton population is balanced between the zone of nutrient-poor water above and light-lacking water below. It is possible that *G. prisca* behaved like modern phytoplankton and was most concentrated at a deep chlorophyll maximum. The oceanographic changes that led to the switch from shale to carbonate deposition increased the penetration of light at depth and accelerated photosynthesis, allowing for *G. prisca* to thrive and increased burial of organic matter. Possibly a sea-level rise opened up new avenues for influx of nutrient-rich deep waters from the Taconian foreland basin into the cratonic interior (Fanton et al., 2002).

The environmental conditions in the Hollandale Embayment during the change from shale- to carbonate-dominated wedges appear to coincide with a craton-wide δ^{13}C excursion (Patzkowsky et al., 1997). However, the time lag between the TOC and *G. prisca* peaks and the excursion indicates that these two processes were independent (Fig. 4). Furthermore, the difference in initiation of the excursion across the study area (Fig. 4) suggests that local effects have influenced the timing and shape of the excursion. This offset has been recorded in many sections across Iowa and Wisconsin (Ludvigson et al., 2000). It is unclear whether the apparent delay was a result of sediment condensation, relatively low-resolution sampling, environmental conditions, or a combination thereof. We think that the consistency of the isotopic record rules out a sampling problem. Apparently, local environmental conditions prevailed over the regional carbon isotope signature. Furthermore, if the excursion was of global event, in the cratonic interior its signature was diminished in magnitude and postponed in time.

CONCLUSIONS

1. By using four regionally traceable and geochemically ''fingerprinted'' K-bentonites,

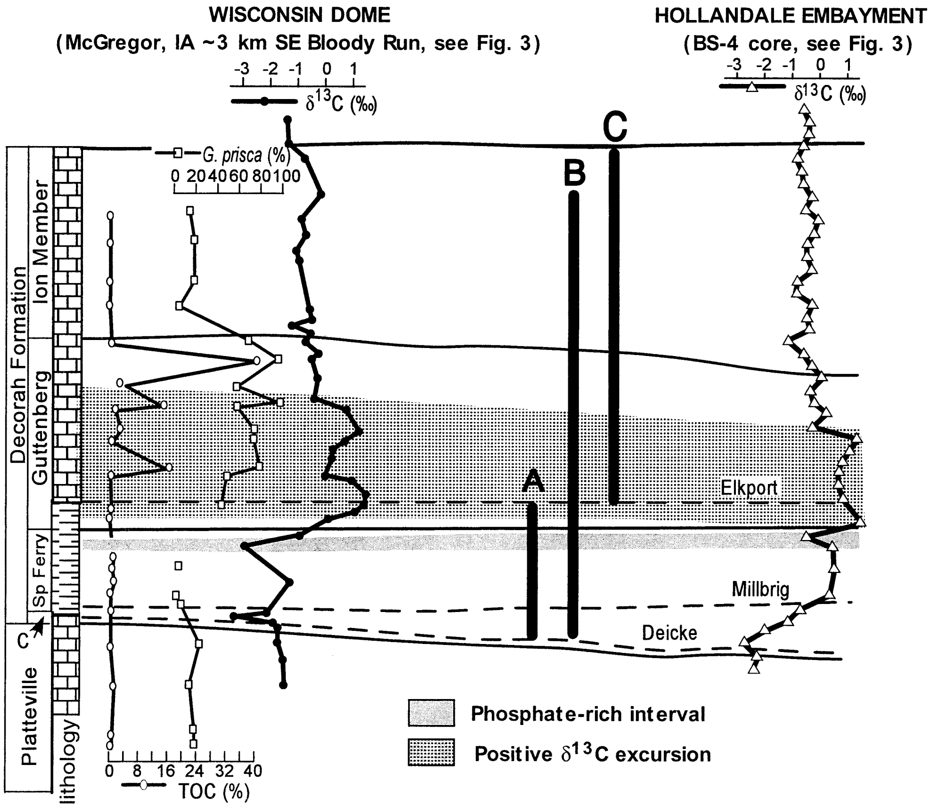

Figure 4. Lithostratigraphy of Decorah Formation including stratigraphic positions of key K-bentonites (horizontal dashed lines), concentrations of *G. prisca*, and δ^{13}C and total organic carbon (TOC) values. Brachiopod species range lines A, B, and C refer to three major groupings of species (see text). A—species generally confined to shale-rich facies, B—shared species present in both facies, C—species generally confined to carbonate-rich facies. TOC and *G. prisca* values are adapted from Pancost et al. (1998), brachiopod data are from Emerson (2002). C—Carimona Member, Sp. Ferry—Spechts Ferry Member.

the Midcontinent Decorah Formation was correlated across a carbonate-shale facies change.

2. We envision two stages of deposition. Exposure of the Transcontinental Arch and freshwater runoff created a salinity-stratified water column accompanied by deposition of a shale-rich wedge of sediment during times of intermittent dysoxic conditions. At a later stage of deposition, following the submergence of the Transcontinental Arch, the clastic input and freshwater runoff diminished. This change allowed for a clearer water column, an expanded photic zone, and a switch to carbonate deposition with times of high primary productivity and *G. prisca* burial, followed by dilution by prograding carbonates.

3. The lag time between the *G. prisca* peak (and subsequent TOC accumulation) and the δ^{13}C excursion suggests that these are not coeval processes and probably do not represent cause and effect.

4. Within the K-bentonite and sequence stratigraphic framework, across the study area ($<$100 km), the δ^{13}C excursion started at different times, although it peaked at the same time. This finding suggests that the initiation of a regional carbon isotope excursion was affected by local environmental conditions.

5. This scenario points to a North American Ordovician epeiric sea wherein subtle topographic changes divided the flooded continent into different depositional areas with distinct physical, biological, and chemical signatures (Holmden et al., 1998). Subtle topography modified storm currents and restricted circulation within the sea in such a way that small variations in sea level, runoff, and evaporation may have drastically changed the water chemistry, leading to major facies and faunal changes.

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