PS Filling in Gaps in the Sedimentary Record: An Integrated Study of Microfacies and Discontinuity Surfaces in Devonian Epeiric Sea Carbonates, Iowa*

Christopher M. Bowie[1] and Mara E. Brady[1]

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[1] Department of Earth and Environmental Sciences, California State University, Fresno, CA (bowie@mail.fresnostate.edu; mebrady@csufresno.edu)

Abstract

Discontinuity surfaces develop in carbonate successions due to environmental changes that result in a hiatus in sediment accumulation or erosion of previously deposited sediment. Each discontinuity surface therefore, represents a gap in the sedimentary record. Although the depositional record is missing at an unconformity, the diagenetic record is continuous and contains information about the environment and climate leading up to, during, and after a depositional break. By studying discontinuity surfaces, it is possible to gain insight into the cause of these breaks in sedimentation and fill in these gaps in the sedimentary record.

The Middle-Late Devonian Cedar Valley Group was deposited in the Iowa Basin during four third-order transgressive-regressive cycles that flooded the Laurentian craton and depositing subtidal and peritidal carbonates across Iowa and adjacent states. The apparent lack of systematic parasequence stacking patterns and evidence of missing depositional cycles in these cratonic ramp carbonates are thought to be the result of lowered sedimentation rates and frequent depositional hiatuses. Periodic oceanographic changes that resulted in inhospitable conditions in the shallow epeiric sea may have stressed the carbonate factory and contributed to these unique and condensed strata. This study integrates microfacies analysis and discontinuity surface characterization in the Little Cedar and Coralville Formations to constrain the environmental factors that contributed to possible suppression of the Middle-Late Devonian carbonate factory in the Iowa Basin.

A depositional model for the Cedar Valley Group was developed from 12 different microfacies identified during this study, which fall into five distinct facies tracts spanning the inner, middle, and outer shelf. One hundred and five discontinuity surfaces were documented and classified as either erosion surfaces, omission surfaces, or exposure surfaces. Erosional surfaces are the dominant surface type at the inner and middle shelves, most of which are interpreted to be the result of storm currents (i.e. tempestites). Omission surfaces increase in frequency from inner toward the outer shelf, indicating more frequent submarine hiatuses in the offshore direction. Exposure surfaces are most common in the inner shelf, where they are organized into closely spaced intervals, interpreted to be “sequence boundary zones” (after Montanez and Osleger, 1993; Hillgartner, 1998). The lateral and vertical distribution of discontinuity surfaces gives important clues as to the morphology of the lower Cedar Valley Group shelf, which is characterized here as a storm dominated epeiric ramp.

Carbonate sediments were generated principally in the inner shelf from peloids, ostracods and calcareous algae. A second cite of sedimentation generation was the high energy shelf margin, where open marine fauna such as crinoids, bryozoans, and corals contributed to grain stone shoals that were probably tidally influenced. Reef builders were never able to establish a rigid reef barrier because of the frequency of powerful storms, which would topple coral colonies and obliterate patch reefs the at the middle shelf margin periodically. Middle shelf sediment was washed into the inner shelf in storm washover lobes and transported to the outer shelf by turbidity currents during storm ebb flows. During sea level highstands, the intertidal zone prograded toward the middle shelf margin and peloid rich muddy sediment could be transported to the outer shelf by the same mechanism.

Documenting and characterizing discontinuity surfaces aids in sequence stratigraphic analysis in the absence of recognizable parasequences and stacking patterns. The results of this study allowed identification of systems tracts for the upper Little Cedar and Coralville formations. Most sediment was accumulated in the highstand systems, which culminates with sequence boundary zones at the inner shelf only. The inner shelf was left emergent for most of the lowstand systems tract, at which time evaporitic ponds and paleosols developed in the inner shelf and the resulting diagenetic fluids altered the underlying highstand systems tract. The transgressive systems tract thins and pinches out in the shoreward direction where it may be represented entirely by a single discontinuity surface.

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Christopher M. Bowie and Mara E. Brady
Department of Earth and Environmental Sciences, California State University, Fresno, 2576 East San Ramon Ave., Fresno, CA

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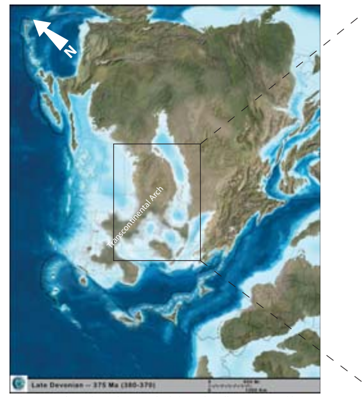


Figure 1: North American Paleogeography during Cedar Valley Group Deposition (Blackey, 2013). Above picture is probably representative of the sea level falling stage or lowstand of Iowa T-R Cycle 5 (Figure 4:B). During maximum highstand, the transcontinental arch was breached by the impinging Devonian seas and migration pathways were established between the cratonic interior and western continnental margin basins.

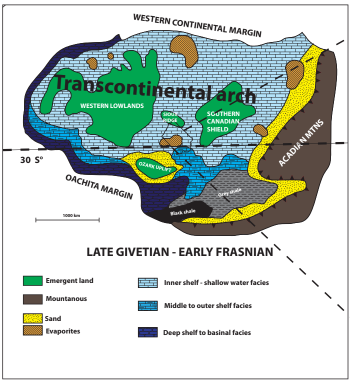


Figure 2: Sedimentary facies of the midcontinent carbonate shelf during Cedar Valley deposition (*modified after* Bunker and Witzke, 2004). Above figure is representatlve of the sea level highstand of Iowa T-R cycle 5 (Figure 4: B). Note subtropical location of Iowa Basin and straits connecting the continental interior and Western Continental Margin.

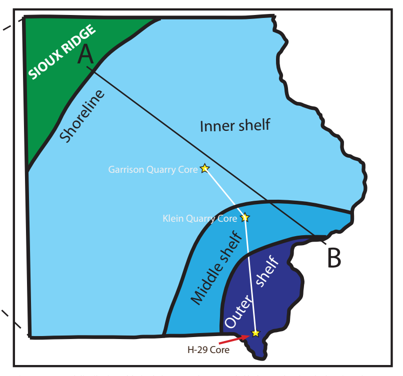


Figure 3: General distribution of facies belts across the eastern half of Iowa showing the location of cores taken used in this study (yellow stars) and cross section in Figure 12. Cross section A-B is shown in Figure 4:A.

INTRODUCTION

The Iowa Basin strata are a remarkable example of Devonian epeiric sea sedimentation that has no modern analog. The Cedar Valley Group was deposited during 4 successive 3rd-order sequences that flooded the North American craton (Laurasia) in the Middle Devonian (Figure 1-4). When compared to contemporaneous passive margin deposits, the Cedar Valley Group strata is typified by thinner units and incomplete cycles indicative of very low and intermittent sedimentation (Brady, 2012; Figure 5). These breaks in sedimentation are marked by discontinuity surfaces, resulting in condensed or truncated parasequence-style cycles.

Discontinuity surfaces represent abrupt tectonic, environmental, or eustatic changes that resulted in a hiatus in sediment accumulation, and/or erosion of previously deposited sediment, of whatever duration (Clari et al., 1995), and have been the subject of increasing interest due to their importance in resolving high frequency sea level fluctuations and basin evolution below biostratigraphic resolution (Hillgartner, 1998; Chow and Wendte, 2011; Christ et al., 2012). In particular, Hillgartner (1998) demonstrated how discontinuity surfaces may be distributed among omission-dominated and exposure dominated-zones which reflect larger scale transgressions and regressions (Figure 6), emphasizing that these surfaces are just as important as the sedimentary units they delimit. Careful study of discontinuity surfaces also has the potential to reveal "hidden sedimentary units", or evidence of previously deposited beds that have been eroded (Figure 7).

The character and distribution of discontinuity surfaces can have important implications for reservoir compartmentalization and fluid migration (Christ et al., 2012; Saller et al., 1994). Additionally, the potential influence of discontinuity surfaces in fracture propagation during hydraulic fracturing underscores the importance for understanding how and why these surfaces form, and how they may be distributed within the stratigraphic record. This study aims to explain the condensed and discontinuous Cedar Valley Group deposition within in a sequence stratigraphic framework by characterizing discontinuity surfaces and microfacies in the Iowa Basin.

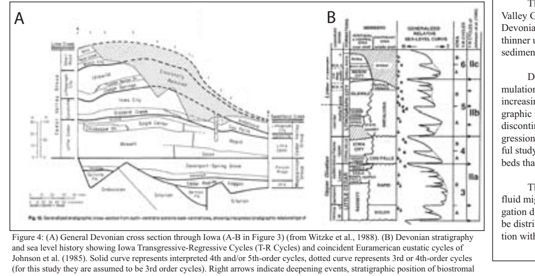


Figure 4: (A) General Devonian cross section through Iowa (A-B in Figure 3) (from Witzke et al., 1988). (B) Devonian stratigraphy and sea level history showing Iowa Transgressive-Regressive Cycles (T-R Cycles) and coincident Euramerican eustatic cycles of Johnson et al. (1985). Solid curve represents interpreted 4th and/or 5th-order cycles, dotted curve represents 3rd or 4th-order cycles (for this study they are assumed to be 3rd order cycles). Right arrows indicate deepening events, stratigraphic position of biostromal units (b) and evaporites (e) are shown (*from* Witzke and Bunker, 1997). Note formations, and in some cases, members are delimited by

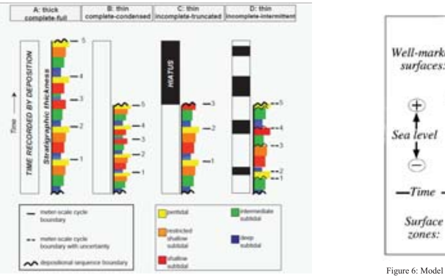


Figure 5: Hypothetical stratigraphic columns showing parasequence scale stacking patterns and relationships between thickness and time recorded by deposition, i.e., "completeness "(*from* Brady, 2012). (A) Ideal scenario, particularly for sequence stratigraphic studies and representative of passive margin sedimentation. (B) Equally temporally complete but thinner than A, possibly due to slower subsidence and equally slow sedimentation rate. (C) Similar subsidence and sedimentation rates to A but incomplete due to significant erosional truncation along an unconformity. (D) Combination of B and C:Thin and incomplete due to slow sedimentation and periodic nondeposition and/or erosion. Scenario D is representative of the Cedar Valley Group.

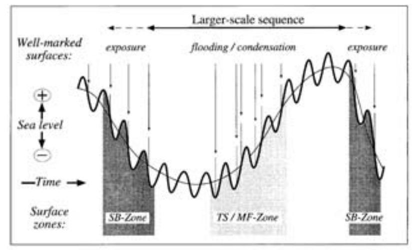


Figure 6: Model for formation of "discontinuity surface zones" dominated by either exposure surfaces or condensation surfaces (omission surfaces in this study). The superimposition of high-frequency, or parasequence scale sea level fluctuations on longer-term, or lower-order transgressive-regressive trends is expressed by alternating intervals dominated by exposure surfaces or condensation surfaces (*from* Hillgartner, 1998).

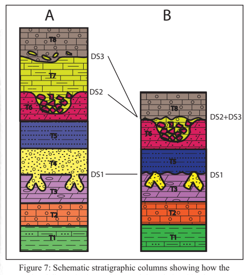


Figure 7: Schematic stratigraphic columns showing how the study of discontinuity surfaces and the relationships between underlying and overlying units can elucidate evidence of sedimentary units that are no longer present. Column B may represent the same amount of time as column A, but units T4 and T7 have been erosionaly removed. The only evidence that units T4 and T7 existed is in the burrow fills of DS1 and solution vugs of DS2, respectively. DS2 could be considered a composite surface necause it shows evidence of both subaerial exposure and erosion (*Modified* after Clari et al., 1995).

Methods

Polished slabs and thin sections were prepared from cores taken at three locations in a proximal to distal transect across the Iowa Basin. Over 55 m of core was described at a cm-scale with coverage through most of the Little Cedar and Coralville Formations. Parts of the lower Lithograph City Formation were captured in the Inner shelf and Outer shelf cores only. Thin sections were impregnated with a blue dyed epoxy and stained with a mixed Alizarin Red S and potassium ferricyanide solution to distinguish porosity and carbonate minerals. Microfacies analysis was used to characterize the depositional system by identifying the major sediment types in thin section, depositional environments, and the nature of the "carbonate factory" (Box 1).

Discontinuity surfaces were classified largely according to the scheme described by Hillgartner (1998; Figure 8), and categorized as either exposure surfaces, omission surfaces, or erosional surfaces. Evidence of erosional surfaces is includes sharp contacts, flute casts, truncated grains, non-Waltherian breaks, and evidence of traction deposition (Box 3). Key evidence of subaerial exposure includes karsting, collapse breccias, and meteoric digenesis (Box 4). Omission surfaces show evidence of submarine condensation and non-deposition, such as mineralized crusts and impregnated surfaces, which are often bored, burrowed, and encrusted by sessile organisms (Box 5).

This study was based primarily off of core and thin section observations. However, visits to key outcrops and field areas helped reaffirm our interpretations and illuminate some of the limitations inherent in core-only studies (Box 2).

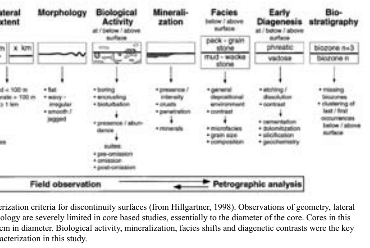


Figure 8: Characterization criteria for discontinuity surfaces (from Hillgartner, 1998). Observations of geometry, lateral extent, and morphology are severely limited in core based studies, essentially to the diameter of the core. Cores in this study were 3 to 5 cm in diameter. Biological activity, mineralization, facies shifts and diagenetic contrasts were the key discontinuity characterization in this study.

Results and Interpretations

- ►Twelve distinct microfacies are recognized for the study interval, and are grouped from proximal to distal into 5 facies belts (facies tracts) that span the inner, middle, and outer shelf (Box 1 and Table 1).
- ►There were two primary sites of sediment generations, 1) the inner shelf peloidal carbonate factory and 2) the middle shelf high energy open marine carbonate factory, corresponding to microfacies MF6 and MF7, respectively.
- ►A total of 105 discontinuity surfaces were documented between the three cores and were classified as either erosional (Box 3), omission (Box 4), or exposure surfaces (Box 5). Frequencies of different discontinuities are shown in Figure 9.
- ►During this investigation 8 distinct subclasses became apparent, all of which fall into one of the three general classifications (Figure 10 and Table 2).

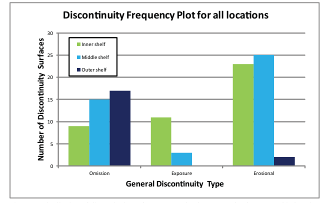


Figure 9: Distribution of discontinuity suface types at the three general paleogeographic locations where cores were taken in this study (actual locations shown in Figure 3). Note that the frequency of omission surfaces increases toward the outer shelf, and and the frequency of exposure surfaces increases in the opposite direction, with zero exposure surfaces observed in the outer shelf. Erosional surfaces dominated the Inner and middle shelves, while two were observed in the outer shelf core.

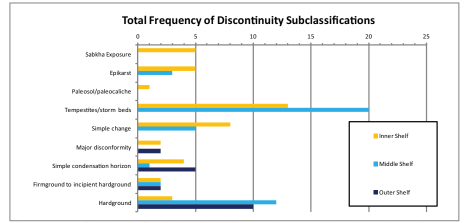
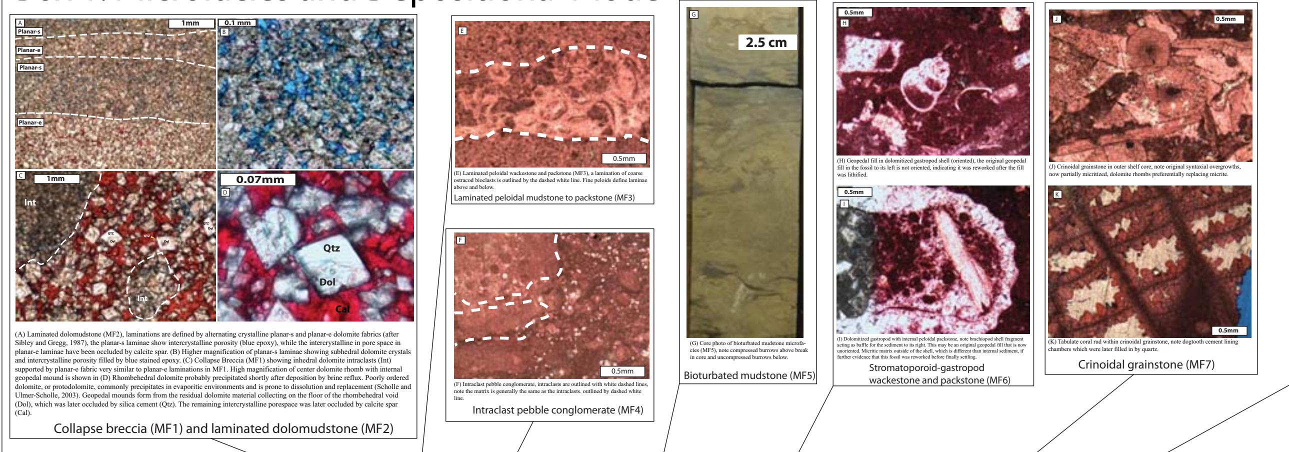


Figure 10: Interpreted subclasses for discontinuity surfaces in the Iowa Basin. Most omission surfaces are interpreted as submarine hardgrounds. Note that most erosional surfaces in the inner and middle shelf areas are attributed to storms. Only erosional surface in the outer shelf are major disconformities and are interpreted as sequence boundaries.

Box 1: Microfacies and Depositional Model



Collapse breccia (MF1) and laminated dolomudstone (MF2)

Laminated pelloidal mudstone to packstone (MF3)

Intraclast pebble conglomerate (MF4)

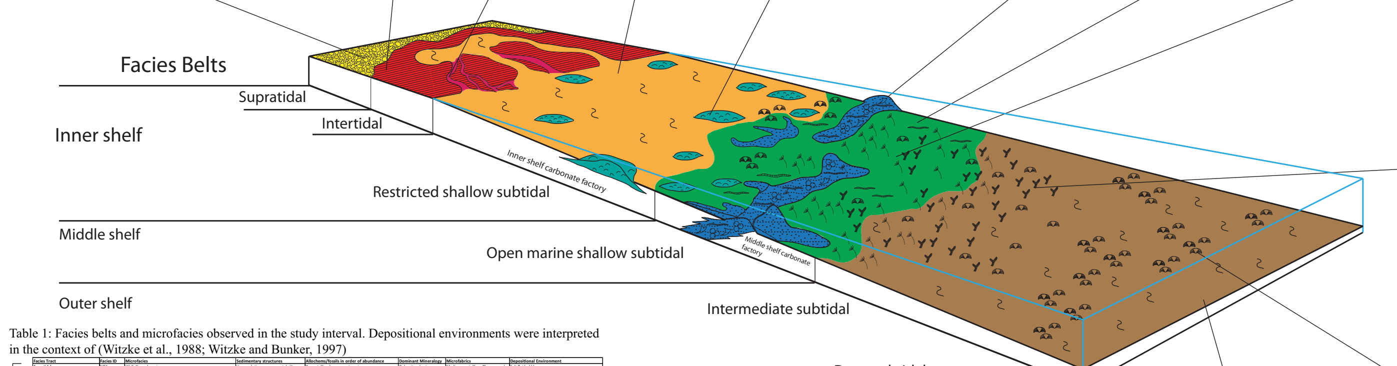
Bioturbated mudstone (MF5)

Stromatoporoid-gastropod wackestone and packstone (MF6)

Crinoidal grainstone (MF7)

(K) Laminar stromatoporoids in micrite matrix, these organisms probably acted as sediment stabilizers.

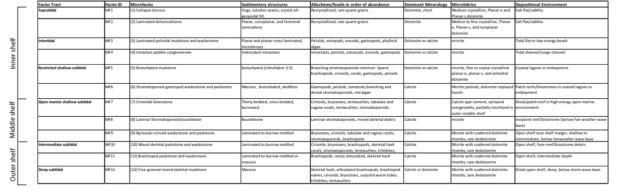
Laminar stromatoporoid boundstone (MF8)

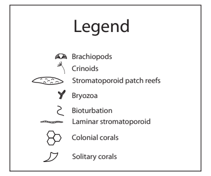


Bryozoan-crinoid wackestone and packstone (MF9)

Mixed skeletal wackestone and packstone (MF10)

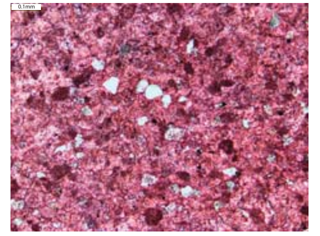
Table 1: Facies belts and microfacies observed in the study interval. Depositional environments were interpreted in the context of (Witzke et al., 1988; Witzke and Bunker, 1997)





Brachiopod wackestone and packstone (MF11)

Fine-grained skeletal mudstone (MF12)

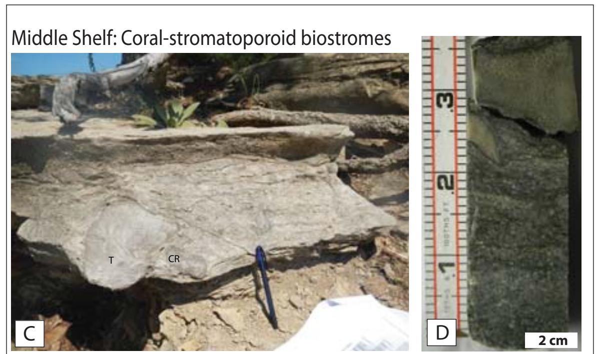


Box 2: The Biostrome Problem: Limitations of Core Based Studies

Inner Shelf: "Stromglomerate"

(A) Dr. Jim Walters of University of Northern Iowa pointing to a biostromal unit dominated by boulbus stromatoporoids in Messerly Quarry, approximately 8 km northwest of Waterloo, Iowa (*from* Walters et al., 2004). (B) Core photo of similar unit, because of the limitations of core studies (discussed below) these biostromal units, which are affectionately refered to as "stromglomerates" (*after* Groves, 2004) are catagorized based on their matrix as stromatoporoid-gastropod packstone and wackestone (MF6).

Middle Shelf: Coral-stromatoporoid biostromes



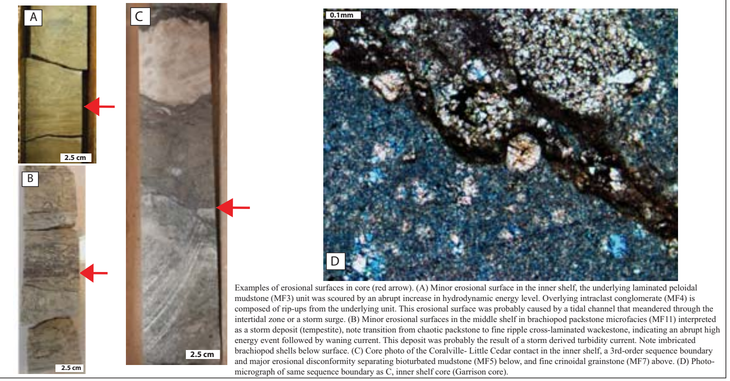
(C) Outcrop photo of the "lower Rapid biostrome" at Devonian Fossil Gorge, Iowa. Note tabulate coral (T) and colonial rogosan coral (CR) are larger than the diameter of cores used in this study. Pen for scale. (D) Example from outer shelf core used in this study which penetrates a large coral colony, probably in a biostromal unit similar to that shown in C. For reasons discussed below, this coral and the underlying grainstone are considered one unit and are assigned to the crinoidal grainstone microfacies (MF7). Photomicrographs of this unit are shown above in Box 1: Figure J and K.

Issues with biostromal units arise because of the limitations of core based observations. The cores in this study have a diameter between 3.8 and 5 cm (1.5 – 2 inches), significantly smaller than some of the larger bioclasts such as coral colonies and stromatoporoids which may reach over 50 cm in diameter and may be over a meter apart (compare figures A–B and C-D above). Consequently, cores may penetrate through biostromal units without intersecting any bioclast of these important reef builders. Alternately, core can, and does penetrate through coral and stromatoporoid colonies that are larger than the diameter of the core (Figure D above). Therefore, biostromal units are included with the microfacies that characterize their matrix. This avoids misinterpreting large colonial reef builders as reef framework (framestone of boundstone), when they are actually bioclasts (i.e., not in life position).

Table 2: Types of discontinuity surfaces identified in the Cedar Valley Group

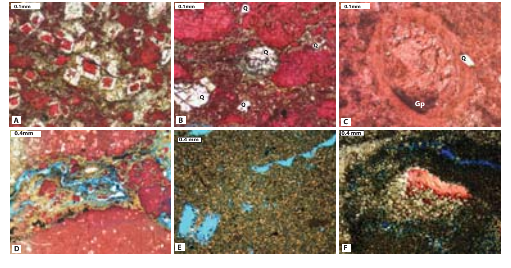
Discontinuity Classification	Subclass	Interpreted Temporal Significance of Hiatus	Features	Interpretation	Total Inner Shelf	Total Middle Shelf	Total Outer Shelf
Exposure surfaces							
1	**Sabkha package**	Minor	Pervasive dolomitization, solution collapse breccia, meteoric diagenesis	Progradation and periodic flooding of supratidal zones	5	0	0
2	**Epikarst**	Minor or Major	Solution collapse breccia, vugs, solution seams, meteoric diagenesis	Drop in relative sea level, often exposing subtidal sediment subaerially	5	3	0
3	**Paleosol/paleocaliche**	Major	Meteoric diagenesis, pedogenisis, solution seams	Prolonged exposure leading to soil development, may be underlain by epikarst	1	0	0
Erosional surfaces							
4	**Tempestites/storm beds**	Minor	Rip-up clasts, skeletal pavements, flute casts, graded beds and ripple cross laminations above surface	High energy event, scouring of soft sediment, no significant removal and return to normal sedimentation	13	20	0
5	**Simple change**	Minor or Major	Sharp contact between different lithologic units, may be stylolitic, rip-up clasts, argillaceous partings	Change in sedimentation patterns or shift in facies belts, transgressive surfaces or flooding surfaces	8	5	0
6	**Major disconformity**	Major	Sharp contact between different lithologic units, may be stylolitic, strong diagenetic contrast, underlying unit often shows evidence of meteoric diagenesis	Sequence boundary, major erosional truncation, often associated with subaerially exposure features below discontinuity	2	0	2
Omission surfaces							
7	**Simple condensation horizon**	Minor	Phosphatic and glauconitic lag, pyritized horizon, organic laminations	Very slow sedimentation to minor temporal hiatus	4	1	5
8	**Firmground to incipient hardground**	Minor or major	Burrows, phosphatic and glauconitic lag, weak mineralization, organic laminations	Submarine hiatus with partial sea floor lithification	2	2	2
9	**Hardground**	Major	Borings, burrows, phosphatic and glauconitic lag, strong mineralization, biological encrustation, organic laminations, burrows may be filled in by different lithology	Submarine hiatus with complete lithification and prolonged exposure on the sea floor	3	12	10

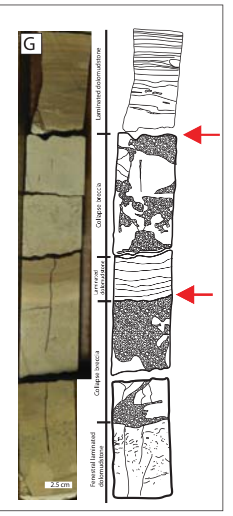
Box 3: Erosional Surfaces



Examples of erosional surfaces in core (red arrow). (A) Minor erosional surface in the inner shelf, the underlying laminated peloidal mudstone (MF3) unit was scoured by an abrupt increase in hydrodynamic energy level. Overlying intraclast conglomerate (MF4) is composed of rip-ups from the underlying unit. This erosional surface was probably caused by a tidal channel that meandered through the intertidal zone or a storm surge. (B) Minor erosional surfaces in the middle shelf in brachiopod packstone microfacies (MF11) interpreted as a storm deposit (tempestite), note transition from chaotic packstone to fine ripple cross-laminated wackestone, indicating an abrupt high energy event followed by waning current. This deposit was probably the result of a storm derived turbidity current. Note imbricated brachiopod shells below surface. (C) Core photo of the Coralville- Little Cedar contact in the inner shelf, a 3rd-order sequence boundary and major erosional disconformity separating bioturbated mudstone (MF5) below, and fine crinoidal grainstone (MF7) above. (D) Photomicrograph of same sequence boundary as C, inner shelf core (Garrison core).

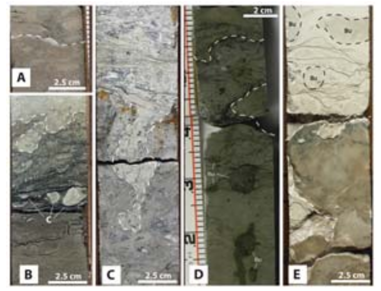
Box 4: Exposure Surfaces



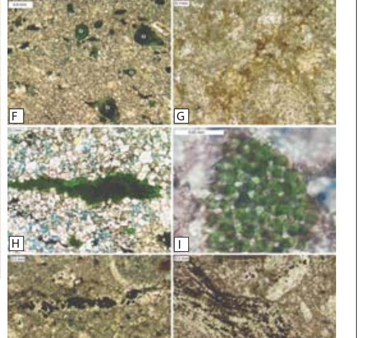


Examples of petrographic features associated with exposure surfaces and evidence of meteoric diagenesis. (A) Dedolomite rhombs with calcite cores. Dolomite precipitated in hypersaline lagoons and evaporite flats often have poorly ordered inclusion rich cores which are prone to dissolution and replacement, in this case by late calcite spar (red). (B) Detrital quartz sand grains (Q) in an argillaceous matrix, the larger grains appear to have been fractured in situ, and the cracks are filled in by the same argillaceous material. This is interpreted as the result expansive clays shrinking and swelling under alternating dry and wet conditions. (C) Geopedal fill (Gp) in a vug that was once open and later healed by calcite spar. This may have originally been an ostracod fossil, or it could be a root cast. Residual insoluble material collected on the floor of the vug after original internal material dissolved or decomposed. The concentric micritic coating enveloping a quartz grain (Q) is likely of microbial origin. (B) Solution collapse breccia in solution seam/vug with void filling argillaceous material, note insoluble pyrite collecting on the floor of the vug. Brecciation may have resulted or been accentuated by wetting and drying of expansive clays. (E) Moldic porosity in subhedral dolomite matrix below Coralville-Little Cedar sequence boundary, the fossils were dissolved by meteoric fluids during sea level lowstands when the inner shelf was emergent, preserving the shape of a crinoid segment (lower left) and brachiopod valve (upper right). (F) Dolomite crystal silt forming a geopedal mound in a vug that was later filled by calcite spar. (G) Core photo and interpretive sketch of repeated exposure surfaces, or sabkha packages. Alternating laminated dolomudstone (MF2) and Collapse breccias (MF1) show repeated flooding of the supratidal zone, probably due to storms. Dissolution of the evaporites led to collapse of unstable sediment as the next layer was deposited.

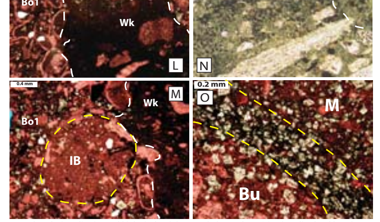
Box 5: Omission Surfaces



Examples of omission surfaces in core. (A) Inner shelf minor condensation surface. The discontinuity is defined by a pyritic horizon (dashed white line), thin chert parting replaced original evaporites. Blackish grains above discontinuity are glauconitized fossils and phosphatic debris (shown in figure F and I). (B) Organic laminations at omission surface (middle shelf), coral skeleton lag resting on the surface, note burrows penetrating organic laminations (dashed white line). (C) Mineralized omission surface cut by borings which are filled with sediment from the overlying unit. (D) Mineralized irregular surface (white dashed line). Burrows in lower mudstone unit are filled with an anomalous packstone (missing facies), unit overlying discontinuity is a wackestone, this surface probably looked like Figure (P) when it was exposed on the sea floor. (E) Hardground on an encrusting domal stromatoporoid (white dashed line), this organism has been bored and mineralized, the borings filled with sediment of the overlying unit.



Examples of glauconite and pyrite at omission surfaces. (F) Inner shelf: Glauconite peloids and fossil casts, glauconitized crinoid debris(Cr) is also partially pyritized. (G) Middle Shelf: Glauconite disseminated in a micrite matrix, possibly preserving the outlines of original peloids. (H) Inner Shelf: Lenticular glauconite (microlense) in coarse crystalline planar-e dolomite matrix (I) Middle shelf: High magnification (630x) of a crinoid segment that has been completely replaced by glauconite preserving internal pore structure. (J) Inner shelf: Pyrite framboids(Fr) and euhedral pyrite (white arrow) in micritic and partially dolomitized matrix, euhedral crystals are obscuring what is probably a brachiopod valve in middle of photo. (K) Outer shelf: Example of skeletal fabric preserving pyrite, euhedral crystals mimic the original shell structure of this brachiopod.



Examples of mineralization and biological activity at omission surfaces.(L) Mineralized and bored wackestone (Wk) hardground, above packstone (Pk) fills borings, the walls of boring Bo1 is encrusted by serpulid worm tubes. (M) Photo extension of boring Bo1 showing internal burrow (IB) within the boring fill. (N) Quartz sand grian(Q) resting on a mineralized hardground surface that is impregnated by pyrite and draped by a glauconite parting. (M) Organic lining (dashed yellow line) of burrow wall below hardground in figure D. Differences beterrn burrow (Bu) and matrix (M) are shown.

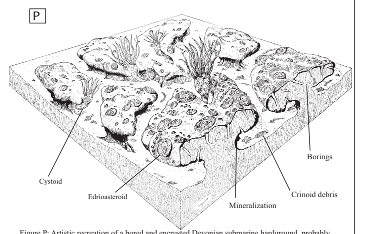


Figure P: Artistic recreation of a bored and encrusted Devonian submarine hardground, probably representative of the hardground in Figure D (upper left). (*From* Koch, and Strimple, 1968.)

Discussion

The distinct differences between stacking patterns and the distribution of discontinuity surfaces in all three cored locations provide key evidence of the general morphology of the Cedar Valley Group shelf (Figure 11). The Cedar Valley Group shelf is characterized here as a storm-dominated epeiric ramp based on the following three lines of evidence. 1) Submarine omission surfaces increase in frequency basinward, while exposure surfaces increase in frequency shoreward, indicating an increase in sediment starvation in the offshore direction. 2) Shallow restricted marine to supratidal deposition dominated the inner shelf, while the middle to outer shelves are dominated by intermediate to deep subtidal deposition. 3) The dominant discontinuity surface type in the inner and middle shelves is erosional surfaces, most of which are interpreted as the erosional base of tempestites.

The absence of clear parasequences is interpreted as the result of interruptions in sedimentation or erosion. Discontinuity surfaces delimit meter scale cycles, many of which are incomplete or truncated and may be just a few cm thick (Figure 5:D). The stacking patterns, nature of the discontinuity surfaces, and microfacies were used to interpret systems tracts for the Coralville and upper Little Cedar Formations (Figure 11). The inner shelf strata exhibit a repetitive stacking pattern for each sequence (Figure 12:A). Relatively thick shallow subtidal intervals characterize the base of each sequence, which progressively thin upward, defining an overall progradational trend. Each sequence culminates with an interval of closely spaced exposure surfaces which are interpreted here as a sequence boundary zones (SBZ) (Montanez and Osleger, 1993; Hillgartner, 1998), and probably represent the beginning of the lowstand systems tract (LST). Evidence of meteoric diagenesis, including paleosols, in and below the SBZ, along with relatively thin units indicates that the inner shelf was left emergent for much of the LST. The transgressive systems tracts are generally thickest in the middle and outer shelves, but pinch out or are extremely condensed in the inner shelf, often represented by a single transgressive surface. These interpretations are consistent with the sequence stratigraphic model for a homoclinally dipping ramp (Handford and Loucks, 1993; Figure 12:B).

The discovery of inner shelf sediment (peloids) in the Coralville Formation in the outer shelf core was key in placing the Lithograph City-Coralville sequence boundary. During late sea level highstand the peritidal zone prograded toward the shelf margin (Witzke and Bunker, 1997). Muddy peloidal sediment from the inner shelf was transported from the shelf margin to the outer shelf by currents by storm induced turbidity and density currents (Figure 13).

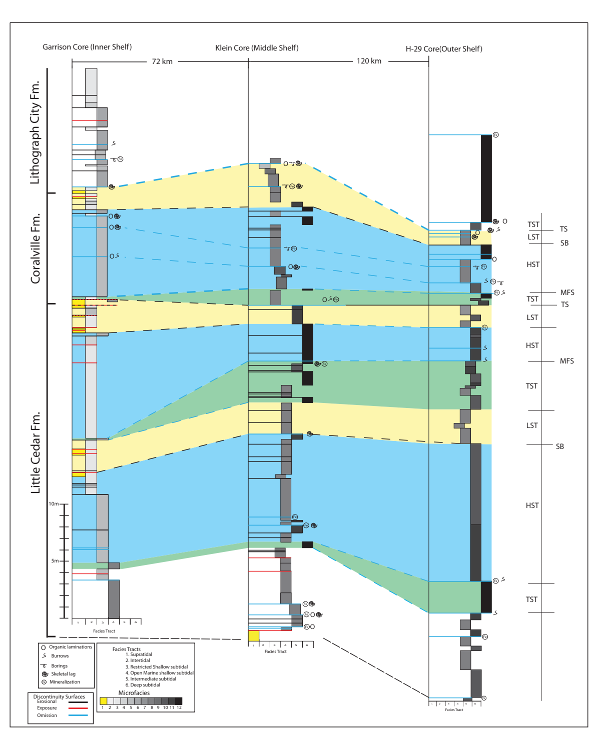


Figure 11: Stratigraphic sections of the three cores described in this study. Microfacies are shown and organized into facies tracts. Discontinuity surface types are shown, many of which are correlatable across the shelf. See Figure 3 for map of core locations.

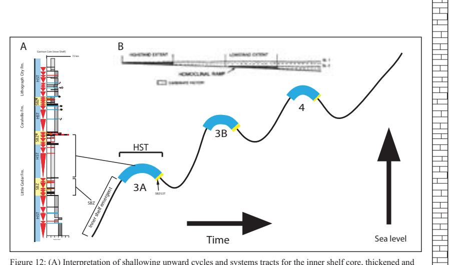


Figure 12: (A) Interpretation of shallowing upward cycles and systems tracts for the inner shelf core, thickened and colored lines correspond to deposition during sytems tracts. The inner shelf was emergent for most of the LST and TST. 3rd-order sequences correspond to Iowa T-R cycles in Figure 4:B. (B) General model for a homoclinally dipping ramp, which bears many similarities to the sequences identified in this study (*from* Handford and Loucks, 1993)

Conclusion

Documenting and characterizing discontinuity surfaces provides additional valuable information that may not be apparent in traditional stratigraphic studies that focus on lithostratigraphy. Such surfaces and can be useful in sequence stratigraphic analysis in the absence of recognizable parasequences and stacking patterns.

The Iowa Basin is an extraordinary example of starved epeiric sea sedimentation which has no modern analog. Documenting microfacies and discontinuity surfaces in the Cedar Valley Group resulted in new insights into Middle Devonian deposition in the Iowa Basin which are summarized by the following points:

- ► Sediment was generated in situ by two "carbonate factories"; the restricted inner shelf factory and the middle shelf open marine carbonate factory.
- ► Storms were the dominant sedimentary process, destructively inhibiting reef growth and redistributing sediments across the shelf.
- ► Transgressive systems tracts thin or pinch out shoreward due to the morphology of the epeiric ramp and are often represented in the inner shelf by a single flooding surface.
- ► Most sediment was accumulated during the highstand systems tract, as the rate of sea level rise slowed and sedimentation could keep pace. Toward the end of the highstand systems tract the peritidal zone prograded toward the shelf margin and inner shelf sediment could be transported to the outer shelf by storm currents.
- ► Subaerial exposure surfaces dominate the inner shelf during the lowstand systems tracts, where they are characterized as "sequence boundary zones" correlated to shift to shallower subtidal facies in the outer shelf.
- ► The findings presented in this study can are used to characterize the Iowa Basin during the Cedar Valley Group deposition as a storm dominated epeiric ramp.

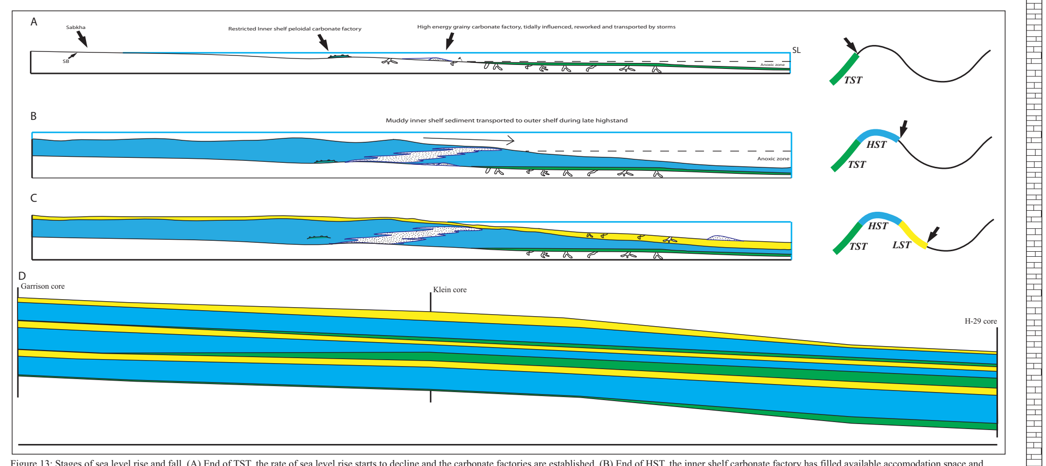


Figure 13: Stages of sea level rise and fall. (A) End of TST, the rate of sea level rise starts to decline and the carbonate factories are established. (B) End of HST, the inner shelf carbonate factory has filled available accomodation space and spill over is washed into the outer shelf by receeding storm surges. (C) Late LST, the inner shelf is subaerially exposed and the sabkha has prograded toward the shelf margin, evaporite ponds and paleosols were scattered across the emergent area. (D) Structural cross section of Figure 11, extremely vertically exaduated, 192km total length.

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