ORIGINAL RESEARCH ARTICLE

Discontinuity surfaces and microfacies in a storm-dominated shallow Epeiric Sea, Devonian Cedar Valley Group, Iowa

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ABSTRACT

Discontinuity surfaces develop in carbonate successions in response to a range of environmental changes and represent an integral part of the stratigraphic record. In Palaeozoic shallow epeiric basins that are typified by extremely slow subsidence and intermittent sedimentation, discontinuity surfaces may represent the majority of the time-rock record. A depositional and sequence-stratigraphic model was developed through microfacies analysis and discontinuity surface characterization using three cores in a proximal to distal transect across the Middle to Upper Devonian Iowa Basin. Twelve microfacies are recognized, spanning supratidal to deep subtidal facies tracts. A total of 105 discontinuity surfaces were documented and classified as either submarine omission surfaces, subaerial exposure surfaces or submarine erosional surfaces. Omission surfaces increase in frequency basinward, indicating increased sediment starvation in the offshore direction. Exposure surfaces increase in frequency shoreward, indicating more frequent subaerial exposure in a shallower setting. Erosional surfaces are dominant in the inner and middle ramp and interpreted as the base of storm beds (tempestites); these surfaces are rare in the outer ramp due to its generally deeper setting below storm wave base. Moreover, discontinuity surfaces exhibit systematic groupings stratigraphically (vertically) across the three localities spanning the Devonian carbonate ramp. Zones of either exposure-dominated, erosion-dominated or omission-dominated surfaces were recognized and correlated with their landward or basinward equivalents (along with shifts in major facies belts) and interpreted in a sequence-stratigraphic context. This study highlights the importance of including a detailed characterization of both depositional facies and non-depositional discontinuity surfaces in order to better understand the stratigraphic history of a basin. The framework of analysis provided here is particularly useful for marine carbonate strata deposited in epeiric basins, which are especially common in the Palaeozoic and where non-deposition and erosion occur frequently, but can also be applied to other geological time periods and settings.

INTRODUCTION

Discontinuity surfaces can reveal information about environmental, eustatic and tectonic changes and are as important as the sedimentary units that they delimit (Hillgärtnert, 1998). These stratal surfaces occur due to a hiatus in sedimentation and/or erosion of previously deposited material, and represent a break in the time-stratigraphic record of any duration (Clari et al., 1995). Discontinuity surfaces (or discontinuities) are of interest due to their importance in resolving high-frequency sea-level fluctuations and basin evolution at scales finer than chronostratigraphic resolution typically available (Hillgärtnert, 1998; Sattler et al., 2005; Bishop et al., 2010; Chow & Wendte, 2011; Christ et al., 2012a,b; Brlek et al., 2013a,b; Godet et al., 2013). Furthermore, each surface...
can retain its own complex history revealing multiple geological events superimposed on a single stratigraphic break (Clari et al., 1995; Hillgärtner, 1998; Sattler et al., 2005; Rameil et al., 2012). Documenting the geographical and stratigraphic occurrence of discontinuity surfaces can reveal important tectonic and eustatic processes, which are manifested by subtle regional and local environmental changes and can aid in sequence-stratigraphic analysis (Hillgärtner, 1998).

Palaeozoic inland seas (i.e. cratonic, epeiric or epicontinental seas) are perplexing to sedimentologists and stratigraphers because there are few to no adequate modern analogs (Irwin, 1965; Allison & Wells, 2006; Immenhauser, 2009). Epicontinental basins are characterised by slow subsidence (<10 m per Myr) and extremely poor stratigraphic completeness with, on average, only 10% of geological time represented by sedimentation (Sloss, 1996). This implies that the sedimentary record in such basins is dominated by non-deposition, and that the bulk of the time-rock record is represented by discontinuity surfaces. These conditions are not conducive to applying sequence-stratigraphic principles, a model that was developed by studying rapidly subsiding passive margins, and is largely based on assuming relatively constant and high rates of subsidence and sedimentation (Catuneanu, 2006).

The Devonian Iowa Basin strata are a remarkable example of shallow epeiric sea sedimentation. When compared with contemporaneous passive continental margin deposits in Western North America, the Cedar Valley Group strata are typified by both thinner and fewer depositional units, many of which are bounded by discontinuity surfaces (Brady, 2015). Previous studies have attributed this discontinuous and condensed section to a stressed benthic carbonate factory that was inhibited by restricted circulation due to its isolation from the open ocean, enhanced freshwater influx (and associated upwelling of nutrients), and/or increased terrigenous influx (and associated nutrient input) (Witzke, 1987; Witzke et al., 1988, 1996; Witzke & Bunker, 1996, 1997; Brady, 2015). The Cedar Valley Group strata provide an excellent opportunity to apply discontinuity surface characterization to better constrain the basin’s history in light of tectonic, eustatic and sedimentological drivers.

The purpose of this study was (1) to document and characterize microfacies and discontinuity surfaces in the Cedar Valley Group to better determine controls on sedimentation in the Middle Devonian Iowa Basin, and (2) to integrate these findings into a sequence-stratigraphic framework that takes into account discontinuity surfaces, depositional facies and their stacking patterns. This study finds that Devonian strata in the Iowa Basin show a systematic and cyclic pattern in the occurrence of discontinuity surfaces that is related to both depositional setting and relative sea-level. The concepts presented here can be used to improve existing models of facies distribution and basin architecture in this and other epeiric basins, as well as other settings characterized by condensed strata. This study highlights the important information captured in discontinuity surfaces in addition to the depositional units they bound.

**Geological and stratigraphic context**

The Iowa Basin is centrally located within the North-American Craton (Laurentia) and is bound to the northwest by the Transcontinental Arch and by the Ozark uplift to the south (Witzke et al., 1988; Fig. 1). The North-American Craton (Laurentia) has remained relatively tectonically stable since the development of the Precambrian Midcontinent rift system (Green, 1983; Van Schmus & Hinze, 1985; Davis & Paces, 1990; Paces & Miller, 1993). The rift ultimately failed at ca 1087 Ma after over 20 Myr of volcanism that filled the rift valley with up to 30 km of volcanic and clastic sedimentary rocks (Ojakangas et al., 2001). The post-rift stability of the cratonic interior has preserved several large-scale ‘supersequences’ that deposited marine sediments across much of North America (Sloss, 1963). Johnson et al. (1985) divided the Devonian Kaskaskia supersequence of Sloss (1963) into six smaller scale transgressive-regressive (T-R) cycles with durations of 1 to 10 Myr. The strata targeted in this study were deposited during Johnson (1970) and Johnson et al.’s (1985) cycle IIa, also termed the Taghanic Onlap. The Taghanic Onlap is recognized as the single largest magnitude transgressive event of the Kaskaskia supersequence (Johnson, 1970). This transgression deposited shallow-marine carbonates across Iowa and adjacent states during the Middle Devonian and was the first transgressive stage to breach the Transcontinental Arch since the Early Devonian (Johnson, 1970; Johnson et al., 1985). Additional higher order sequences have been recognized by previous workers in the Iowa Basin and are referenced herein as ‘Iowa T-R cycles’ (sensu Day et al., 1996; Day, 2006; Witzke & Bunker, 1996; Figs 2 and 3).

The shallow Devonian strata onlap onto the Transcontinental Arch and deepen distally from the Sioux Ridge towards the southeast where the Sangamon Arch divides the Iowa Basin from the adjacent Illinois Basin (Witzke et al., 1988). The Cedar Valley Group was deposited across a broad epeiric ramp with minimal tectonic influence (Witzke & Bunker, 1996), although some evidence suggests local variations in subsidence between Iowa and adjacent basins (Witzke et al., 1988), and minor tectonic upwarping along the Sangamon Arch (Whiting & Stevenson, 1965).
The Cedar Valley Group strata is characterized by shallow restricted subtidal carbonate and evaporite (sabkha) facies that transition into open-marine shallow to deep subtidal facies across an expansive epeiric ramp (Witzke & Bunker, 1996, 1997). Diverse coral-stromatoporoid biostromes characterize the ‘middle shelf margin’ which

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**Fig. 1.** Palaeogeographic map of North America and present day study area (left). North America (then Laurasia) during the Middle-Late Devonian showing major depositional regimes. Palaeonorth (arrow) and palaeolatitude are shown (modified from Bunker & Witzke, 1992) (right). Eastern half of Iowa showing generalized facies belts and locations of cores used in this study.

**Fig. 2.** Chronostratigraphic and lithostratigraphic chart of Middle-Late Devonian time periods covered in this study (modified from Brady, 2015). Based on Day (2006) and Morrow and Sandberg (2008). Ages (mya) from Kaufmann (2006). Chronostratigraphic placement of lithostratigraphic units after Witzke et al. (1988), Day (2006), Morrow and Sandberg (2008), Warme et al. (2008), Sandberg (2009)]. Thicknesses of each lithostratigraphic unit measured in this study are indicated in parentheses. Unlabelled conodont zones: * = hermanni, ** = norrisi, *** = hermiansatus.

The Cedar Valley Group strata is characterized by shallow restricted subtidal carbonate and evaporite (sabkha) facies that transition into open-marine shallow to deep subtidal facies across an expansive epeiric ramp (Witzke & Bunker, 1996, 1997). Diverse coral-stromatoporoid biostromes characterize the ‘middle shelf margin’ which
transition distally into argillaceous and low-diversity wackestones and mudstones of the 'outer shelf' (Witzke et al., 1988; Witzke & Bunker, 1996, 1997). For this study, the Cedar Valley strata are divided into inner, middle and outer ramp facies belts (Fig. 1), which correspond to the inner, middle and outer-middle 'shelf' belts of Witzke & Bunker (1996, 1997), respectively. The formations of the Cedar Valley Group are defined by transgressive – regressive cycles (Iowa T-R Cycles) and are considered third-order (1 to 3 Myr) depositional sequences based on their depositional time scale as determined by biostratigraphic controls (Witzke & Bunker, 1996; Fig. 2).

Previous workers have documented that Iowa T-R Cycles are generally capped by subaerial exposure surfaces in the inner ramp that transition laterally into submarine...
hardgrounds in the distal areas (Witzke & Bunker, 1996). Low long-term rock accumulation rates (6 to 12 m per Myr), condensed facies and depositional cycles (relative to continental margin coeval records) and regionally widespread hardgrounds suggest a suppressed carbonate factory with intermittent sedimentation due to environmental stresses associated with epeiric seas. Poor circulation, hypersalinity and episodic anoxia (associated with enhanced nutrient flux) have been suggested as mechanisms that suppressed the shallow subtidal carbonate factory (Witzke et al., 1988; Witzke & Bunker, 1996; Brady, 2015).

MATERIALS AND METHODS

Three cores (totalling over 55 m, cumulatively) were described in detail with coverage through most of the Little Cedar and Coralville Formations, and part of the Lithograph City Formation (Iowa T-R Cycles 3A, B, 4, and 5; as defined in Witzke & Bunker, 1996) in a proximal to distal transect across the Iowa Basin. Core descriptions and interpretations were compared with previously described sections for the same study interval (Witzke et al., 1988; Witzke & Bunker, 1996; Brady, 2015). Microfacies and discontinuity surface descriptions were supplemented with field checks of local outcrops and with supplemental cores in the middle ramp area (Johnson County, Iowa) (Fig. 3).

Thin sections were impregnated with a blue dyed epoxy to observe porosity and stained with a mixed Alizarin Red S and potassium ferricyanide solution (after Dickson, 1966) to distinguish among carbonate minerals. Microfacies were characterized by a combination of polished faces of split core and thin section \((n = 71)\) observations following Flügel (2004) and described according to Dunham’s (1962) classification with an emphasis on identifying the primary sediment components. Bioturbation was classified in terms of ichnofabric index (Droser & Bottjer, 1986). When appropriate, dolomite microfabric was described using the nomenclature of Sibley & Gregg (1987).

Discontinuity surfaces in carbonate strata are generally interpreted as either the result of erosion, subaerial exposure, a hiatus in sedimentation leading to lithification of the sea floor, or some combination thereof (Clari et al., 1995; Hillgärtner, 1998; Sattler et al., 2005). In this study, discontinuities are assigned to one of three general categories using the surface morphology, biological activity, mineralization, facies contrasts and diagenetic contrast between underlying and overlying units: (i) exposure surfaces, showing evidence of subaerial exposure and alteration; (ii) erosional surfaces, associated with evidence of removal of previously deposited material or (iii) omission surfaces, showing evidence of a submarine sedimentary hiatus (following Hillgärtner, 1998; Sattler et al., 2005; Brady, 2015). A total of 105 discontinuity surfaces were documented in the study interval; 43 in the inner ramp, 43 in the middle ramp and 19 in the outer ramp.

FACIES AND DISCONTINUITY SURFACE DESCRIPTIONS AND INTERPRETATIONS

Carbonate ramp depositional system

Microfacies and depositional facies tracts

Based on thin section analysis and core description, the inner, middle and outer ramp areas are divided into six depositional facies tracts, and a total of 12 individual microfacies are recognized (see Table 1 for detailed descriptions). Within the study area, this portion of the epeiric ramp is characteristic of a carbonate ramp (Fig. 4). The inner ramp is comprised of a supratidal sabkha and tidal flat facies dissected by tidal channel deposits and low-diversity, restricted lagoonal muddy environments with brachiopods, ostracods, stromatoporoids and rare phylloid algae. The restricted shallow marine waters of the inner ramp transition into more open-marine and high-energy grainstone shoal and biostromal facies of the middle ramp consisting of crinoids, corals, byrozoans and brachiopods. The outer ramp is characterized by intermediate to deep subtidal marine wackestone and mudstones with crinoid, byrozoan and brachiopod debris, primarily concentrated in thin beds (3 to 10 cm) with scoured bases. Deep-marine facies are primarily mudstones with scattered fine-grained skeletal debris derived from the middle ramp (commonly fine crinoid debris), are more argillaceous and contain organic-rich stringers with rare articulated brachiopods.

The observed distribution of sedimentary components indicates that the inner and middle ramps were the primary sources of sediment generation and accumulation, whereas the distal outer ramp was sediment starved. Sediment was sourced from the inner and middle ramp, redistributed across the ramp by storms, and delivered to the outer ramp via fine-grained (muddy) sediment gravity flows. The slope was likely similar to that of the present-day lower Coralville contact, which is 0-0007 (0.045°) between the middle and outer ramp cores (based on depth to this contact in both cores and present-day horizontal distance between cores). The facies associations, low-angle slope and lack of a reef rim indicate that the morphology is consistent with a homoclinal carbonate ramp (Burchette & Wright, 1992). The low-angle slope precludes slumping or earthquake triggered mass wasting events such as reef apron debris flows and grain flows due to overfilling. The most likely mechanism for
| Facies tract (interpretation) | Facies ID | Microfacies | Sedimentary structures | Sedimentary components and fossils (in order of abundance) | Dominant mineralogy | Microfabric | Depositional environment |
|-----------------------------|-----------|-------------|------------------------|-------------------------------------------------------------|---------------------|-------------|-------------------------|
| 1 (Supratidal)              | MF1       | (1) Collapse breccia | Vugs, solution seams, crystal silt, geopetal fill, chert nodules and breccia | Recrystallized, rare quartz grains | Dolomite | Medium crystalline, Planar-e and Planar-s dolomite | Salt flat/sabkha |
|                             | MF2       | (2) Laminated dolomudstone | Planar, curviplanar, and fenestral laminations, chert nodules and breccia | Recrystallized, rare quartz grains | Dolomite | Medium to fine crystalline, Planar-e, Planar-s, and nonplanar dolomite | Salt flat/sabkha |
| 2 (Intertidal)              | MF3       | (3) Laminated peloidal mudstone and wackestone | Planar and planar-cross-laminated, microlenses | Peloids, ostracods, oncoids, gastropods, phylloid algae, rare quartz grains | Dolomite or calcite | Micrite | Tidal flat or low-energy beach |
|                             | MF4       | (4) Intraclast pebble conglomerate | Imbricated intraclasts | Intraclasts, peloids, ostracods, oncoids, gastropods, rare quartz grains | Dolomite or calcite | Micrite | Tidal channel/surge channel |
| 3 (Restricted shallow subtidal) | MF5     | (5) Bioturbated mudstone | Bioturbated (ichnofabric 3 to 5) | Branching stromatoporoids common. Sparse brachiopods, crinoids, corals, gastropods, peloids, rare quartz grains | Dolomite or calcite | Micrite, fine to coarse crystalline planar-e, planar-s and anhedral dolomite | Coastal lagoon or embayment |
|                             | MF6       | (6) Stromatoporoid-gastropod wackestone and packstone | Massive, bioturbated, skalithos | Gastropods, peloids, ostracods, branching and domal stromatoporoids, red algae, rare quartz grains | Calcite | Micritic peloids, dolomite-replaced fossils | Patch reefs/biostromes in coastal lagoon or embayment |
| 4 (Open-marine shallow subtidal) | MF7     | (7) Crinoidal Grainstone | Thinly-bedded, cross-bedded, burrowed | Crinoids, bryozoans, tentaculites, tabulate and rugose corals, tentaculites, stromatoporoids, rare quartz grains | Calcite | Calcite spar cement, syntaxial overgrowths, partially micritized in outer-middle ramp | Shoal/patch reef in high-energy open-marine environment |
|                             | MF8       | (8) Laminar Stromatoporoid boundstone | Boundstone | Laminar stromatoporoids, brachiopods, bryozoans, mixed skeletal debris, serpulids, rare quartz grains | Calcite | Micrite | Quiet water open marine, below Fair weather wave base |

(Continued)
| Facies tract (interpretation) | Facies ID | Microfacies | Sedimentary structures | Sedimentary components and fossils (in order of abundance) | Dominant mineralogy | Microfabric | Depositional environment |
|-------------------------------|-----------|-------------|------------------------|-------------------------------------------------------------|---------------------|-------------|-------------------------|
| 5 (Intermediate subtidal)     | MF9       | (9) Byrozoan-crinoid wackestone and packstone | Laminated to burrow-mottled | Bryozoans, crinoids, tabulate and rugose corals, stromatoporoids, brachiopods, rare quartz grains | Calcite | Micrite with scattered dolomite rhombs, rare dedolomite | Open ramp near ramp margin, shallow to intermediate, below fairweather wave base |
|                               | MF10      | (10) Mixed skeletal packstone and wackestone | Laminated to burrow-mottled | Crinoids, bryozoans, brachiopods, skeletal hash corals, stromatoporoids, tentaculites, trilobites, rare quartz grains | Calcite | Micrite with scattered dolomite rhombs, rare dedolomite | Open ramp, fore-reef/biostrome debris |
|                               | MF11      | (11) Brachiopod packstone and wackestone | Laminated to burrow-mottled or massive | Brachiopods, rarely articulated, skeletal hash, trilobites, tentaculites, rare quartz grains | Calcite | Micrite with scattered dolomite rhombs, rare dedolomite | Open ramp, intermediate depth |
| 6 (Deep subtidal)             | MF12      | (12) Fine-grained mixed skeletal mudstone | Massive | Skeletal hash, articulated brachiopods, brachiopod valves, crinoids, bryozoans, surpulid worm tubes, trilobites, tentaculites, rare quartz grains | Calcite or dolomite | Micrite with scattered dolomite rhombs, rare dedolomite | Distal open ramp, deep, below storm wave base |
sediment transport to the outer ramp is through storm-generated turbidity currents (Aigner, 1982; Osleger, 1991; Badenas & Aurell, 2001). Storms have been suggested as a sediment transport mechanism in previous studies (Witzke et al., 1988; Witzke & Bunker, 1997) and are consistent with observations in this study (hummocky cross-stratification, microlenses, toppled coral heads and stromatoporoids within grainstone units). In addition, fully articulated crinoids as well as other well preserved delicate fossils have been attributed to rapid mud burial in the middle ramp area, with storm-generated density currents as a likely mechanism (Witzke & Bunker, 2010).

Small-scale depositional cycles

Here, we recognize ‘small-scale depositional cycles’ defined by stacked beds and facies with gradational internal trends that are interrupted by discontinuity surfaces, which reflect an abrupt vertical juxtaposition of non-contiguous facies tracts, observations that indicate non-deposition, erosion, subaerial exposure or some combination of these processes. These metre-scale cycles (ca 0.5 to 10 m thick) were delineated based on core descriptions and thin section interpretation of discontinuity surfaces. As described and defined here, these depositional cycles need not, and often do not, exhibit a cyclical or strictly shallowing-upward pattern. These small-scale cycles can exhibit different kinds of internal facies stacking patterns (shallowing, deepening, no change in interpreted water depth or some combination of trends) and can be bounded by different types of discontinuity surfaces (Fig. 3 and discussed below). The scale and definition of cycles used here most closely follow Strasser et al. (1999)’s ‘small-scale depositional sequence’ and is consistent with those described in carbonate-dominated records by several other authors (e.g. Schlager, 1993; Spence & Tucker, 2007; Bishop et al., 2010).

Characterization of discontinuity surfaces

All discontinuity surfaces were classified into one of three general categories: exposure surfaces, erosional surfaces or omission (hiatal) surfaces. Within these three categories, nine discontinuity surface types were recognized and ranked according to prominent physical characteristics, which can be interpreted as reflecting the temporal significance of the sedimentary hiatus or degree of erosional removal (Table 2; see Table S1 for details on each discontinuity surface encountered the study).

Subaerial exposure surfaces

The primary diagnostic features of these surfaces are solution seams, vugs, zones of collapse breccia or stylol breccia, indicative of karsted horizons. Subaerial-exposure surfaces commonly cap intertidal or supratidal small-scale cycles,
| Discontinuity Type | Subclass | Interpreted Temporal Significance of Hiatus | Features | Interpretation | Total Inner Ramp | Total Middle Ramp | Total Outer Ramp |
|--------------------|----------|---------------------------------------------|----------|---------------|-----------------|------------------|-----------------|
| **Subaerial exposure surfaces** | | | | | | | |
| Ex1                | Sabkha surface | Minor | Pervasive dolomitization, solution collapse breccia, vadose-zone diagenesis | Progradation and periodic flooding of supratidal zones | 5 | 0 | 0 |
| Ex2                | Epikarst | Minor or Major | Solution collapse breccia, vugs, solution seams, meteoric diagenesis | Drop in relative sea-level, often subaerially exposing subtidal sediment | 5 | 3 | 0 |
| Ex3                | Palaeosol | Major | Meteoric diagenesis, pedogenisis, solution seams | Prolonged exposure leading to soil development | 1 | 0 | 0 |
| **Erosional surfaces** | | | | | | | |
| Er1                | Tempestites | 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 |
| Er2                | 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 |
| Er3                | Composite disconformity | Major | Sharp contact between different lithologic units, may be stylolitic, strong diageneric contrast | Major erosional truncation, often associated with subaerial exposure in underlying unit | 2 | 0 | 2 |
| **Omission surfaces** | | | | | | | |
| O1                 | Diastem | Minor | Phosphatic and glauconitic lag, pyritized horizon organic laminations | Very slow sedimentation to minor temporal hiatus | 4 | 1 | 5 |
| O2                 | 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 |
| O3                 | Hardground | Major | Borings, burrows, phosphatic and glauconitic lag, strong mineralization, biological encrustation | Submarine hiatus with complete lithification and prolonged exposure on the sea floor | 3 | 12 | 10 |
and more rarely occur within subtidal facies. The rocks underling most subaerial exposure surfaces are commonly dolomitized and may include chert pseudomorphs after evaporite. Petrographic evidence of subaerial exposure is indicated by vadose-zone diagenesis and includes geopetal mounds of dolomite crystal silt and Fe-oxides lining the base of vugs and solution seams, dedolomite and meniscus cement (Fig. 5A-F). Most secondary porosity associated with vugs and seams is occluded by calcite spar; however, open mouldic and vuggy porosity is associated with some surfaces that define formation boundaries (Fig. 3C). Additional evidence of vadose-zone diagenesis and possibly pedogenesis includes brecciated quartz grains with clay fillings, carbonate breccia in clay-filled solution seams, calcrite with rhizocretions and pisoids with concentric micrite laminations (Fig. 5D-F; Wright, 1994).

Three distinct types of exposure surfaces are recognized in the Cedar Valley Group strata in this study and ranked in terms of the interpreted duration of subaerial exposure: sabkha surfaces (type Ex1), epikarst surfaces (type Ex2) and palaeosols (type Ex3).
Sabkha surfaces (Ex1)

Ex1 surfaces associated with sabkha facies (Facies Tract 1, Table 1) typically consist of thin collapse breccia beds (3 to 10 cm) (MF1, Table 1) interbedded with laminated dolostones. Dedolomite with calcite and silica replacement is common and often associated with geopetalial mounds and chert pseudomorphs after evaporite (Fig. 6A-D). Geopetal mounds form from the residual dolomite material collecting on the floor of the rhombohedral void (Dol), which was later occluded by silica cement (Qtz). The remaining intercrystalline porosity was later occluded by calcite spar (Cal). (B) MF1: collapse breccia. (C) Enterolithic anhydrite that has been replaced by microcrystalline (MC) chert. (D) Anhydrite (An) and dolomite (Dol) rhombs floating in microcrystalline chert matrix, visible under XPL and 630× magnification. See Fig. 3 for sample locations corresponding to A-D.

Fig. 6. Examples of Sabkha (Ex1) surfaces in core and thin section. (A) 630× magnification of centre dolomite rhomb in B, showing internal geopetal mound (Dol). Poorly ordered dolomite, or protodolomite, commonly precipitates in evaporitic environments and is prone to dissolution and replacement (Scholle & Ulmer-Scholle, 2003). Geopetal mounds form from the residual dolomite material collecting on the floor of the rhombohedral void (Dol), which was later occluded by silica cement (Qtz). The remaining intercrystalline porosity was later occluded by calcite spar (Cal). (B) MF1: collapse breccia. (C) Enterolithic anhydrite that has been replaced by microcrystalline (MC) chert. (D) Anhydrite (An) and dolomite (Dol) rhombs floating in microcrystalline chert matrix, visible under XPL and 630× magnification. See Fig. 3 for sample locations corresponding to A-D.

Epikarst (Ex2)

Ex2 surfaces occur within subtidal units and are characterized by evidence of solution collapse breccia within karst cavities and evidence of vadose-zone diagenesis. Compaction results in dissolution and suturing between brecciated clasts in some epikarst surfaces (i.e. stylolitization). Ex2 surfaces are interpreted as reflecting a relative sea-level fall that resulted in subaerial exposure of the sea floor (Hillgartner, 1998). The result is typically a shallow subtidal small-scale cycle truncated by an epikarst surface, i.e. a ‘catch-down’ cycle (Soreghan & Dickinson, 1994). The interpreted formation of these surfaces differs from Ex1 surfaces in that the formation of the exposure surface forms independently of sedimentation rate, such that subtidal facies (as opposed to supratidal or intertidal facies) are truncated by subaerial exposure features.
**Palaeosols (Ex3)**

Both Ex1 and Ex2 surfaces have the potential to develop into Ex3 surfaces (palaeosols) under prolonged subaerial exposure. Ex3 surfaces are underlain by calcrete that may exhibit rhizocretions, root traces and pisoids. Brecciated grains and cavities filled with green clay are also indicative of subaerial exposure and may suggest shrinking and swelling of expanding clays due to wetting and drying in the vadose zone (Fig. 5E and F) (Deconinck & Strasser, 1987). Concentric micrite laminations surrounding rhizocretions or other grains can displace or envelop the surrounding grains (Fig. 5D), and may be a microbial precipitate or the result of evaporation in the soil zone (Wright, 1994). The presence of palaeosols, in addition to the apparent activity of expanding clays, suggests a semi-arid climate (Wright, 1994).

**Erosional surfaces**

Erosional surfaces show evidence of a change in hydrodynamic energy level and removal of previously deposited material at any scale. Evidence of traction deposition, flame structures, scours, flute casts and rip-up clasts indicate minor erosional events that displace or remove soft to semi-lithified sediment. Such discontinuities are often associated with a change in grain-size or texture; bioclasts and/or intraclasts are common above many erosional surfaces and may show crude upward grading. Imbricated brachiopod valves and shelter porosity are also associated with increased hydrodynamic energy and traction deposition.

Sharp contacts juxtaposing two different facies tracts (non-Waltherian contacts) typically show diagenetic contrasts between underlying and overlying units and indicate regional erosional events. Petrographic observations of these major erosional surfaces show that the discontinuity is defined by an Fe-oxide rich parting that may be stylolitic in part with resistant grains protruding from the underlying unit.

Three erosional surface subdivisions are proposed for this study interval, based primarily on the interpreted magnitude of the erosional event. These range from minor and short-lived, high-energy events (Er1) or changes in hydrodynamic regime (Er2) to major migrations of facies belts punctuated by regional erosional events (Er3).

**Tempestite surfaces (Er1)**

Er1 surfaces are characterized by scouring of the underlying bed by flute cast or flame structures marking the base of decimetre-scale sequences. The surface is typically overlain by rip-up clasts or shell lags, depending on the depositional environment and are sometimes capped by planar and/or ripple cross laminaions (Fig. 7A). There is generally no change in depositional environment and the complete interval over which they are expressed is typically no

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**Fig. 7.** Examples of erosional surfaces in core. (A) High-energy event deposit in an outer-middle ramp wackestone/packstone (MF10) interpreted as a tempestite (Er1). Note basal scour surface with imbricated brachiopod shells, escape burrows (b) in overlying skeletal hash, and an upper ripple cross-laminated muddy wackestone unit. (B) Simple change surface (Er2) in intertidal laminite (MF3), overlying pebble conglomerate (MF4) consists of rip-up clasts from underlying unit. Interpreted as tidal channel deposit incised into a tidal flat mudstone. Sample is from the Little Cedar – Coralville Formation contact in the middle ramp found in a supplemental core near the Klein Core highlighted in this study (Mid-America Pipeline, Iowa City terminal, core 4; NE NW SE SE sec. 27, T79N, R5W, Johnson Co., reposited in the Department of Natural Resources Geological Survey Bureau, Iowa City, Iowa; Witzke & Bunker, 1997). (C) Composite disconformity (Er3) in the inner ramp juxtaposing crinoidal grainstone (MF7) with coral head on top of lagoonal mudstone (MF5). This surface is interpreted as the contact between the Little Cedar (underlying) and Coralville (overlying) Formations. See Fig. 3 for sample locations corresponding to A and C.

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more than 10 cm thick. These intervals are compositionally different at the inner and middle ramp localities. The inner ramp skeletal lags typically consist of restricted marine fauna and rip-up clasts in a peloidal matrix, whereas the middle ramp lags are commonly coral fragments, bryozoans, brachiopod and crinoid debris in a micritic matrix.

The sedimentary structures and bed forms overlying most Er1 surfaces are consistent with storm-event deposits (tempestites) described in the literature (Aigner, 1982; Dott & Bourgeois, 1982; Seilacher & Aigner, 1991). Therefore, Er1 surfaces are interpreted as the base of tempestites and are not thought to represent significant removal of material or prolonged break in sedimentation. These surfaces are interpreted as reflecting abrupt and short-lived, high-energy events followed by a return to normal sedimentation. Their abundance in the study interval supports storm currents as an important mechanism for sediment redistribution across the ramp (Witzke & Bunker, 2010).

**Simple change (Er2)**

Er2 surfaces are typified by a sharp contact juxtaposing two different microfacies (Fig. 7B). These are dominated by microfacies transitions within the same facies tract and are generally interpreted as autogenic processes operating within a given depositional environment, e.g. migration of tidal channels through the tidal flat, or a prograding shoreline. Er2 surfaces are defined by scoured surfaces, flame structures, and/or rip-up clasts and may be accentuated by stylolites (Hillgartner, 1998). Er2 surfaces are similar to Er1 surfaces, but are distinguished by a shift in facies reflecting a change in depositional environment, rather than a single sedimentary event. It is possible, however, that these changes can be triggered by a single storm event, as hurricanes and typhoons are capable of rearranging the shoreline and obliterating reef habitats (Flügel, 2004). Some Er2 surfaces may mark basin-wide deepening events and are interpreted as transgressive or flooding surfaces that delimit depositional sequences.

**Composite disconformity (Er3)**

Er3 surfaces are characterized by a sharp juxtaposition of two different microfacies commonly showing a diagenetic contrast between underlying and overlying units (Fig. 7C). These surfaces are usually defined by a sharp non-Waltherian contact that juxtaposes different facies tracts (e.g. outer ramp on top of inner ramp). Er3 surfaces are exemplified by erosional surfaces in the inner ramp that are underlain by rocks showing evidence of meteoric diagenesis (mouldic and vuggy porosity) suggesting that the inner ramp was subaerially exposed prior to erosion. The lithofacies contrast across these surfaces reflects a relative deepening. Resistant grains protruding off of these surfaces reflect pre-existing microtopography and indicate that the underlying unit was lithified prior to the erosional event (Fig. 8). Er3 surfaces in the outer ramp are similarly associated with diagenetic contrasts, but display no evidence of subaerial exposure. Er3 surfaces are interpreted as regionally widespread erosional surfaces associated with a relative sea-level fall and subsequent rise (where associated with deepening across the surfaces). Diagenetic contrasts between underlying and overlying units suggest Er3 surfaces represent major temporal hiatuses and a lithified substrate prior to erosional truncation.

**Omission surfaces**

Omission surfaces show evidence of a submarine hiatus in sedimentation. Depositional breaks are indicated by
clay and/or organic stringers, mineralized horizons and hardgrounds that exhibit evidence of biological colonization of the sea floor. Glaucnite is common at most omission surfaces in the form of microlenses, glaebules, peloids, grain coatings, fossil casts, disseminated in the rock matrix or draped over the discontinuity surface (Fig. 9). Glaucnitized grains concentrated at omission surfaces are typically intermixed with phosphatic skeletal debris and pyrite in the form of euhedral crystals, framboids, partial to complete fossil casts, and/or dispersed in the matrix. Mineralized crusts are diagnostic of major omission surfaces and can penetrate a few centimetres into the underlying unit. Some omission surfaces, particularly in the outer ramp, also consist of stylolite swarms or anastomosing sets of stylolites and are often associated with organic partings.

Evidence of biological activity includes borings and burrows (distinguishable by sharp vs. fuzzy burrow walls, respectively), and encrusting fossils of sessile benthic fauna (Fig. 10). In many cases, burrows and borings are filled by sediment of the overlying unit and in rare cases are filled with a completely different lithofacies than the overlying unit (Fig. 10D). Taxonomic composition of skeletal lags resting on omission surfaces vary across depositional environments following these general trends: branching stromatoporoids at the inner ramp; corals, crinoids and bryozoans at the middle ramp and articulated brachiopods in the outer ramp. Several omission surfaces preserve concentrations of organic matter at or around the discontinuity. Black organic material occurs either as single partings less than 1 cm in extent or as zones of fine wavy laminations that can extend up to 30 cm above or below the surface.

Based on the evidence described above, three omission surface types are differentiated and ranked in terms of increasing magnitude of the hiatus represented (adapted from Christ et al., 2012a). Type O1 surfaces (diastems) are minor hiatuses in comparison to Type O2 (firmgrounds to incipient hardgrounds). Type O3 surfaces (hardgrounds) are the most prominent omission surfaces in the study interval and are interpreted as representing the longest duration depositional hiatuses.

**Diastems (O1)**

In this study, these surfaces are marked by phosphatic lags and concentrated glauconite grains. Pyrite and glauconite-draped O1 surfaces indicate dysoxic to anoxic and
reducing conditions, particularly when organic laminations are also present. These surfaces often mark a break in bioturbation, with burrows generally re-appearing several centimetres above the break. These surfaces are common in the inner and outer ramp cores, and less common in the middle ramp. Chert pseudomorphs after evaporites are generally limited to the inner ramp, suggesting a shift to hypersalinity caused by isolation from open ocean currents (Fig. 10A). The key characteristic of O1 surfaces is that the sea floor sediment remained unlithified although brittle pyrite and evaporite crusts may have developed at the sediment-water interface. Based on these observations, these surfaces indicate a minor submarine depositional hiatus due to environmental change that inhibited the production and/or deposition of carbonate sediment.

**Firmgrounds to incipient hardgrounds (O2)**

O2 surfaces can exhibit all of the same features as diastems with the addition of bioturbation cutting across the surface. Burrows or boreholes penetrating into the underlying unit are commonly filled with sediment of the overlying unit (Fig. 10C). Skeletal lags commonly rest on the discontinuity surface and weak mineralization may penetrate into the underlying unit. Mineral impregnation coupled with burrows and boreholes penetrating underlying units indicate a submarine depositional hiatus where the sea floor sediment was partially to fully lithified, implying a longer duration hiatus relative to O1 surfaces (Hillgärtner, 1998).

**Hardgrounds (O3)**

O3 surfaces exhibit strong mineralization, which penetrates several centimetres into the underlying unit, as well as borings and biological encrustation indicative of a fully lithified sea floor. In addition to the features described for O1 and O2 surfaces, borings in O3 surfaces are generally filled with sediment from the overlying unit and may show multiple generations of biological activity (Fig. 11). These observations indicate that these surfaces represent major depositional hiatuses with a greater magnitude of depositional change and a longer non-depositional duration than O1 and O2 surfaces.
DISCUSSION

Geographical distribution of discontinuity surfaces

The occurrence and frequency of discontinuity surfaces differs between the inner, middle and outer ramp (Fig. 12). These variations give insight into the balance of controlling factors operating across the study area, particularly with regards to sedimentation, erosion, transportation and creation or loss of accommodation space. Each facies belt has a unique signature with respect to the types and frequency of discontinuity surfaces described in this study.

Exposure surfaces are most frequent in the inner ramp, rare in the middle ramp and absent in the outer ramp (Fig. 12A). These observations are consistent with expectations that subaerial exposure should decrease distally. The peritidal environments that characterize the inner ramp would presumably be more prone to subaerual exposure from minor relative sea-level oscillations. The middle ramp is dominated by shallow to intermediate subtidal facies and is generally interpreted as a higher energy environment. Consequently, vertical aggradation would have been limited by wave sweeping as accumulating sediment approached wave base (Osleger, 1991). Subaerial exposure surfaces in the middle ramp were likely the result of a significant drop in relative sea-level. The three exposure surfaces that occur in the middle ramp are epikarst (Ex2 surfaces) and may actually represent subaerially exposed hardgrounds (Hillgartner, 1998). The absence of exposure surfaces in the outer ramp suggests that it remained below sea-level for the duration of the study interval.

Erosional surfaces are the dominant surface type at the inner and middle ramp, and rare in the outer ramp (Fig. 12A). Most erosional surfaces in the inner and middle ramp are interpreted as the basal surface of tempestites (Er1 surfaces) (Fig. 12B). These observations support previous studies that suggested storms as mechanism for sediment transport (Witzke et al., 1988; Witzke & Bunker, 1997; Groves, 2004; Preslicka et al., 2010; Witzke & Bunker, 2010; Day et al., 2013). The two erosional surfaces recognized in the outer ramp are major erosional disconformities (Er3 surfaces) that likely developed during maximum sea-level lowstands as they are the only evidence that suggests wave base got low enough to scour the sea floor. There are no tempestite (Er1) surfaces in the outer ramp, presumably because deposition was infrequent enough that the sea floor was lithified between depositional events or bioturbation may have obscured original sedimentary structures.

The frequency of omission surfaces increases from the inner ramp towards the outer ramp (Fig. 12A), indicating increased sediment starvation and more frequent submarine hiatuses in the offshore direction. These observations are consistent with the inner and middle ramps acting as the primary sources of sediment supply and sedimentary hiatuses increasing away from the locus of sedimentation. The abundance of hardgrounds (O2 and O3 surfaces) in the outer ramp suggest that these sedimentary hiatuses were longer in duration relative to O1 surfaces, allowing for sea floor cementation, biological colonization and mineralization.

Taken together, the distribution of discontinuities is characterized by storm-dominated deposition in shallow water and sediment starvation in deeper water. The abundance of omission surfaces in all studied sections supports previous interpretations of a suppressed or stressed
benthic carbonate factory (Witzke et al., 1988; Witzke & Bunker, 1996; Brady, 2015). Lower carbonate production rates could be caused by several environmental and ecological factors. The frequent occurrence of omission surfaces, associated minerals (glauconite, pyrite, phosphate), abundance of organic-rich and argillaceous rich beds documented here are consistent with lower carbonate production rates resulting from anoxic or dysoxic conditions (Figs 9 and 10). Excess nutrients due to upwelling and/or increased terrigenous sediment input in this epeiric setting could lead to occasional benthic oxygen stress and attenuated light levels factory (Hallock & Schlager, 1986; Witzke, 1987; Hallock, 1988; Heckel, 1991; Pope & Steffen, 2003; Cramer & Saltzman, 2007; Baird et al., 2012; Brady, 2015). Based on these factors, sedimentation would have been intermittent; and the sediment that was generated in shallow water was frequently redistributed by storm currents.

Stratigraphic distribution of discontinuity surfaces and sequence-stratigraphic interpretations

The stratigraphic distribution of discontinuities appears to exhibit a systematic grouping of related surfaces. That is, rather than randomly distributed through the section, clusters of similar surfaces (erosional, omission or exposure) occur together and are also related to the depositional units they delimit. Therefore, zones of either exposure-dominated, erosion-dominated or omission-dominated surfaces can be recognized and correlated with their landward or basinward equivalents (along with shifts in major facies belts) and interpreted in a sequence-stratigraphic context (Fig. 13). The sequence-stratigraphic interpretation of systems tracts and associated surfaces is presented here in the context of previously defined T-R cycles to show how this study relates to previous work (Day et al., 1996; Witzke & Bunker, 1996). Note that T-R cycles are defined based on identifying transgressive (deepening) and regressive (shallowing) trends, but those same trends can also be interpreted in the context of sequence-stratigraphic terminology as discussed below, especially when considering the significance and distribution of stratigraphic surfaces.

Inner ramp

The inner ramp strata exhibit cycle stacking patterns and zones of discontinuity surfaces that define three depositional sequences, corresponding to the third-order Iowa T-R cycles 3A through 5 (Day et al., 1996; Witzke & Bunker, 1996). Each sequence is separated by an interval of closely spaced exposure surfaces that define decimetre-scale supratidal cycles. These ‘exposure-dominated zones’ can be interpreted as sequence boundary zones (SBZ) (sensu Montañez & Osleger, 1993; Hillgärtner, 1998; Bover-Arnal & Strasser, 2013). Each SBZ marks a longer term trend of falling sea-level, where the sabkha and intertidal facies prograded across the inner ramp. Palaeosols (Ex3 surfaces) and regional erosional (Er3) surfaces

Fig. 12. Frequency of discontinuity surfaces across major depositional settings: by (A) major categories and (B) subtypes (see Table 2).
developed during episodes of prolonged exposure. Each SBZ separates a relatively thick succession of metre-scale restricted shallow subtidal cycles that generally thin upward. Upward-thinning cycles in shallow-water facies are generally considered an indicator of decreasing accommodation space (Read & Goldhammer, 1988; Montañez & Osleger, 1993; Sadler et al., 1993; Husinec et al., 2008) and suggest that the overall (third-order) rate of sea-level rise was decelerating while these cycles were deposited. These subtidal intervals between SBZs are considered most representative of the highstand systems tract (HST), which was deposited as the rate of sea-level rise...
decelerated, and restricted lagoonal sediments began accu-
mulating in the inner ramp (Fig. 13).

Together, each inner ramp sequence exhibits an overall progradational stacking pattern consisting of thinning upward shallow subtidal cycles (HST) that transition into supratidal cycles (SBZ), which is consistent with the high-
stand prograding wedge, typical of homoclinal carbonate ramps (Burchette & Wright, 1992). The absence of ret-
rogradational stacking in the inner ramp suggests the transgressive systems tract (TST) is not represented here, though a discontinuity capping each SBZ marks a slight deepening and correlates to the TST down depositional dip (Fig. 13). The presence of Er3 surfaces within two of the SBZ showing evidence of vadose-zone meteoric dia-
genesis in the underlying units suggest the inner ramp was emergent for much of the time when the lowstand system tract (LST) and TST were deposited in deeper settings, and these Er3 surfaces correspond to regionally extensive erosional surfaces that mark the sequence boundaries between formations (Witzke et al., 1988; Witzke & Bunker, 1997). The postulated ramp morphology and observations presented here suggest that the higher elevation inner ramp was only submerged during maximum sea-level highstands.

Middle ramp

The middle ramp is dominated by subtidal cycles delimited by hardgrounds (O3 surfaces) or tempestites (Er1 surfaces) (Figs 3 and 13). These observations are consistent with expectations for a storm-dominated carbonate ramp, where currents limit sediment accumulation above wave base (Osleger, 1991; Bädenas & Aurell, 2001; Christ et al., 2012a). These limits to sediment accumulation would be compounded in the Devonian Iowa Basin where a stressed benthic carbonate factory (due to enhanced nutrient flux and/or siliciclastic input in the epeiric setting) could not always keep pace with rates of sea-level rise (Pomar, 2001; Allison & Wright, 2005; Brady, 2015). Moreover, facies and discontinuity surface interpretations,
and the depositional cycles they delimit, become increasingly important for these sections because systems tracts in homoclinal carbonate ramps are generally only represented by landward and basinward shifts in facies tracts (Tucker et al., 1993; Schlager, 2005).

Sequence boundaries are represented in the middle ramp by prominent hardgrounds (O3 surfaces) that correlate to regional erosional (Er3) surfaces and subaerial exposure surfaces in the inner ramp (Witzke et al., 1988; Witzke & Bunker, 1996). Although there are no apparent SBZs in the middle ramp section due to a lack of subaerial exposure surfaces, there appears to be zones dominated by erosional surfaces that are interpreted here as the basinward equivalent of the SBZs found in the inner ramp. These surfaces would form more readily during relative sea-level fall and associated lowering of storm wave base. Furthermore, these erosional-surface-dominated zones alternate stratigraphically with zones dominated by omission surfaces in the middle ramp section. The omission-dominated intervals can be interpreted as reflecting maximum flooding zones (MFZs) and associated condensed intervals during the TST. Indeed, similar discontinuity surface types (erosion, erosional or omission) seem to occur together in stratigraphic intervals (zones) that reflect a dominant non-depositional process, and are characterized by either subaerial exposure, erosion or a submarine hiatus in sedimentation (Fig. 13). The TST, HST and LST are therefore identified in the middle ramp by deepening and shallowing trends and formational boundaries that represent sequence boundaries (Fig. 13).

Outer ramp

The outer ramp is characterized by intermediate to deep subtidal deposition (mostly facies tract 5 and 6), with relatively thin shallow-subtidal intervals that occur in the appropriate stratigraphic position to be the basinward equivalent of the SBZ and LST (Fig. 13). The entire section is dominated by omission surfaces with only two erosional surfaces present. TST’s are defined in this section based on the presence of the deepest facies tracts and associated omission surfaces. These relatively thin, deep intervals, and surfaces with glauconite, pyrite and organic-rich laminae, are consistent with condensed intervals that form during maximum transgression. These observations are in contrast to the inner and middle ramp section where alternating discontinuity surface zones are present. The dominance of omission surfaces throughout the outer ramp indicates that subaerial exposure and erosion are rare or absent in the deepest water settings. This makes interpretation of the distinct erosional surfaces all that more essential as they are likely valuable for sequence-stratigraphic interpretation.

The two erosional surfaces are interpreted as Er3 (composite disconformities) and actually mark the top and base of the Coralville Formation (Iowa T-R cycle 4). The diagenetic contrast across these surfaces indicates that the underlying units were affected by meteoric phreatic fluids (e.g. Fig. 8B). The freshwater meteoric lens can extend for a considerable distance past the shoreline during sea-level lowstand, and discharge at the sea floor (Chafetz et al., 1988; Burchette & Wright, 1992). There is no evidence, such as vadose-zone diagenesis, to suggest the outer ramp was exposed subaerially in this study interval.

Summary

Based on the observations of vertical and lateral trends in lithofacies and discontinuity surfaces, a sequence-stratigraphic model has been developed (Fig. 13) that builds on previously published interpretations in the study interval (Witzke & Bunker, 1997; Brady, 2015). In summary, the TST thins or pinches out landward due to the morphology of the epeiric ramp and may be represented in the inner ramp by a single erosional flooding surface. In the middle and outer ramp, basinward shifts in facies and groups of omission surfaces typically define the TST and comprise condensed intervals that form during maximum flooding. Most sediment was accumulated during the HST, as the rate of sea-level rise slowed and sedimentation could keep pace (Witzke & Bunker, 1997; Brady, 2015). Towards the end of the HST, the peritidal zone prograded towards the basin. Frequent subaerial exposure and erosion typify the SBZ in the inner ramp, whose basinward equivalent (the LST) is marked by a shoreward shift in facies tracts and erosional surfaces in the middle ramp. During sea-level fall and lowstands, the inner ramp was left emergent, whereas the freshwater meteoric lens altered submarine sediments in the middle and outer ramp, which were subject to submarine erosion during the lowstand.

Implications for epeiric depositional settings and sequence stratigraphy

Inhibited sedimentation due to environmental stresses is one of the defining characteristics of the Cedar Valley Group carbonates (Witzke et al., 1988, 1996; Witzke & Bunker, 1997; Brady, 2015), thus making it an ideal study interval to show how the stratigraphic distribution of non-depositional surfaces can be used to illustrate variations in sedimentation and accommodation across the carbonate ramp, and how these variables change through time.

The systematic variation in discontinuity surfaces across the study interval provides insight into the
CONCLUSIONS

The Iowa Basin is an extraordinary example of epeiric sea sedimentation, which has no modern analog. The Cedar Valley Group strata described here are characterized as a sediment-starved, storm-dominated epeiric carbonate ramp based on the distribution of microfacies and discontinuity surfaces: (i) Peritidal facies dominate the inner ramp, whereas the middle to outer ramp zones are characterized by intermediate to deep subtidal facies; (ii) Submarine omission surfaces increase in frequency basinward, indicating increased sediment starvation in the offshore direction; (iii) Exposure surfaces increase in frequency landward, indicating more frequent subaerial exposure associated with a shallower depositional setting; and (iv) The predominant discontinuity surface type in the inner and middle ramps are erosional surfaces; and most of these are interpreted as the erosional base of tempestites.

This study demonstrates a distinct distribution of surfaces for the Cedar Valley Group carbonate ramp, which differs markedly from the expected distribution on flat-topped carbonate platforms (Hillgärtner, 1998). Discontinuity surfaces in the Cedar Valley Group ramp occur in bathymetrically controlled zones: the inner ramp zone is prone to subaerial exposure, the middle ramp zone has more frequent submarine erosion and the outer ramp zone is characterized by more frequent submarine sedimentary omissions. Due to the ramp morphology, these zones shift back and forth like facies tracts as sea-level rises and falls (Fig. 14). Importantly, recognition of these discontinuity surface zones and their lateral equivalents is essential for sequence-stratigraphic analysis. This work provides an important framework for conducting sequence-stratigraphic analysis with particular attention to the characterization and distribution of discontinuity surface in addition to the depositional units they delimit. This approach proves especially useful in epeiric strata, which may be exemplified by slow and intermittent sedimentation, and exhibit distinct facies and surface stacking patterns compared to continental margin strata for which sequence stratigraphy was first developed.

ACKNOWLEDGEMENTS

The authors thank Brian Witzke and Bill Bunker for valuable discussions and feedback on this work as well as assistance with accessing field localities and core repository samples housed at the Iowa Geological Survey. Thank you to Robert Dundas and Mathieu Richaud, who provided constructive feedback on earlier drafts of this manuscript. Associate Editor James Klaus, André Strasser and an anonymous reviewer provided constructive feedback that greatly improved the manuscript. This study
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**Supporting Information**

Additional Supporting Information may be found online in the supporting information tab for this article:

- **Table S1.** Database of discontinuity surfaces encountered in Garrison Core (inner ramp).
- **Table S2.** Database of discontinuity surfaces encountered in Klein Quarry Core (middle ramp).
- **Table S3.** Database of discontinuity surfaces encountered in H-29 core (outer ramp).