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Depositional environments and sequence stratigraphy of Upper Ordovician epicontinental deep water deposits, eastern Iowa and southern Minnesota

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ABSTRACT

This study examines depositional environments, stratigraphy, paleontology, and petrology of the Upper Ordovician upper Dubuque Formation and Elgin Member (basal Maquoketa Formation) in eastern Iowa and southern Minnesota within a sequence stratigraphic framework. Dubuque-Elgin deposition occurred within a subcycle of the Maquoketa depositional cycle and records a single transgressive-regressive event; the Dubuque Formation and lowermost Elgin Member deposits are transgressive, lower Elgin deposits are highstand, and middle and upper Elgin deposits are regressive. The transgressive Dubuque Formation grades from an open marine benthic environment in its lower portions, to slightly oxygen stressed environments in its upper portions, with an associated loss of calcareous algae and tempestites, and increase in trilobite grain frequency and mud matrix. The Dubuque-Elgin contact is marked at all but the northernmost localities by a regional condensed section consisting of transgressive phosphatic hardgrounds and overlying highstand dark brown pelagic shale. The nature of overlying regressive Elgin Member deposits is dependent upon geographic location, with thick carbonates (~25 m [~82 ft]) present in the north and north-central areas, mixed carbonates and shales in the south-central area (~15 m [~48 ft]), and thin shales in the southern area (~8 m [~25.6 ft]). Depositionally, this wedge represents shelf (thick carbonates), shelf-slope boundary (mixed carbonates and shales), and slope-basin (shales) environments.

The epicontinental Maquoketa seaway is interpreted to have had significant maximum depths (>200 m [650 ft]), and to have contained a density-stratified water mass. Upwelling and associated phosphate deposition resulted from a gyre circulation pattern driven by Taconic fresh-water runoff and surface winds, with net surface currents in the study area flowing basinward, replaced by deep upflowing waters. Depths are estimated from regional facies associations, depth-dependent nautiloid septal implosion measurements, and whole-rock carbonate $\delta^{13}C$ isotopic trends indicating increasing burial of organic carbon.

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INTRODUCTION

Recently developed research tools and stratigraphic concepts allow for reevaluation of previously studied Ordovician units in eastern Iowa and southern Minnesota. Paleogeographic and environmental interpretations of Witzke (1980, 1987, 1990), Witzke and Glenister (1987), Witzke and Kolata (1988), and Witzke and Bunker (this volume) provide a regional context in which new petrographic and geochemical data may be examined and elucidate further implications as to depositional history. Historically, interpretation of environments of deposition for Upper Ordovician deposits (in particular the classic Elgin Member site at Graf, Iowa) have traveled full circle; from deep water (Hall, 1858), to shallow water (Calvin and Bain, 1899; Ladd, 1929; Miller and Youngquist, 1949; Tasch, 1955; Snyder and Bretsky, 1971), back to deep water (Witzke and Glenister, 1987; Witzke and Kolata, 1988; Raatz et al., 1992b). This report integrates historic and modern depositional interpretations using detailed petrologic analysis within a sequence stratigraphic framework.

Study area and stratigraphic overview

The study area is located within the Ordovician outcrop belt that extends from Fillmore County in southern Minnesota to Jackson County in eastern Iowa (Fig. 1). The units investigated include the upper Dubuque Formation of the Galena Group, and Elgin Member of the Maquoketa Formation, traditionally designated as upper Edenian and lower Maysvillian, respectively (see Sweet, 1984). Recent work, however, suggests the Elgin Member is early Richmondian (Bergström and Mitchell, 1992; Fig. 2).

This chapter divides the study region into four smaller areas, north, north-central, south-central, and south, each containing one major Elgin depofacies (Fig. 1). In most cases facies overlap into bordering areas, but are not lithologically dominant. Within each area, a generalized stratigraphic column has been constructed, synthesized from a number of individual measured sections (Fig. 3). Of the various sites investigated, one section was chosen in each area for its superior preservation and stratigraphic control to be examined in petrographic, and in two cases geochemical, detail. These sections include Rifle Hill exposure in the north, Big Spring core #5 in the north-central area, Graf exposure in the south-central area, and Jackson County core Cominco #SS-7 in the south.

Paleogeography and sedimentary provenances

During Middle Ordovician time, the Upper Mississippi Valley was covered by an epicontinental sea, which was bounded by the Transcontinental Arch to the paleo-north, the Ozark Uplift to the paleo-southwest, the Wisconsin Arch to the paleo-east, and the Taconic orogenic source area (Appalachians) to the paleo-southeast (Fig. 4). In early Late Ordovician time, the subaerially exposed Precambrian basement rocks of the Transcontinental Arch were located within the humid equatorial zone, and served as a clastic source for the mixed carbonate-clastic depositional systems of the adjacent Platteville and Decorah formations (Witzke, 1980; Sloan, 1987; Witzke and Kolata, 1988; Fig. 2). Subsequent sea-level rise drowned the arch, greatly reducing clastic output, and allowed for deposition of the dominantly carbonate Dunleith and Wise Lake formations. The Ozark Uplift then became pronounced and the Transcontinental Arch was reexposed, probably due to uplift (Witzke, 1980; Sloan, 1987), and the mixed carbonate-clastic Dubuque Formation was deposited.

By Elgin time in the Late Ordovician (Figs. 2 and 4), eastern Iowa had moved southward and was located in the arid trade wind belt at ~20° south latitude (Witzke, 1980). The Transcontinental Arch exerted little if any clastic influence, as evidenced by the presence of carbonate-dominated lithologies in areas bordering the arch, such as Oklahoma, Nebraska, northern Iowa, and southern Minnesota. Contemporaneous erosion of Ozark Uplift–sourced sediments were deposited as the Thebes Sandstone of southern Illinois and Missouri. It is possible that Ozark Uplift material contributed to the clastic rocks of the southern Elgin, although the most likely source for the majority of terrigenous material was the Taconic Uplands (Witzke, 1980; Witzke and Glenister, 1987; Witzke and Kolata, 1988). The shedding of clastics from the Taconic Uplands created a wedge of material extending from the eastern United States to eastern Iowa, corresponding to the thin shales present in the basal Elgin Member.

Remaining Ordovician deposits include the mid-Maquoketa Clermont and Fort Atkinson members, and upper Maquoketa Brainard and Neda members (Fig. 2). These units record later sea-level cycles, and included depositional environments ranging from skeletal wackestone-packstones deposited near fair-weather wave base, to unfossiliferous dark shales deposited within anoxic, stratified bottom water conditions (Witzke and Kolata, 1988; Witzke and Bunker, this volume). Silurian carbonates unconformably overlie the Maquoketa in the study area (Witzke and Glenister, 1987).

PETROLOGY

The Elgin Member of the Maquoketa Formation, and where available the underlying upper Dubuque Formation, have been studied in each of the four depositional areas. The sites offer an opportunity to compare intrabasinal lithic and biologic trends within deposits interpreted to represent deep slope and basin to shallower water shelf environments. All measured sections of the Elgin Member except the northernmost Rifle Hill exposure exhibit a basal phosphatic bed overlain by dark brown, pelagic shale. These two lithologic units meet the following criteria established for a condensed section [CS] (Loutit et al., 1988): thin but regionally continuous beds (the <1 m [3.2 ft] thick Elgin CS is present in Iowa, Illinois, Indiana, and Missouri); pelagic to hemipelagic sediment; abundant and diverse pelagic and benthic

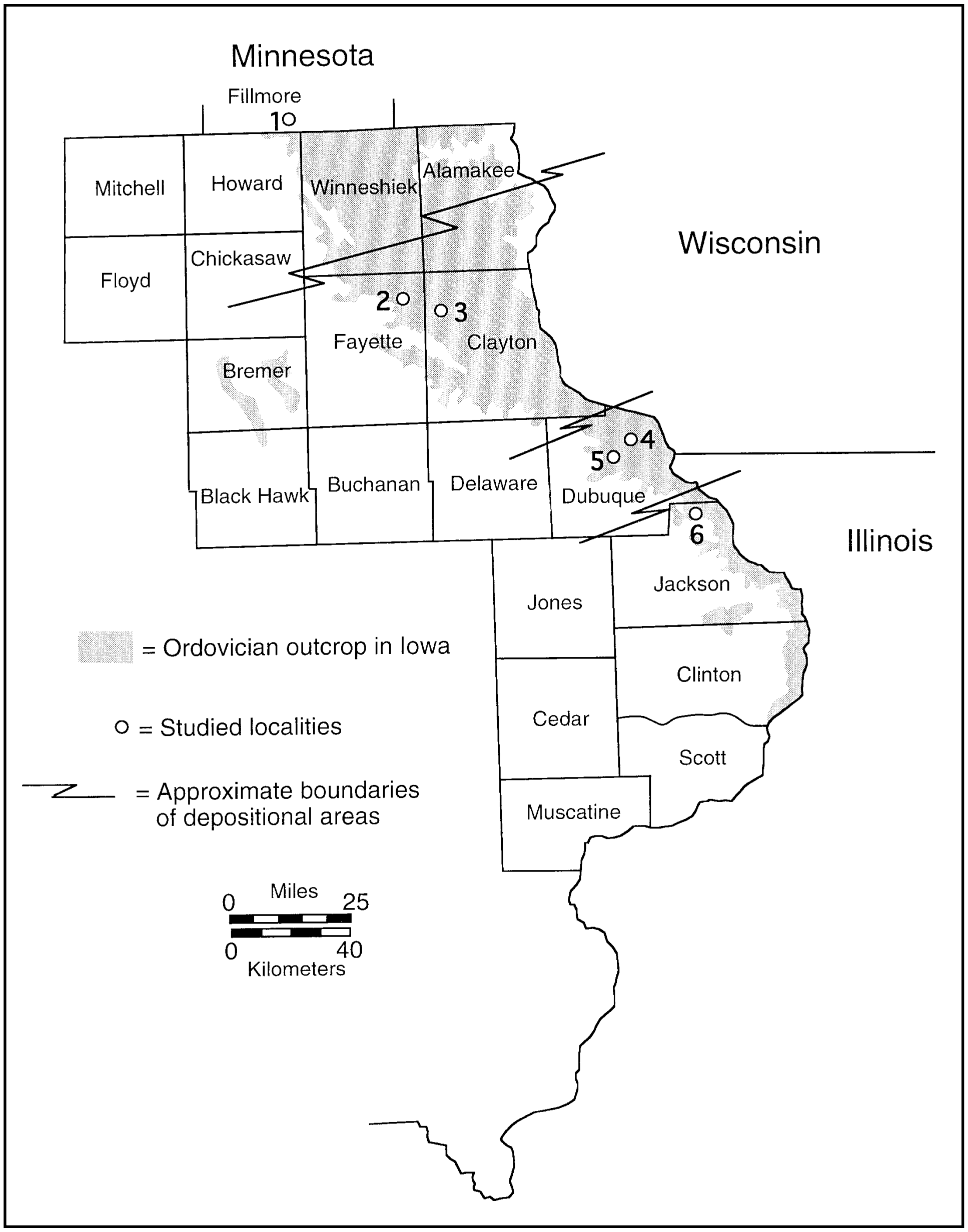

Figure 1. Map of study area with approximate boundaries separating the northern area (1, Rifle Hill exposure, Fillmore County, Minnesota), north-central area (2, Montauk exposure, Fayette County, Iowa, and 3, Big Spring core no. 5, Clayton County, Iowa), south-central area (4, Asbury quarry, Dubuque County, Iowa, and 5, Graf exposure, Dubuque County, Iowa) and the southern area (6, Cominco core no. SS-7, Jackson County, Iowa).

microfauna (the Elgin CS contains diverse depauperate molluscan fauna, *Hindia* sponges, conodonts, ostracodes, lingulid brachiopods, and graptolites); hardgrounds (the Elgin CS contains well-developed, often multiply stacked hardgrounds); abundant authigenic minerals (the Elgin CS contains apatite and/or phosphate and iron sulfide); abundant organic matter (the Big Spring locality basal Elgin Member dark shales contain 7.44% total organic carbon (Jim Palacas, U.S. Geological Survey, 1993, personal commun.); burrows and/or borings; interpreted slow sedimentation rates; and interpreted deposition close to or during maximum transgression.

Southern area

Elgin Member. The complete Elgin Member succession (8.01 m [26.28 ft]) was studied from a core in Jackson County, Iowa (Fig. 1, locality 6; Fig. 3). Lithologies in the southern area exhibit a thick phosphatic section (Fig. 3, unit 2, 0.45 m

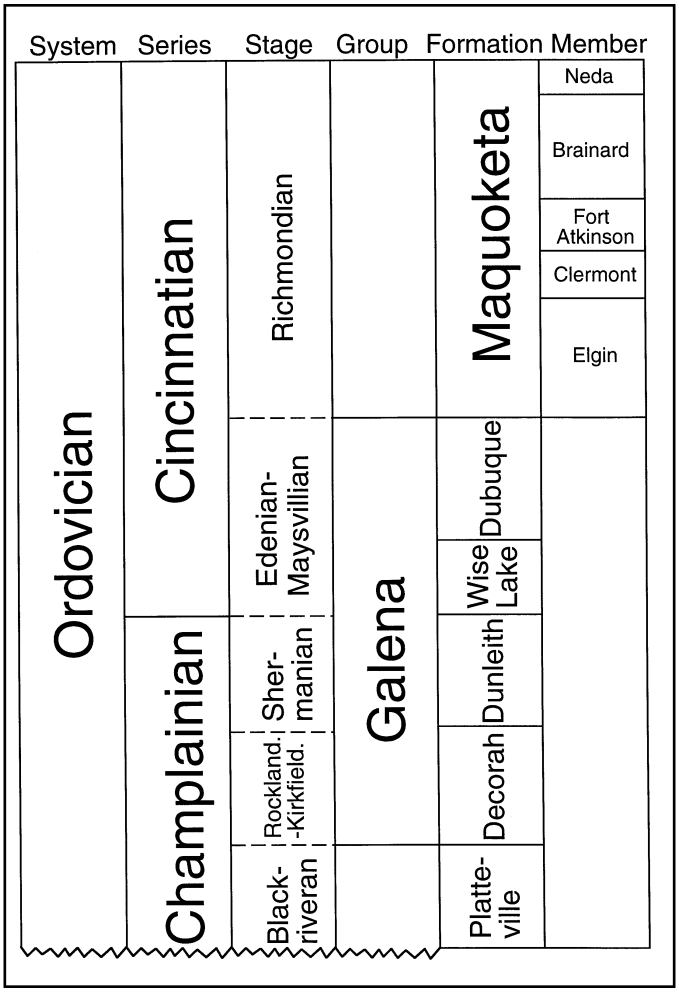

Figure 2. Stratigraphic column illustrating time and lithologic units for Middle and Upper Ordovician rocks in eastern Iowa. Designation of the Maquoketa Formation as Richmondian rather than Maysvillian is the result of recent conodont and graptolite biostratigraphy by Bergström and Mitchell (1992).

[1.48 ft]) underlain and overlain by dark brown to olive-green shales (Fig. 3, unit 1, 0.24 m [0.79 ft] and unit 3, 7.32 m [24.02 ft]). The shales are laminated and contain rare trilobites and graptolites.

South-central area

Elgin Member. A complete section of the Elgin Member (13.26 m [43.50 ft]) was measured and studied in this area (Fig. 1, localities 4 and 5; Fig. 3). The south-central area is a geographically narrow band of deposits that represent transitional lithologies between northern carbonates and southern shales. The condensed phosphatic deposit (Fig. 3, unit 1, 0.25 m [0.82 ft]) and overlying dark brown shales contain lingulid brachiopods, graptolites, *Hindia* sponges, and a diverse, phosphatized, diminutive molluscan community (depauperate zone of Ladd, 1929; see Snyder and Bretsky, 1971). Thin dolomitic interbeds (Fig. 3, unit 2, 6 m [19.69 ft]) grade upward into more massive dolomites containing pelagic and hardy benthic faunal elements (gastropods, trilobites, scaphopods) with shale interbeds (Fig. 3, unit 3, 1.85 m [6.07 ft]). At Graf, Iowa, unit 4 deposits contain four distinct layers of nautiloid cephalopod coquinas, which are dolomitic packstone beds 0.1 to 0.2 m (0.33 to 0.66 ft) thick containing abundant orthocones of the nautiloid *Isorthoceras sociale*. Many individual orthocones in the coquinas display an unusual phenomenon of telescopic nesting, where one or more (up to five or six) conical shells are deeply imbedded through the septa of another (Fig. 5). Above the coquinas, dolomite and shale interbeds continue, with dolomite lithologies becoming dominant over dwindling volumes of shale (Fig. 3, units 4–7, 5.16 m [16.93 ft]). The uppermost dolomites (Fig. 3, unit 7) contain open water marine benthic organisms, mainly crinoids and articulate brachiopods, in cross-bedded wackestone-packstone fabrics.

North-central area

Upper Dubuque Formation (Fig. 3, units 1-3, 3.44 m [11.29 ft]) and a complete section of the Elgin Member (Fig. 3, units 4–9, 27.22 m [89.31 ft]) have been measured and studied at two major localities (Fig. 1). The basal Elgin Member CS includes multiple hardground surfaces, the lowermost of which represents the Dubuque-Elgin contact (Fig. 6).

Dubuque Formation. Unit 1 (Fig. 3, 2.75 m [9.02 ft]) is a trilobite, brachiopod, echinoderm wackestone with local burrow-fill and storm event packstones. The matrix comprises light colored micrite and dark shaley lenses; dolomite occurs as infrequent floating rhombs and in burrow fillings. Rare blocky calcite cements are present filling voids after dissolved mollusc shells and internal void fillings of whole-shell ostracodes and brachiopods. Micritic limestone intervals lack evidence for significant compaction, in contrast with intervening dolomitic shaley layers that contain winnowed brachiopod packstones with broken shells and draping effects.

The succeeding unit 2 (Fig. 3, 0.51 m [1.67 ft]) retains wackestone and/or burrow-fill packstone characteristics, but has increases in the abundance of dolomite and iron sulfide; there are also blocky calcite cements in the form of void-fillings after dissolved mollusc shells, rare echinoderm syntaxial overgrowths, and internal void-fillings of whole-shell brachiopods, bryozoans, and ostracodes. Small grainstone lenses, possibly related to burrows, are present. Although dolomite rhombs are largely confined to the matrix, echinoderm and trilobite skeletal grains also show minor dolomite replacement.

The overlying unit 3 (Fig. 3, 0.18 m [0.59 ft]) consists of lingulid brachiopod, trilobite, echinoderm, articulate brachiopod wackestones, containing a matrix of rhombohedral dolomite (long axis 100–300 µm) with local concentrations of iron sulfides. Skeletal grains remain dominantly calcitic, although most have ragged edges that are partially replaced by dolomite. Cements consist of clear blocky void and shell fillings, some

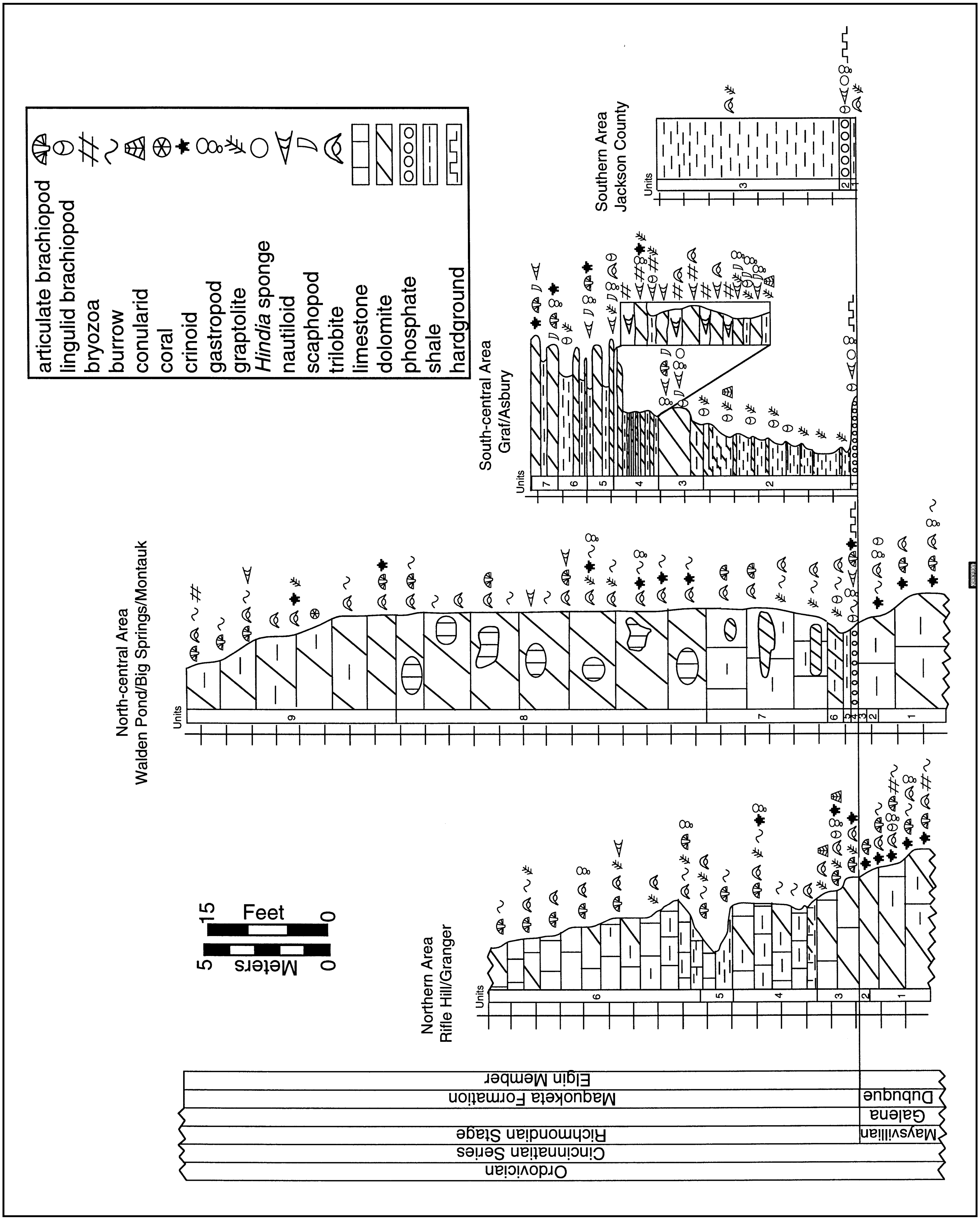

Figure 3. Composite graphic measured sections from the northern, north-central, south-central, and southern depositional areas.

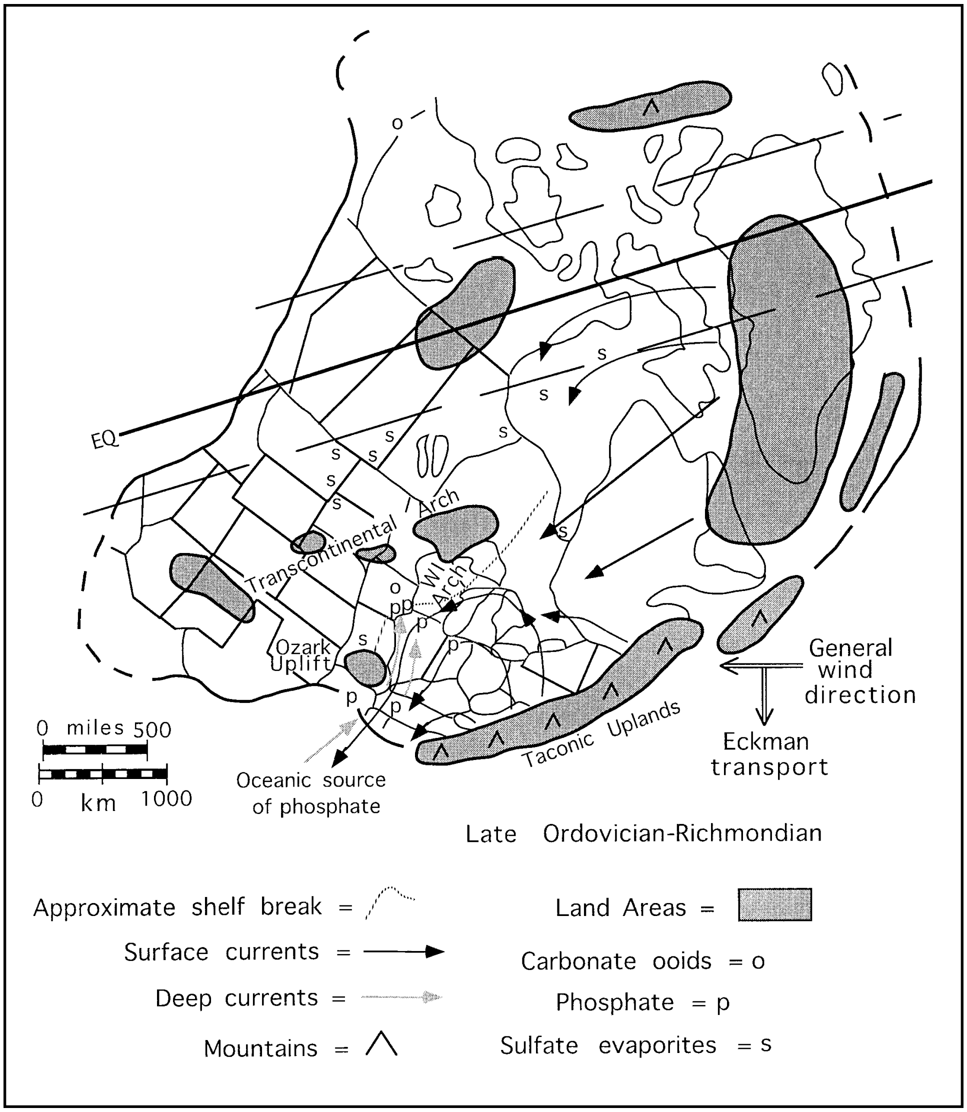

Figure 4. Late Ordovician paleogeographic reconstruction showing major land areas, mountains, lithic paleoclimate indicators, and seaway current patterns. The two lines that parallel the equator designate divisions between humid and arid climatic conditions. Surface current patterns form a quasiestuarine gyre circulation pattern created by Taconic upland fresh-water runoff and surface winds. Although surface currents are close to paralleling the Transcontinental Arch, net surface transport was basinward, drawing deep, anoxic, phosphate-rich waters to the surface and forming an area of upwelling at the shelf margin. Modified from Witzke (1980, 1987, 1990).

with large dolomite rhombs incorporated within the edges. The uppermost 5 cm of the unit contains a matrix of mixed dolomite (long axis 75–350 µm) and phosphatic minerals. The contact with the Elgin Member is an irregular hardground surface of pyrite-impregnated phosphate (in cases of multiple hardgrounds, the boundary is defined as the lowermost hardground surface; Fig. 6). Large (3–5 cm), clear, blocky calcite void fillings of uncertain origin (possibly burrow and/or boring voids) are present in an interval ~10 cm below the hardground contact. These large vugs are also associated with multiple stacked hardgrounds in the Elgin Member CS (Fig. 6). Calcitic vugs commonly have dolomite and phosphate linings, and in some instances small fluorite crystals resting with geopetal fabric on older calcite crystal faces (see Brown, 1967).

Elgin Member. The basal CS of the Elgin Member (Fig. 3, unit 4, 0.32 m [1.05 ft]) contains one or more hardground surfaces with intermixed phosphatic peloids and ooids, iron sulfide impregnation, burrows, calcite vugs, and dolomite (long axis 50–300 µm). Fossils include inarticulate and articulate brachiopods, bryozoans, echinoderms, trilobites, gastropods, *Hindia* sponges, and nautiloids. Clear blocky calcite burrow and fracture-filling cements also occur. Phosphatic peloids and

Figure 5. Partially imploded nautiloid, with imploded septa (A), and the first intact septum (B) (used for strength measurements) clearly visible. The unusual telescopic nesting phenomenon common in Graf samples (~60% of cut and polished specimens) also is observable in this sample. Note the outer, host shell (H) contains an inner, nested individual (N). In cases of nested samples, only the innermost shell, with no nested shells within it, can be used for septal strength measurements. Also note that the posterior tip of the inner nautiloid's phragmacone is broken (C), probably the result of high energy, violent impact with the host nautiloid's hardened cameral deposits. Specimen SUI83944A and SUI83944B. Scale is in centimeters (total length of nautiloid ~8 cm).

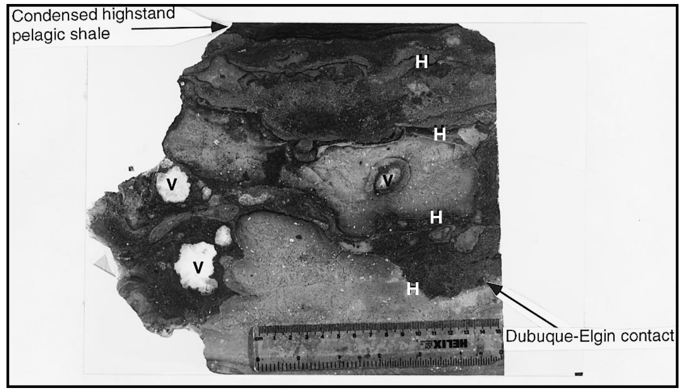

Figure 6. A slab from the north-central area in western Clayton County, Iowa, with multiple stacked hardgrounds (H), and large calcite- and fluorite-filled voids (V), exemplifying the phosphatic condensed section. The Dubuque-Elgin contact is designated as the lowermost hardground surface. The very top of the photograph shows the lower portion of the maximum flooding surface pelagic dark brown highstand shale. Scale is in centimeters and inches (ruler is 15 cm in length).

ooids form poorly sorted, variably packed grainstones that are enveloped by poikilotopic clear calcite cement. Overlying the phosphatic bed is a thin dark brown shale with pelagic graptolites and inarticulate brachiopods grading upward into a dark argillaceous carbonate mudstone (Fig. 3, unit 5, 0.45 m [1.48 ft]), and finally into a lighter, organic-rich, laminated dolomitic mudstone with pyrite, graptolites, and occasional burrows (Fig. 3, unit 6, 0.47 m [1.54 ft]). Organic remains occur as flattened light brown organic-walled microfossils. Sedimentary iron sulfides occur as elongate pyritized organic-walled microfossils (100×10 µm), framboids (50 µm in diameter), cubes floating in the matrix (20 µm), and spherical concretions (1.2 mm in diameter). Above the shale and carbonate mudstone of the lower Elgin is a burrowed brachiopod, graptolite, trilobite carbonate mudstone to wackestone with irregular dolomitized shale interbeds (Fig. 3, unit 7, 5.07 m [16.64 ft]). Macrofossils are preferentially preserved in the limestones, which also contain floating dolomite rhombs (long axis 75 µm), pyrite, and chert nodules in an organic-rich micritic matrix. Pervasively dolomitized shaley layers show evidence of greater compaction relative to limestone beds. Nodular limestones contain fractures filled contrary to gravity with dolomitic shale injected from below, indicating early lithification of limestones relative to shaley interbeds. The overlying thick unit 8 (12.67 m [41.57 ft]) contains iron-stained argillaceous dolomite interbedded with irregularly fractured limestone nodules of brachiopod, echinoderm, graptolite, trilobite wackestones to mudstones. The limestone nodules are partially dolomitized, but still retain original shell material and uncompacted burrowed fabrics. Cements include calcite fillings in dissolved mollusc shells, burrow fillings, and fracture void fillings in limestone nodules. Silica cement is locally significant, and is spatially associated with chert nodules and sponge spicule concentrations. The uppermost Elgin Member (Fig. 3, unit 9, 8.24 m [27.04 ft]) consists of argillaceous dolomite with brachiopods, trilobites, nautiloids, graptolites, tabulate corals, burrows, and scattered chert nodules.

Northern area

The upper Dubuque Formation (Fig. 3, units 1–2, 2.85 m [9.35 ft]) and lower to middle Elgin Member (Fig. 3, units 3–6, 14.95 m [49.05 ft]) were measured and studied at Rifle Hill (Fig. 1). The phosphatic CS marker bed that consistently delineates the Dubuque-Elgin contact in more southerly sections is not present in this area, therefore the Dubuque-Elgin contact has been inferred from biological markers, mainly the first appearance of graptolites. Upper Elgin deposits in the northern area and all Elgin deposits north of Rifle Hill are absent due to erosion.

Dubuque Formation. The upper Dubuque Formation is a trilobite, brachiopod, echinoderm wackestone to packstone with pervasive horizontal and vertical burrow networks (2.5–5 mm in diameter) controlling lithologies and fabrics. Iron sulfides are rare to locally common, often occurring as nodules (Delgado, 1983). Dolomite frequency increases upward in the section. The lower portion (Fig. 3, unit 1, 2.35 m [7.71 ft]) has a micritic matrix with local lenses and burrow fills of dolomite (long axis 25–50 µm), and the upper portion (Fig. 3, unit 2, 0.5 m [1.64 ft]) contains a matrix composed dominantly of dolomite. Skeletal grains exhibit dolomite replacement in varying degrees throughout the section. Calcite cements are present as void fillings of whole-shell ostracodes and small brachiopods, dissolved mollusc shells, and occur rarely (upper unit 1) as poikilotopic cements enveloping skeletal grains in thin grainstone intervals. Sulfides occur as partial replacements of phosphatic grains (blebs 100 µm, framboids 50 µm, and cubes 100 µm in diameter).

Elgin Member. The Elgin Member is an echinoderm, trilobite, graptolite, brachiopod mudstone to wackestone with abundant organic-walled microfossils and pervasive burrowing. Local shaley laminations (Fig. 3, unit 4, 3.35 m [10.99 ft]), packstones (upper unit 4), and iron sulfides are present. Iron sulfides occur as partially replaced organic-walled microfossils (chitinozoans), and as cubes (150 µm in diameter). The matrix consists of rhombohedral dolomite (long axis 50–75 µm) with lesser amounts of micrite (lower unit 3, 2.29 m [7.51 ft]), and finer-grained dolomite (long axis 25–50 µm) with lesser amounts of micrite (units upper 3–4, 5.64 m [18.51 ft]). Cements consist of calcite fillings of brachiopod and ostracode shells, and small calcitic veins. Silica is present in minor amounts, locally associated with concentrations of sponge spicules and partial replacement of echinoderm fragments (upper unit 3). Unit 6 (Fig. 3, 8.62 m [28.28 ft]) contains higher energy wackestone and packstone fabrics, with an increase in abundance of benthic articulate brachiopods, and a notable decrease in the abundance of graptolites and trilobites.

DEPOSITIONAL ENVIRONMENTS

A number of general lithic and biologic trends are useful in interpreting Dubuque-Elgin environments (Table 1). Fabrics are interpreted as being reflective of the energy present in the depositional system; shales and mudstones indicate low-energy, wackestones moderate-energy, and packstones and grainstones high-energy environments. Burrows alter this fabric and are relatively independent of system energy, and indicate at least episodic availability of oxygenated bottom water. Fossil community assemblages are also useful in determining general environmental conditions and trends. Qualitative observations consistent throughout the study area indicate that trilobites, graptolites, and lingulid brachiopods are the major faunal elements associated with low-energy shales and mudstones. This is interpreted to represent a deep water environment with little or no available bottom water oxygen. Similar faunal assemblages (e.g., "graptolite facies" of Berry et al., 1989) have been recognized as representing dysoxic-anoxic communities by other workers (Kammer et al., 1986; Ludvigson and Witzke, 1988; Berry et al., 1989; and Lehmann et al., 1990). Higher energy wackestone to grainstone fabrics incorporate a greater diversity of benthic constituents, suggestive of more favorable, oxygenated bottom waters and shallower environments.

Dubuque Formation

The upper Dubuque Formation wackestones are interpreted to represent transgressive deposits of moderately deep shelf environments. The lower studied section (Fig. 3, northern area unit 1, north-central area unit 1) contains an open marine assemblage of crinoids, brachiopods, trilobites, bryozoans, and gastropods, suggesting depth within storm wave base with current activity and oxygenated bottom conditions. The upper studied section (Fig. 3, northern area, unit 2; north-central area, units 2–3) becomes progressively more shale rich, with a decrease in abundance of benthic calcareous algae (Bakush, 1985) and tempestites (Levorson et al., 1979), and increases in trilobite grain frequency, matrix mud, and organic-walled microfossils (Witzke and Kolata, 1988; Ludvigson, 1987; Ludvigson et al., 1992), suggesting more oxygen-stressed, deeper conditions.

Elgin Member

The Elgin Member is interpreted to consist of transgressive, highstand, and regressive deposits. A north-south cross section (Fig. 7) with inferred preerosion thickness in the extreme northern area illustrates that the member forms a wedge of deposits that is thinnest in the southern shales of Jackson County, Iowa, and thickest in the northern carbonates of northern Iowa and southern Minnesota. Within this wedge are five general environments of deposition: (1) Shelf edge (phosphorite) grainstone, (2) slope-basin, (3) shelf-slope boundary, (4) outer shelf, and (5) middle shelf. These environments and associated facies tracts migrated through time with changing sea levels, creating lateral and vertical facies changes.

1. Shelf edge (phosphorite) grainstone facies. The basal Elgin Member phosphatic CS is present in north-central area unit 4, south-central area unit 1, and southern area unit 1 (Fig. 3). The facies contains abundant inarticulate lingulid brachiopods and consists of chemically precipitated phosphate and iron sulfide ooids in a grainstone fabric, interpreted to represent a sediment-starved transgressive deposit with phosphate supplied from upwelling waters.

2. Slope-basin facies. The slope-basin environment is found in the north-central area (Fig. 3, unit 5), south-central area (Fig. 3, unit 2), and southern area (Fig. 3, unit 3). Lithologically this facies is composed of brown to olive-green shales with graptolites, lingulid brachiopods, and trilobites. Deposi-

TABLE 1. SUMMARY OF LITHOLOGIC AND FAUNAL DATA WITH ENVIRONMENTAL INTERPRETATIONS FOR THE SOUTHERN MINNESOTA AND EASTERN IOWA FIELD AREA

Facies	Area(s)	Biology	Lithology	Environmental Interpretations
Shelf Edge (Phosphorite) Grainstone	South, south-central, and north-central.	Lingulid brachiopods, trilobites, nautiloids, sponges, bryozoans, gastropods, articulate brachiopods.	Phosphatic peloids and ooids with iron sulfides and multiple hardgrounds. 0.45 m (1.48 ft) in the south, 0.25 m (0.82 ft) in south-central, and 0.25 m (0.82 ft) in north-central.	Sediment-starved transgressive condensed section.
Slope/Basin	South, south-central, and north-central.	Graptolites, lingulid brachiopods, trilobites.	Dark brown shales. 7.5 m (24.61 ft) in the south, 6.5 m (21.33 ft) in south-central, 0.5 m (1.64 ft) in north-central.	Deep, anoxic water (below storm wave base); clastic material from distant Taconic Uplands.
Shelf/Slope Boundary	South-central.	Nautiloids, trilobites, graptolites, scaphopods, sponges, gastropods, conularids, lingulid and articulate brachiopods, crinoids.	Interbedded dolomites and shales. Lower carbonates are phosphatic. Contains four nautiloid coquina beds. 5.5 m (18.05 ft).	Alternating lithologies represent changes in bottom oxygen conditions, related to episodic deep water storm boundary currents.
Outer Shelf	South-central, north-central, and north.	Trilobites, graptolites, inarticulate and articulate brachiopods, gastropods, crinoids, nautiloids, scaphopods, bryozoans, and conularids.	Mixed carbonates and shales. Carbonate fabrics dominately mudstones and wackestones. 1.14 m (3.74 ft) in south-central, 18.21 m (59.75 ft) in north-central, and 14.95 m (49.05 ft) in the north.	Deep shelf deposits below storm wave base depths.
Middle Shelf	South-central, north-central, and north. (North variably lost to erosion).	Articulate brachiopods, crinoids, trilobites, tabulate corals, bryozoans, graptolites, scaphopods, and gastropods.	Carbonates (largely dolomite) with minor shales. Carbonate fabrics include mudstones, wackestones, and packstones. 1.15 m (3.75 ft) in south-central, 8.24 m (27.04 ft) in north-central.	Open marine shelf deposits at or above storm wave base depths.

tion is interpreted to have occurred below the pycnocline in deep, largely anoxic conditions, allowing for shale deposition and the undisturbed preservation of graptolites.

3. Shelf-slope boundary facies. The shelf-slope boundary environment is observable in the south-central area (Fig. 3, units 2–5). Deposits at Graf and Asbury represent an interfingering of deep shelf phosphatic carbonate wackestone-packstones with slope dark brown shales. Fossils are abundant and diverse and include nautiloids, bryozoans, scaphopods, gastropods, sponges, trilobites, graptolites, articulate brachiopods, lingulid brachiopods, echinoderms, and conularids. The interbedded carbonates and shales represent an environment bordering the dysoxic-anoxic boundary (Kolata and Graese, 1983; Witzke and Glenister, 1987). Small changes in sea level or circulation patterns shifted benthic conditions from dysoxic (phosphatic carbonates) to anoxic (dark shales) and vice versa.

4. Outer shelf facies. The outer shelf facies is represented in the northern area (Fig. 3, units 3–6), north-central area (Fig. 3, units 6–8), and south-central area (Fig. 3, unit 6). The dominant fabrics are low- to moderate-energy carbonate mudstone and wackestone, and lesser shales. Articulate brachiopods, lingulid brachiopods, crinoids, trilobites, conularids, bryozoans, graptolites, and gastropods compose the mixed stressed and open-marine assemblage. Lithic and biologic characteristics are consistent with deposition in partially or episodically oxygenated water below effective storm wave base, allowing for some shale deposition as well as the abundant preservation of graptolites due to lack of wave abrasion. A significant number of trilobites in the hydrodynamically unstable concave-up position at the Montauk outcrop in the north-central area (Fig. 3, unit 8) also supports this low-energy interpretation.

5. Middle shelf facies. The middle shelf facies is exempli-

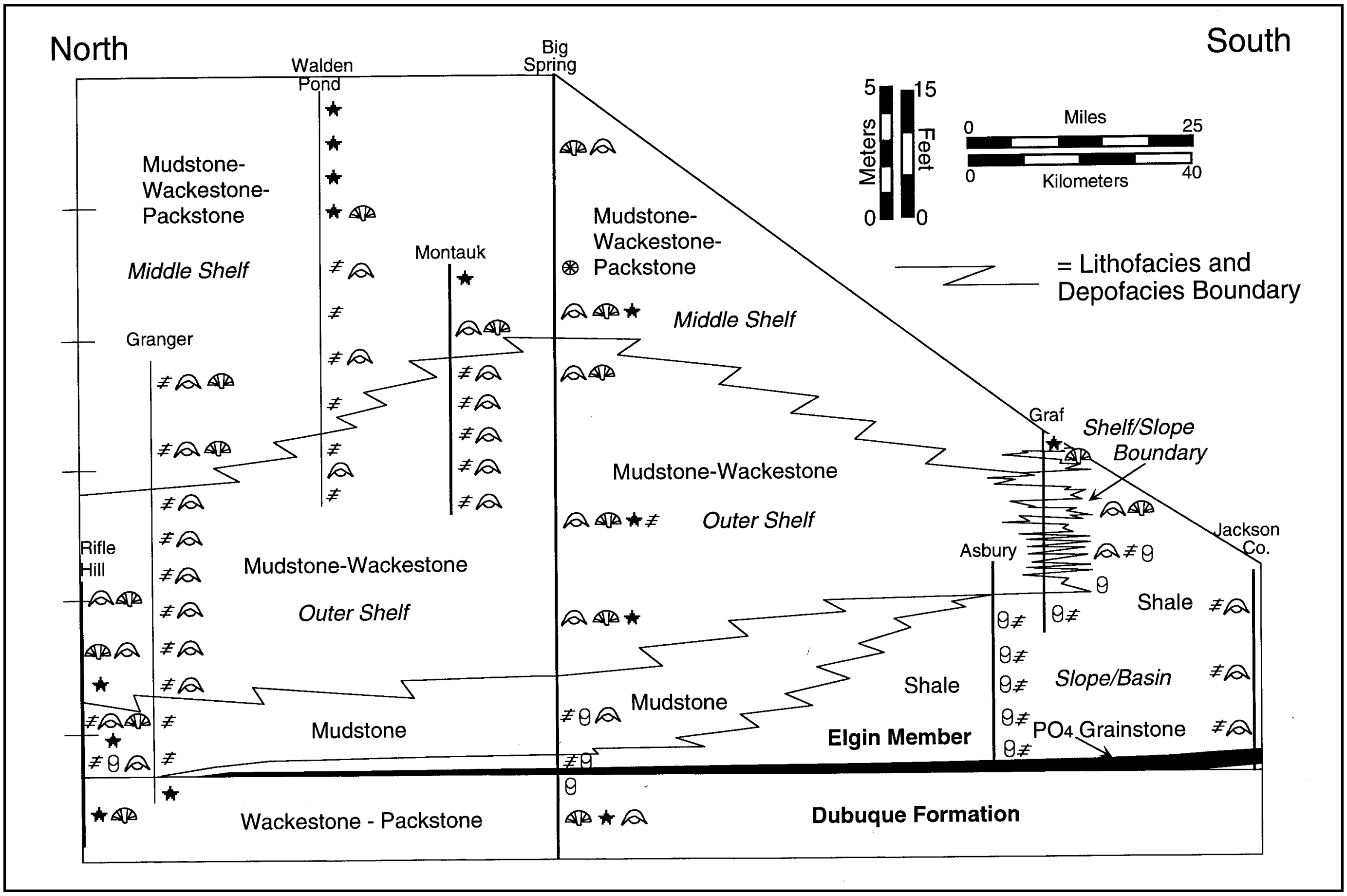

Figure 7. A north-south cross section of the upper Dubuque Formation and Elgin Member in eastern Iowa. Granger exposure in Fillmore County, Minnesota, and Walden Pond in Winneshiek County, Iowa, have been added for greater precision in correlation (Brian Witzke, pers. commun.). Selected ecologically sensitive faunal elements are included (see Fig. 3 for symbol key). Lateral and vertical depositional trends are discernible. The vertical trend is interpreted to result from a transgressive-regressive subcycle, the Dubuque Formation and Elgin Member phosphatic condensed section representing transgressive deposits, the condensed dysoxic-anoxic brown shales representing sea-level highstand, and the thick Elgin carbonates representing regressive deposits. The lateral trend is interpreted to result from a combination of basin geometry and relative sea-level changes, and displays a deep, oxygen-stressed environment in the southern area, and diversified benthic fauna northward, indicating shallowing to the north.

fied in the north-central (Fig. 3, unit 9) and south-central (Fig. 3, unit 7) areas. Lithologies include dolomite and limestone in mudstone, wackestone, and packstone fabrics. Fossils comprise the open marine assemblage of the outer shelf facies with the addition of tabulate corals. There is a notable increase in the abundance of articulate brachiopods and crinoids, and there are decreases in trilobites, graptolites, and lingulid brachiopods. Depositional environments are interpreted to represent well-oxygenated bottom conditions within storm-wave-base depths.

Paleobathymetry

Relative Maquoketa sea bathymetry during Elgin deposition can be deduced from lateral facies geometries. The skeletal-rich carbonates of southern Minnesota, western and northeastern Iowa, and north-central Illinois represent shelf environments, as does the Ozark Uplift area. Pelagic brown shales of eastern and southeastern Iowa and northwestern Illinois represent deeper slope or basinal environments. The transition between shelf and slope is exemplified in the phosphate-rich interbedded carbonate and shale exposure at Graf in eastern Iowa. Depth-dependent trilobite species distributions indicate a deepening trend from southern Minnesota toward eastern Iowa and northwestern Illinois (Hedblom, 1987). These facies patterns delineate a bathymetric depression in eastern Iowa and northwestern Illinois, surrounded by shallower shelf environments (Witzke and Kolata, 1988). Attempts to quantify Maquoketa bathymetry have focused on nautiloid septal implosion strength calculations

(Westermann, 1973, 1977, 1985; Hewitt and Westermann, 1988) and whole-rock $\delta^{13}C$ isotope stratigraphy.

Nautiloid depth-dependent septal implosion measurements. The study of septal implosions in *Isorthoceras sociale* nautiloids from Graf, Iowa, allow absolute depth to be approximated at the shelf-slope break using the most reliable criterion—pressure. Implosion occurs when the force of ambient water pressure is sufficient to overcome the inherent material strength of the septa. This normally occurs after death when soft tissue has deteriorated and the remaining shell sinks into deep waters. Unless leakage through the siphuncle occurs (see Westermann, 1985; Stridsberg, 1990), the atmospheric pressure behind each septa is sealed from the outer environment, creating what is essentially a vacuum at depth. The force of water pressure acting on the outer septal surface is therefore not countered by significant resisting force. If hydrostatic pressure (i.e., water depth) is sufficient, the septa will implode. Westermann (1973) detailed procedures and methods for measuring and calculating septal strength as follows:

$$\text{Strength} = (\text{septal thickness}/\text{septal radius}) \times 1000,$$

and supplied conversions for translating strengths into absolute depths of implosion. Hewitt and Westermann (1988) offered a revised equation:

$$\text{Depth of implosion} = [100\ (131\ \text{MPa}/\ \{\text{septal radius}/\ 2\ \text{septal thickness}\})] - 10\ \text{m}.$$

Previously investigators (Westermann, 1973; Frey, 1989) utilized specimens with intact ultimate septa, and used this septum for all measurements, because it is the largest and therefore weakest, and yields the shallowest depth of possible implosion. The depth values obtained from such studies do not reveal absolute depth of deposition, but rather indicate a maximum depth value that the animal, either while living or dead, did not exceed. Partial or total implosion in the vast majority of Graf samples precludes the use of ultimate septal measurements. However, partially imploded specimens (those with at least one large anterior septa imploded and at least one small posterior septa intact) allow for a rare insight into estimation of absolute water depth of final deposition (Figs. 5 and 8; Table 2). Septal thickness in *I. sociale* is constant; therefore, variances in strength are dependent only upon changes in septal radius. Because each succeeding septa from the posterior end contains a larger surface area than its predecessor, the collection of septa within a single nautiloid specimen represents a range of strengths, from the relatively strong small posterior septa to the relatively weak large anterior septa. A partially imploded nautiloid can therefore reveal the approximate absolute water depth of post mortem deposition by determining the strength and implosion depth of the largest (weakest) unimploded septa. Depth-dependent pressure is inferred to have been sufficient to implode the preceding septum, but not the slightly smaller and stronger intact neighboring septum. Absolute depth of final deposition is therefore slightly less than the depth value calculated for the weakest intact septum. Results from analysis of cut and polished Graf nautiloids collected for this study from middle Elgin strata (Fig. 3; south-central unit 4) indicate an average depth of implosion to have been about 200 m (Table 2; note that the nautiloids were deposited some time after interpreted maximum sea level).

A potential source of error with this method involves physical contact between shells causing premature septal puncturing and implosion. The likelihood of such an event depends upon the taphonomic history of the deposit. Witzke and Glenister (1987) suggested that the deposits may have resulted from a series of mass mortality events, with the nesting phenomenon occurring when septa imploded and opened a vacuum into which neighboring shells were drawn. They cited the deep water environment of deposition, and the pristine, unabraded preservation of shell material as evidence that little physical contact between shells occurred. Raatz (1992) agreed that nesting resulted from the impelling force of septal implosion and vacuum release, but suggested that the coquina deposits resulted from episodic, deep water boundary currents that winnowed fine muds and concentrated larger shell material. He cited the oriented nature of the orthocones, and the vertical pattern of anoxic shales overlain by coquina, overlain by argillaceous carbonates, overlain by anoxic shales, as evidence for higher energy events temporarily oxygenating the normally dysoxic-anoxic sea floor. This hypothesis allows that mechanical puncturing may have occurred. However, any nautiloid that punctured its neighbor's septa would also have likely become permanently nested inside of that individual. The common occurrence of partially imploded but unnested samples suggests that implosion also resulted directly from water pressure force. In all but two cases (83938A and 83939B, Table 2), the analyzed samples for depth

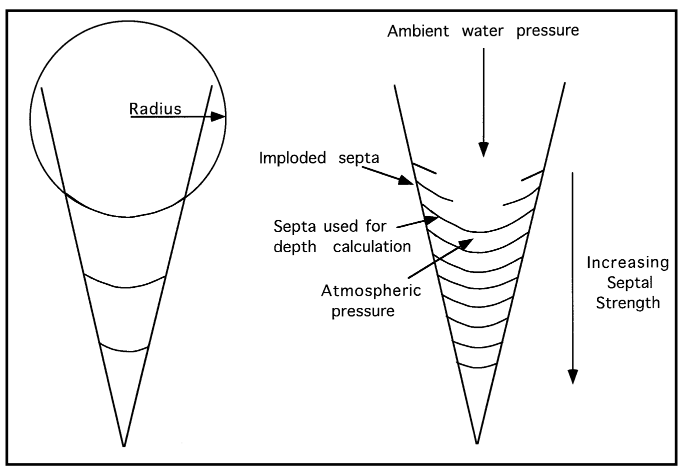

Figure 8. Absolute water depths can be quantified by measuring depth-dependent nautiloid septal implosions (methodology after Westermann, 1973, 1977, 1985; Hewitt and Westermann, 1988). *Isorthoceras sociale* nautiloids from Graf, Iowa, exhibit partially imploded septa. The large, weak anterior septa imploded due to ambient water pressure, whereas the stronger, posterior septa remain intact. Individual nautiloids, with their suite of different sized septa, represent sensitive bathymetric indicators. Measurements of septal strength of the first intact septum following a series of imploded septa yields absolute depth of deposition. For Graf, located on the shelf-slope boundary, the depth during middle Elgin time was ~200 m.

TABLE 2. NAUTILOID SEPTAL STRENGTH MEASUREMENT DATA EMPLOYING BOTH THE WESTERMANN (1973) AND HEWITT AND WESTERMANN (1988) METHODS*

Specimen (SUI)	183935	83936	83937A	83938A	83938B	83939B	83939C	83940	83944B	Average
Septal radius (mm)	5.5	8.5	8.5	6.3	6	7	6.5	6.75	7.0	
Septal thickness (mm)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
Septal spacing (mm)	2.3	....	....	3.25	1.88	2.1	1.4	....	1.75	
Septal strength thickness/radius	0.0091	0.0059	0.0059	0.0079	0.0083	0.0071	0.0077	0.0074	0.0071	
Implosion depth Westermann (1973) method (m)	273	177	177	237	249	213	231	222	213	221
Implosion depth Hewitt and Wester-mann (1988) method (m)	228	144	144	198	208	177	192	184	177	184

*Both equations yield a final depth of deposition for middle Elgin deposits at about 200 m, consistent with the interpretation that the south-central area (Graf) represents a shelf-slope boundary environment. All specimens housed in the Paleontology Repository, Department of Geology, University of Iowa (SUI).

determination lacked internally nested orthocones, implying they imploded from pressure related to water depth.

$\delta^{13}C$ stable isotope stratigraphy methods. Whole-rock sampling for stable isotope analysis involved selecting and milling powdered samples from stratigraphic intervals that contained original calcitic micrite fabrics unaltered by dolomitization. Sampling was restricted to the better preserved north and north-central areas, with no samples from the pervasively dolomitized south-central area. Drilled sample powders were analyzed at the University of Michigan Stable Isotope Laboratory.

Results. $\delta^{13}C$ variations through the stratigraphic sequence suggest deep water environments within this basin during lower Elgin Member deposition. Positive 1.0‰ to 1.5‰ correlatable stratigraphic shifts in both the north and north-central areas at the Dubuque-Elgin boundary (Fig. 9) are inferred to approach a proxy for paleobathymetry, signifying increased organic carbon burial associated with deepening dysoxic-anoxic conditions (Garrels and Lerman, 1984). The generally heterogeneous concretionary limestone fabrics of many Elgin samples led to a concern that individual drilled sites might not be representative of the entire hand sample, possibly making the data set random and meaningless. To test for this possible source of error, 14 microsamples were drilled laterally and vertically to the dolomitized margins of a single concretionary limestone bed previously used for whole-rock analysis. Results indicate consistent intrasample $\delta^{13}C$ isotopic signatures, with values exhibiting a standard deviation of ~±0.05‰ (Fig. 10), adding confidence to the interpretation that the large 1.0‰ and 1.5‰ shifts are real stratigraphic features, and not sampling artifacts of spatial heterogeneity within concretions.

Depositional model

The depositional model for this study is based on local and regional lithic and biologic patterns (Fig. 11; Table 1). A number of consistent trends are observable throughout the Dubuque-Elgin depositional regime. The Dubuque Formation becomes progressively more trilobite- and mud-rich upward, and loses its benthic green algal component (Bakush, 1985). In all but the northernmost section, the contact with the Elgin Member is marked by a CS consisting of a phosphorite bed with overlying dysoxic-anoxic dark brown shales. Above this shale is a thick carbonate package, with dominantly graptolite, lingulid brachiopod, and trilobite low-energy carbonate mudstones in the lower portion, and higher energy carbonate mudstones, wackestones, and packstones with diverse benthic skeletal fauna in the upper portion. This lithic and biotic pattern has been interpreted to represent a transgressive-regressive depositional subcycle (Dubuque-Elgin subcycle of the Maquoketa cycle, Witzke and Kolata, 1988; subcycle 6B of the Maquoketa cycle, Witzke and Bunker, this volume), the Dubuque Formation and condensed phosphatic bed representing transgressive deposits, the dark brown pelagic shale representing sea-level highstand deposits, and the remaining Elgin carbonate representing regressive deposits (Fig. 12).

The nature of the Dubuque-Elgin contact has been a source of controversy. Previously workers (Rooney, 1966; Bromberger, 1968) considered the contact unconformable, the result of uplift and subsequent subaerial exposure. The peloidal and oolitic nature of phosphatic sediment grains, and clear spars resembling meteoric phreatic cements surrounding the grains supported this interpretation. Reinterpretation of this boundary indicates that the contact is either conformable or an example of a submarine disconformity (Witzke, 1980; Witzke and Kolata, 1988; Ludvigson et al., 1992; Raatz et al., 1992a). Facies and basin architecture, bathymetric interpretations, and the poorly sorted nature of the phosphatic peloids and ooids at the contact suggest a low-energy (deep) environment. This study has found no evidence for subaerial exposure, and is in agreement with Witzke and Kolata (1988) in placing the contact near the apex of a significant transgressive event. The multiple phosphatic hardground

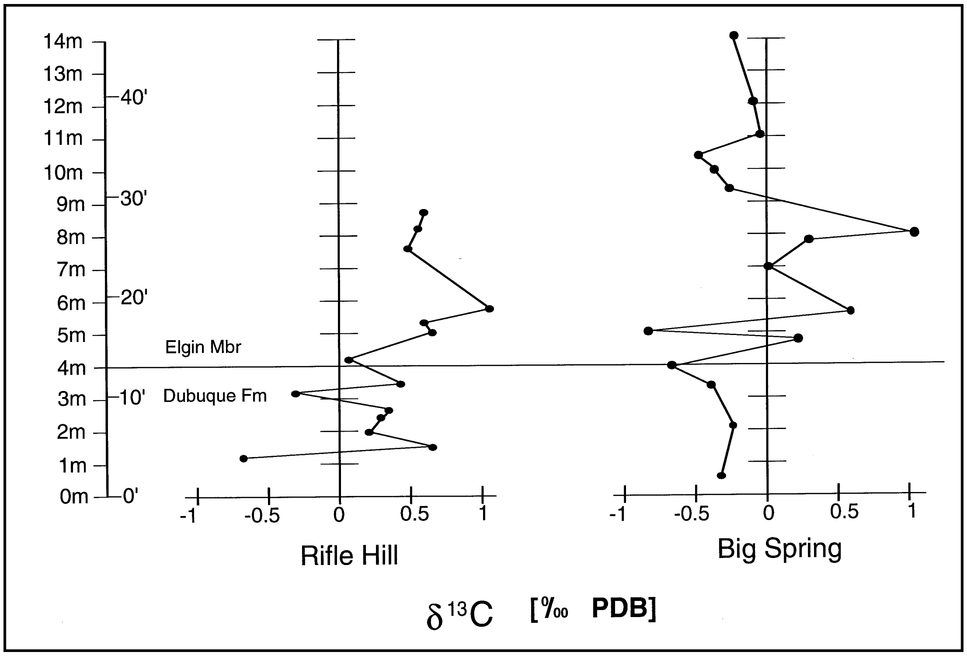

Figure 9. $\delta^{13}C$ whole-rock isotope data (PDB = Peedee belemnite) from the north and north-central areas exhibiting a correlatable stratigraphic shift across the Dubuque-Elgin boundary. The excursion is interpreted to result from increased burial of organic carbon, a function of increased surface productivity resulting from upwelling of deep, nutrient-rich waters, and the subpycnocline anoxic environment of deposition associated with lower Elgin high sea levels.

surfaces are interpreted to represent times of sediment starvation during transgression (Brett and Baird, 1986). The origin of the phosphate is interpreted to be from quasiestuarine circulation and associated upwelling within a density-stratified water column (Heckel, 1977; Witzke, 1980, 1987). Stratification was established due to development of a pycnocline, with a warm, oxygenated upper water mass above a denser, dysaerobic to anaerobic bottom water mass. Quasiestuarine circulation was driven by a gyre circulation pattern created by fresh-water runoff from Taconic highlands and wind-induced surface currents (Witzke, 1980, 1987; Ludvigson et al., 1992; Raatz et al., 1992b; Fig. 4). Although circulation within the study area largely paralleled the Transcontinental Arch, net surface current flow was basinward, which drew deep, phosphate-rich waters shelfward and created an area of upwelling at the shelf break. Upwelled dissolved phosphate was utilized by primary producers to enhance surface productivity. This resulted in an increase in the physical settling of organic matter. Anaerobic decomposition of organic material released dissolved phosphate, which concentrated selectively on original phosphatic lingulid and fecal grains (see Brett and Baird, 1986). This selective precipitation, aided by episodic intense bioturbation during brief, storm-induced oxygenated periods (Kolata and Graese, 1983), created the oolitic and peloidal grains present in the deposit.

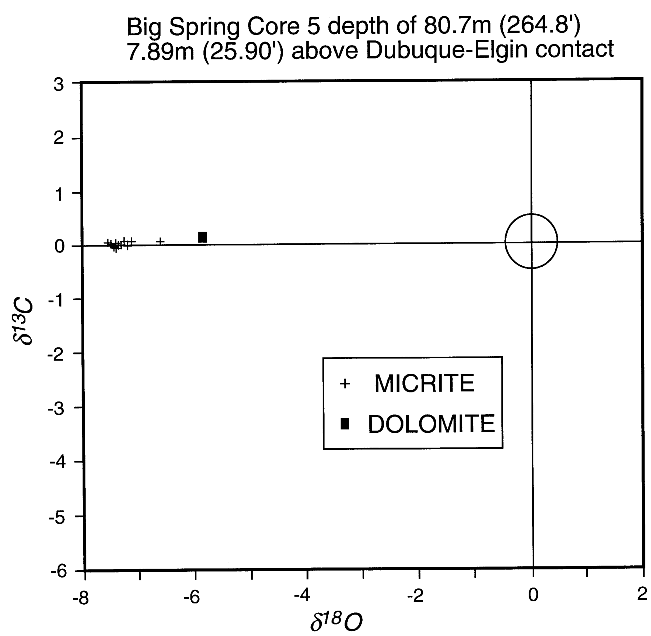

Figure 10. Intrasample carbon isotopic error is negligible (± 0.05‰), providing additional confidence that the 1.0‰ to 1.5‰ stratigraphic variations are real and not sampling artifacts.

Episodic storm-induced boundary currents, occurring below storm wave base along basin margin slopes, are known to exist in modern environments and have been interpreted to

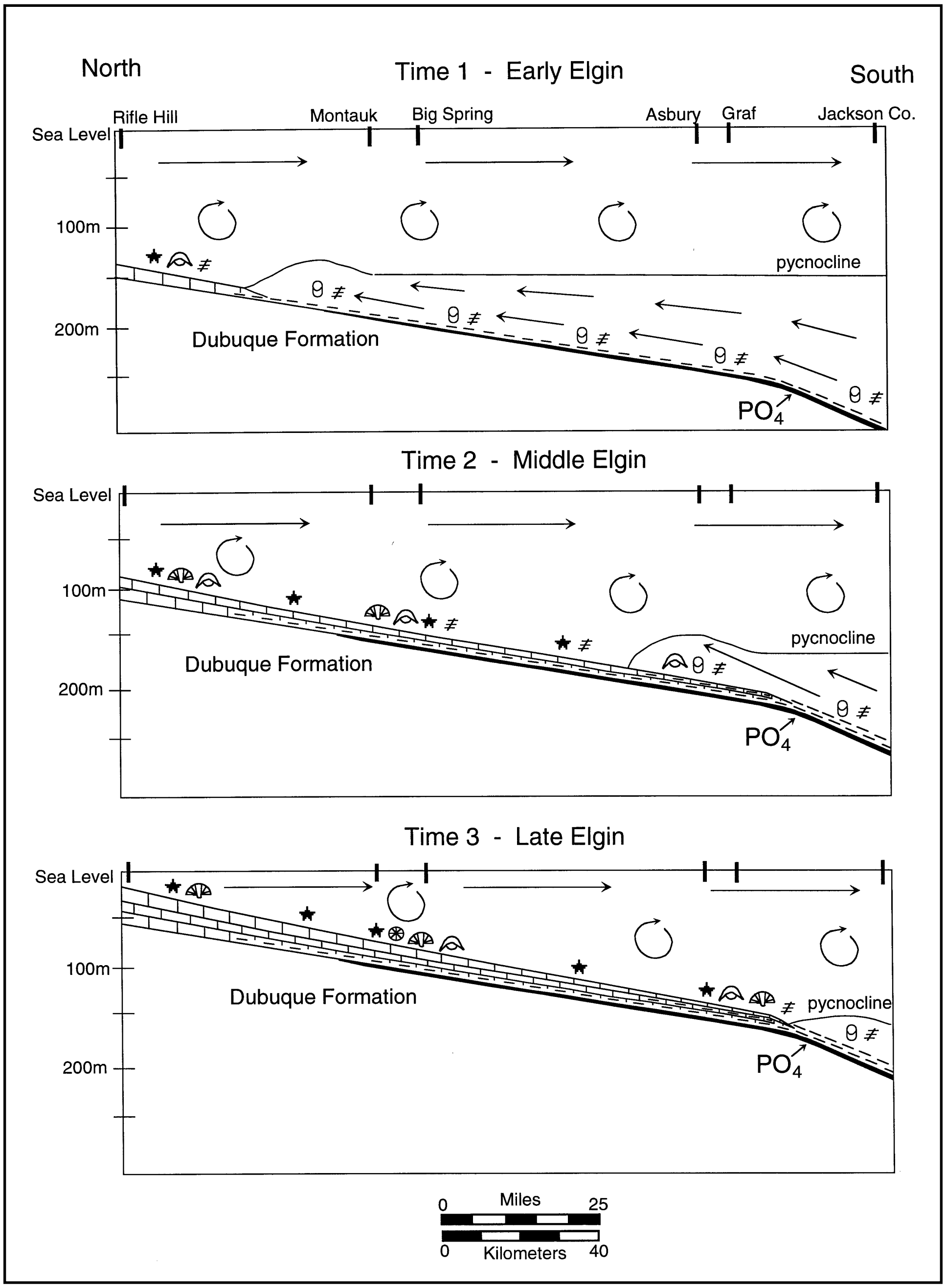

Figure 11. Depositional model for the Elgin Member of eastern Iowa with benthic and pelagic ecologic indicators included (see Fig. 3 for symbols key). Early Elgin (Time 1) deposition is interpreted to have occurred in a deep (>200 m) epicontinental sea with all but the northern shelf below a temperature-induced pycnocline in dysoxic-anoxic water. The basal Elgin Member phosphatic condensed section was deposited as the result of upwelling, phosphate precipitation, and sediment starvation during rapid sea-level rise. Dark brown shales with pelagic fauna were deposited during sea-level highstand, and are composed of organic-rich fine clastics derived from the distant Taconic uplands. Middle Elgin (Time 2) deposition occurred during falling sea level and associated southward migration of the pycnocline, allowing for oxygenation of significant portions of the northern shelf. Late Elgin (Time 3) deposition occurred as sea level continued to fall. The pycnocline migrated southward, allowing for carbonates with diverse benthic fauna to be deposited across the entire shelf. Dysoxic-anoxic pelagic shales continued to be deposited in the southern slope area (Jackson County) despite the fallen sea level, suggesting significant depths during the previous sea-level highstand. Arrows indicate interpreted net deep and shallow water flow, established by surface winds and freshwater runoff creating a gyre circulation pattern.

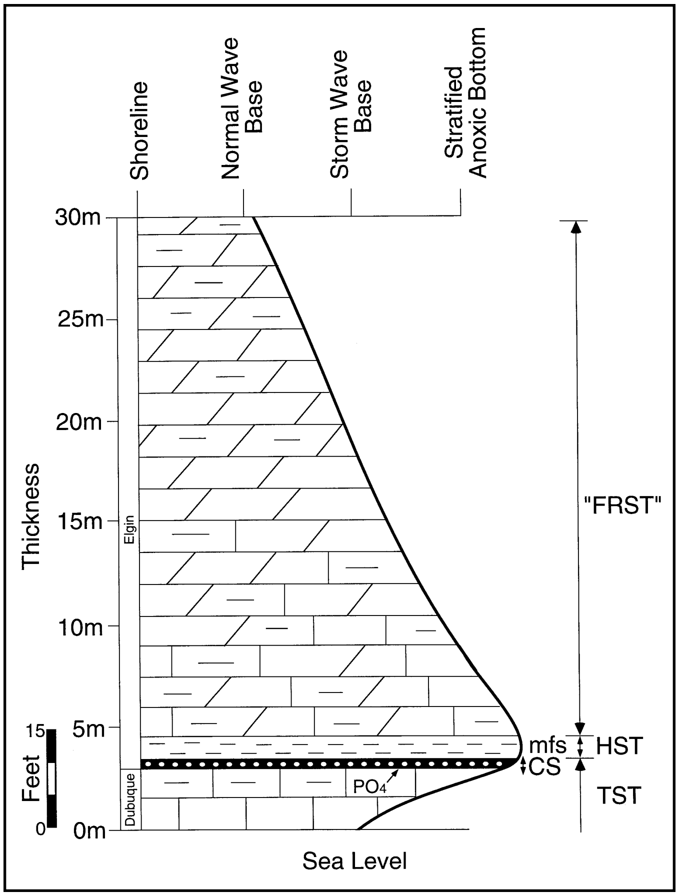

Figure 12. Relative sea level curve for the upper Dubuque Formation and Elgin Member in eastern Iowa, illustrating the Dubuque-Elgin transgressive-regressive subcycle. Sequence stratigraphic nomenclature is superimposed: TST = transgressive systems tract, HST = highstand systems tract, CS = condensed section, mfs = maximum flooding surface, and "FRST" = forced regressive systems tract. The lithologies superimposed on the curve are largely representative of the north-central area. Modified from Witzke and Kolata (1988).

have acted in the past (Hollister et al., 1984; Johnson et al., 1984; Baird and Brett, 1986; Wignall, 1989; Lehmann et al., 1990). These episodic currents could have temporarily reoxygenated the deep bottom waters and allowed brief colonizations by benthic invertebrates into the nutrient-rich environment (Kolata and Graese, 1983).

During sea-level highstand in the early Elgin, fine mud derived from eastern Taconic source areas was transported to the Midcontinent, resulting in distal clastic basinal deposits, represented by the lower Elgin dark shales (Witzke, 1980). As sea level fell during deposition of the middle Elgin, increasing areas of the sea bottom were oxygenated and shallowed into the photic zone, allowing for widespread carbonate production and deposition (Fig. 11). Depositional environments near the pycnocline continued to be affected by episodic storm-induced oxygenating currents. These currents winnowed sediment, temporarily oxygenated the normally dysoxic to anoxic bottom, and produced the pattern of dark shale, overlain by nautiloid coquina, overlain by argillaceous carbonate, overlain by dark shale observed at the Graf shelf-slope boundary outcrop. By late Elgin time, sea level had fallen sufficiently to allow bottom oxygenation of almost the entire shelf (Fig. 11). Open marine, diverse biotas in mudstone, wackestone, and packstone lithologies dominate these upper Elgin shelf deposits. Despite the falling sea level, lowstand dysoxic-anoxic deep water dark shales continued to be deposited below the pycnocline in slope-basin environments of the southern area, consistent with the interpretation of a deep (200 m [650 ft] or more) sea during earlier sea-level highstand (Raatz et al., 1992b).

Sequence stratigraphy

Attempts to apply sequence stratigraphic concepts after the methodology of Sarg (1988) and Von Wagoner et al. (1988) has had mixed success in describing cratonic Dubuque-Elgin deposits (Fig. 12). Sequence stratigraphic parlance denotes the transgressive upper Dubuque Formation a transgressive systems tract (TST), the uppermost boundary of which is composed of the Elgin Member phosphatic CS. The base of the overlying dark dysoxic-anoxic shales represent the maximum flooding surface of sea-level highstand and composes the basal component of the highstand systems tract (HST). The overlying thick regressive carbonate package composes the remainder of the HST, or an as-yet poorly defined forced regressive systems tract (FRST), or the carbonate analog of the clastic falling sea level systems tract (FSLST) (Nummedal, 1992; Nummedal and Riley, 1992; Witzke and Bunker, this volume).

Discussion. The Dubuque-Elgin transgressive-regressive subcycle records a relatively rapid sea-level rise and a relatively slow fall (Witzke and Kolata, 1988), resulting in a thick package of regressive Elgin carbonates. The Elgin shales and carbonates are not sufficiently thick to have built up autogenically from a dysoxic-anoxic environment to fair-weather wave-base depths; therefore regression resulting in base-level fall (forced regression of Posamentier et al., 1990, 1992) not lost accommodation space due to basin infilling, must have been the dominant mechanism for relative sea-level change. For example, Graf deposits in the south-central area grade upward from dysoxic-anoxic dark brown pelagic shales to cross-bedded wackestones and packstones with diverse open marine benthic fauna in an interval of 5.30 m (17.39 ft). Stress on carbonate production due to depth (a combination of relative sea level and basin architecture) and time available for sediment accumulation are the major controls on sediment thickness in the Dubuque-Elgin, not tectonic subsidence or accommodation space limitations. In this instance sea level controlled deposition; deposition did not control sea level. This interpretation of sea-level change as the major control of water depth is in contrast with some models that state sediment volume and depositional infilling control paleodepth, and sea level is limited to the control of stratal boundaries and distribution of lithofacies (Sarg, 1988). If forced regression rather than basin infilling was the mechanism for relative sea-level fall, it must then be questioned whether the regressive Elgin carbonates do in fact represent an HST, or whether this label applies only to lithologies that underwent aggradational sediment infilling. If such a limited view of HST is taken, FRST or FSLST terminology must be employed for those deposits derived from forced regressions where aggradational sediment thickness does not pose a limiting factor to accommodation space.

CONCLUSIONS

1. The Upper Ordovician epicontinental sea was deep (>200 m [650 ft]), and characterized by the development of a density stratified water mass with dysoxic-anoxic bottom conditions.

2. Quasiestuarine circulation, driven by fresh-water runoff from the Taconic highlands and wind-induced surface currents, created a gyre circulation pattern that moved surface currents basinward, and deep water shelfward, causing upwelling of phosphate-rich waters and the inorganic precipitation of phosphatic peloids and ooids during transgression.

3. Episodic, deep water, storm-induced boundary currents affected sediment at the shelf-slope margin, creating repetitive winnowed shell deposits and interbedded shale-carbonate layers within the normally dysoxic-anoxic environment.

4. Upper Dubuque Formation deposits represent transgressive carbonates and shales (TST). The basal Elgin Member phosphatic bed is a sediment-starved CS representing late transgressive deposits. Dark brown pelagic shales above the phosphorites cap the CS and represent the maximum flooding surface, and act as the boundary between TST and HST deposits. The remaining carbonates of the middle and upper Elgin represent regressive strata, deposited as the result of forced regression, not from sediment aggradation and lost accommodation space due to basin infilling.

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