SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY OF A LOWER ORDOVICIAN MIXED SILICICLASTIC–CARBONATE SYSTEM, SHAKOPEE FORMATION, FOX RIVER VALLEY OF EAST-CENTRAL WISCONSIN

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ABSTRACT

The mixed siliciclastic–carbonate facies of the Shakopee Formation in east-central Wisconsin were deposited in a peritidal setting in two depositional sequences separated by a previously undocumented intra-Shakopee unconformity. The intra-Shakopee unconformity is regionally continuous in the study area and is characterized by 8 m of vertical erosional relief in an incised valley network. The incised valley has a channel-like morphology and contains deformed deposits consisting of a thick wedge of siliciclastics and multiple meter-scale, angular, carbonate blocks that dip into the center of the valley. We interpreted the intra-Shakopee unconformity to be a subaerial exposure surface because of the erosional relief, normal faults, and tilted strata; we interpreted the tilted strata and normal faults to have been caused by cave collapse from karstification. Deformation of the siliciclastics and carbonates in the incised valley was probably caused by differential compaction resulting from differential lithification rates of carbonates in relation to siliciclastics. The tilted blocks are truncated by a near-horizontal surface with incised valleys.

The two sequences are 1 and 2, oldest to youngest. The intra-Shakopee unconformity is the upper bounding surface for sequence 1 and the lower bounding surface for sequence 2. The exposed part of sequence 1 consists of a highstand systems tract. Sequence 2 contains a lower transgressive systems tract and an upper highstand systems tract. The highstand system tracts consist of mixed siliciclastic–carbonate facies in meter-scale, shallowing-upward (coarsening-upward) cycles. The cycles are not regionally continuous and in many places are bounded by erosional surfaces. The cycle facies variability suggests an autocyclic peritidal island facies model. The transgressive systems tract consists of deformed siliciclastics that fill the incised valley, which is overlain by a marine flooding surface.

Facies-defining cycles are divided into grainy carbonate, muddy carbonate, sandstone, shale, and stromatolitic–algal mat boundstones. The grainy carbonate facies is further subdivided into quartz sand grainstones, oolitic grainstones, and peloidal grainstones. The grainy and stromatolitic-algal boundstone facies were deposited in a subtidal to supratidal environment. The muddy dolostone, sandstone, and shale facies were deposited in a subtidal environment.

INTRODUCTION

The purpose of this study was to document the previously undocumented intra-Shakopee unconformity associated with an incised valley system as well as the anomalous dips of the strata first recognized by Chamberlin (1877) within the Shakopee and Platteville Formations of east-central Wisconsin. The incised valley contains siliciclastic facies similar to those of the St. Peter Formation, but stratigraphic relationships indicate that it is in the Shakopee Formation. In this study we reconstructed the sequence stratigraphy and the depositional environments of the Shakopee Formation east of the Wisconsin Dome. Because of the discontinuity of the St. Peter Formation in this area, the basal unconformity of the St. Peter and the Platteville Formations is collectively called the post-Shakopee unconformity in this paper.

The Lower Ordovician Shakopee Formation is a mixed siliciclastic–carbonate peritidal part of the Prairie du Chien Group that crops out around the Wisconsin Dome and in parts of Minnesota, Iowa, and Illinois (fig. 1). The Shakopee Formation was deposited in a shallow-water cratonic epeiric sea that flooded North America and consists of heterogeneous litholo-

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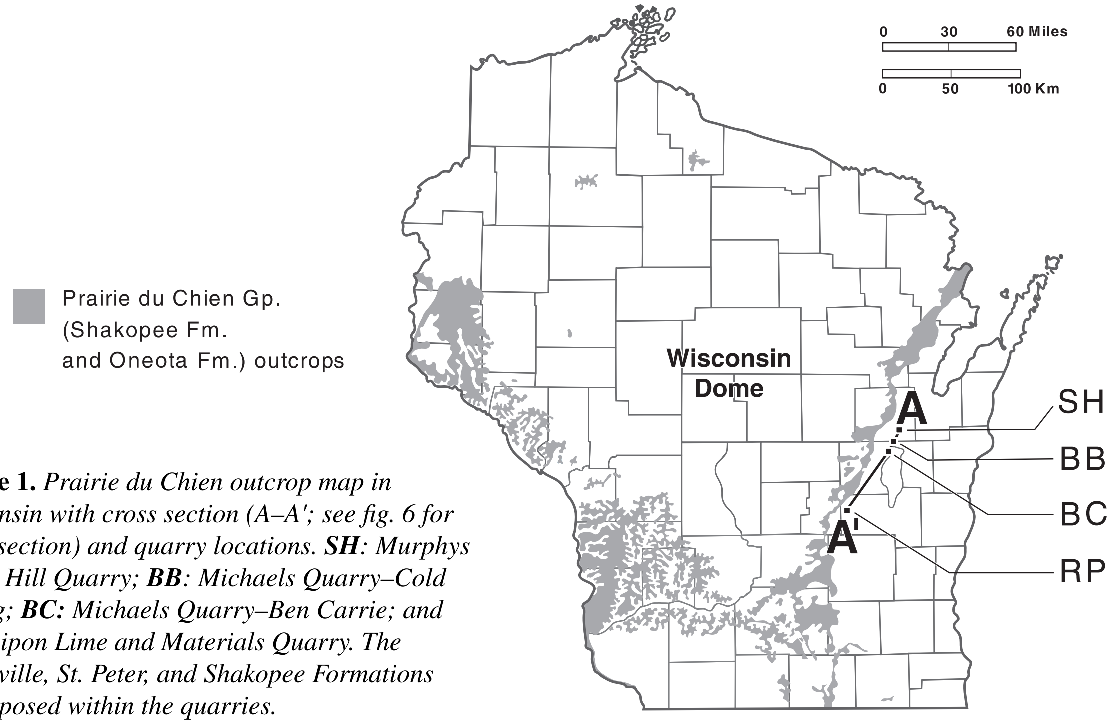

Figure 1. *Prairie du Chien outcrop map in Wisconsin with cross section (A–A'; see fig. 6 for cross section) and quarry locations.* ***SH****: Murphys Skunk Hill Quarry;* ***BB****: Michaels Quarry–Cold Spring;* ***BC:*** *Michaels Quarry–Ben Carrie; and* ***RP****: Ripon Lime and Materials Quarry. The Platteville, St. Peter, and Shakopee Formations are exposed within the quarries.*

gies and shallowing-upward cycles; stromatolites and gastropods indicate a peritidal depositional environment (this study; Davis, 1966; Smith and others, 1993, 1996). Our paper is the result of a senior thesis at the University of Wisconsin–Madison (Johnson, 1998).

Previous work

The Prairie du Chien Group is divided into the Oneota and Shakopee Formations (Ulrich, 1911, 1924). The Shakopee Formation consists of the New Richmond and Willow River Members. Early regional studies of the Shakopee Formation in the Mississippi River Valley in western Wisconsin were conducted by Winchell (1874), Wooster (1882), and Chamberlin (1877). Ulrich (1911, 1924) was the first to recognize the Shakopee and Oneota Formations as unconformity bounded units.

More recent studies were conducted by Davis (1966) on the Willow River Member of the Shakopee Formation in western Wisconsin and by Smith (1991) and Smith and others (1993, 1996) on the Prairie du Chien Group in Wisconsin and Michigan. Davis (1966) described the depositional environments as current dominated, open marine, wave dominated, shallow marine, and intertidal. Davis' interpretation showed a general deepening and decreasing of energy upward throughout the Willow River Member. Davis (1966) suggested that the Wisconsin Dome emerged at the end of the Lower Ordovician. The studies of Smith (1991) and Smith and others (1993, 1996) suggested that eustasy, rather than tectonics, controlled depositional packaging during the time when the Prairie du Chien was deposited. Figure 2 illustrates the regional sequence stratigraphic interpretation adapted from Smith and others (1993, 1996). The unconformity between the Oneota and Shakopee Formations is an emergent sequence boundary. The Willow River Member is capped by an emergent sequence boundary, ending the Sauk Sequence (Smith and others, 1993, 1996). Smith (1991) compared the shoaling-upward sequences in the Shakopee Formation to the "low energy intertidal stromatolite sequences" of James (1984).

METHODS

We developed our descriptions of the strata by measuring detailed stratigraphic sections, sketching cross sections, and mapping three-dimensionally important surfaces with a total station, an infra-red laser distance-measurement device. All percentage measurements in the study are field approximations. The quarries studied (fig. 1) are 1) Ripon Lime and Materials Quarry in Ripon, Wisconsin (Highway 151 north to Highway 49 north to Liberty Road west); 2) Michaels Quarry–Ben Carrie, Neenah, Wisconsin (Highway 151 north to Highway 41 north to Highway

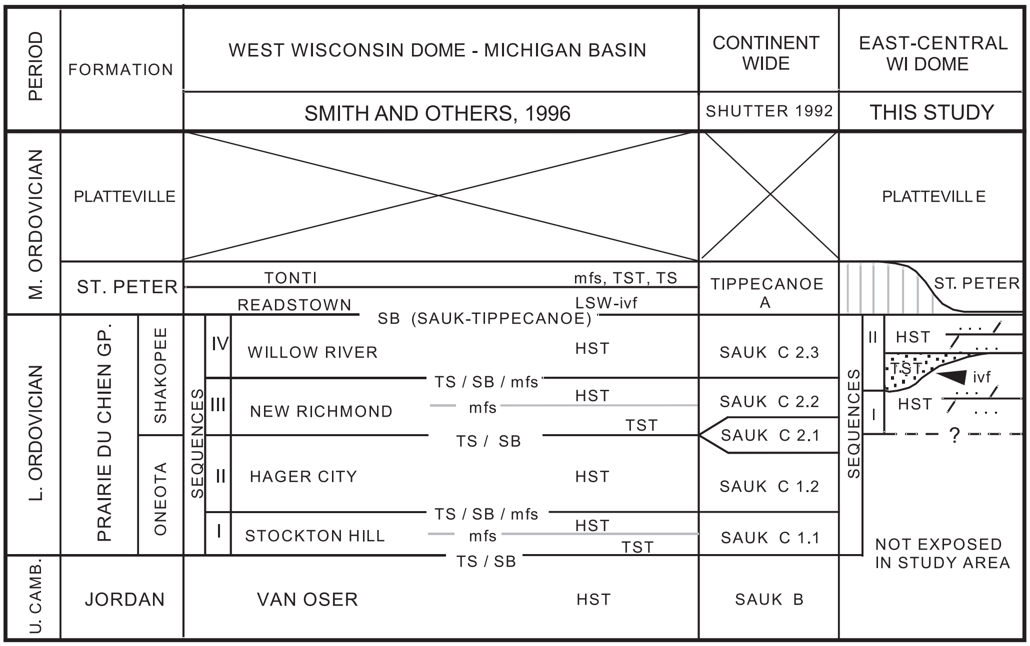

Figure 2. *Formations and sequence stratigraphic interpretations of the Lower Ordovician in Wisconsin (after Smith and others, 1996; Shutter, 1992) compared to this study. HST: highstand system track, TST: transgressive system track; LSW-ivf: incised valley fill of lowstand system wedge; mfs: maximum flooding surface; TS: transgressive surface; SB: sequence boundary; ivf: incised valley fill. Sequence numbers from Schutter (1992).*

114 west to Tuliar Lane north); 3) Michaels Quarry–Cold Spring, Neenah, Wisconsin (Highway 151 north to Highway 41 north to Highway BB west to Cold Spring south); and 4) Murphys Skunk Hill Quarry (Highway 151 north to Highway 41 north to Highway E north to Highway C north).

The basis of the sequence stratigraphic interpretation was the regional correlation of the intra-Shakopee and post-Shakopee unconformities between all four quarries in east-central Wisconsin. We applied sequence stratigraphic concepts and terminology from Van Wagoner and others (1988) to the sequence stratigraphic interpretations. We classified dolostone facies according to Dunham's (1962) textural classification scheme; bedding, according to Ingram (1954).

RESULTS

Facies description

The Shakopee Formation is characterized by a heterogeneous lithology composed of carbonates and siliciclastics on the bedform and bedset scale. Our study showed that the five major facies, in order of decreasing abundance, are 1) grain-supported dolostone (grainy facies); 2) matrix-supported dolostone (muddy facies); 3) sandstone; 4) green shale; and 5) stromatolitic boundstone that contains gastropod and shell-fragment-rich grainstone. The grainy facies is subdivided into quartz sand, oolitic, and peloidal subfacies because of the complexity and abundance of this facies in the Shakopee Formation.

Grain-supported dolostone facies

The grainy carbonate facies are dark gray, medium- to thin-bedded dolostones with moderately well preserved grainstone to packstone textures. Skeletal components are whole-shell gastropods and unidentified shell fragments; non-skeletal components are quartz sand grains, ooids, peloids, and dolostone intraclasts. Sedimentary structures are imbricated flat pebble conglomerates or breccias, oblate to irregularly shaped vugs, mudcracks, shale intercalations (<3 mm), thick high-angle planar cross-beds (approximately 30 cm), and symmetrical ripples that have a 10 to 30 cm wavelength, burrow mottling, and chert nodules.

The following grainy subfacies are listed in order of decreasing abundance:

Quartz sand grainy subfacies. A medium-grained, well rounded quartz sand is in thin cross-bedded layers (2–20 mm), patches, lenses, and along ripple crests.

The concentration of quartz grains ranges from 0 to 50 percent, usually approximately 10 to 25 percent. Vugs, mudcracks, and breccia beds are common. We classify a facies that has greater than 50 percent quartz grains as a sandstone.

Oolitic grainy subfacies. Ooids are the major component (>10%) of this subfacies. Minor components (<10%) are medium-grained quartz sand (not in grain to grain contact), whole-shell gastropods, and other unidentified shell fragments. The ooids are identified by their size and spherical shape; their internal structure was destroyed by dolomitization.

Peloidal grainy subfacies. This subfacies appeared matrix-supported in the field, but thin sections revealed rounded, well sorted, medium-grained peloids. The peloids are structureless spheres of fine-grained dolomite that occur as matrix-supported individuals and in flocculent coalesced clots. Peloid preservation is poor and identification difficult in the field due to dolomitization.

Matrix-supported dolostone facies

The muddy carbonate facies is light gray to light brown, massive to thinly bedded and has moderately well preserved mudstone and packstone textures. Sedimentary structures include plane beds, wavy lamination, thin laminae of clay, thin beds of siltstone, and burrow mottling. Non-skeletal grains are lenses of quartz sand and rare mudstone intraclasts. Skeletal grains are absent.

Sandstone facies

This facies is a white, massive, thickly to thinly bedded, well rounded to subrounded, medium-grained sandstone consisting of mostly quartz grains (>90%) containing minor proportions of subrounded pebbles of mudstone-textured dolostone intraclasts and thin shale intercalations. In one location, angular cobble-size dolostone intraclasts were found. This facies may be well lithified by a calcareous matrix or poorly cemented. Bedding at quarry scale is continuous with minor lateral pinch out. Sedimentary structures are high (approximately 25°) and low (approximately 10°) planar cross-bedding and low amplitude (5-10 cm), wide (approximately 50 cm) basal scours. In one locality, this facies is a thick (approximately 8 m), wide (approximately 50 m) wedge that contains irregularly and thinly layered red chert and undulating shale (approximately 30 cm thick). Dipping dolostone blocks overlie this sandstone wedge, which is located in the incised valley described below.

Green shale facies

This facies is a thinly bedded green shale containing thin lenses of siltstone and sandstone. Beds greater than approximately 5 cm are laterally continuous in places and are recessive in outcrop.

Stromatolitic–algal mat boundstones facies

Stromatolitic heads are approximately 30 to 50 cm wide and thick and commonly are separated by approximately 10 to 50 cm wide areas filled with gastropod and shell-fragment-rich dolostone. In this study, algal mats are distinguished from stromatolites by their flat, wavy laminations. This facies is easily recognized in outcrop and is laterally continuous in places.

Description of stratal geometries

Faulting and stratal tilting

Underneath the post-Shakopee unconformity, the Shakopee Formation exhibits normal faulting and irregular tilting of strata. Four high-angle normal faults are present at the Ripon Lime and Materials Quarry in Ripon, Wisconsin (fig. 3A). The faults are truncated above by the intra-Shakopee unconformity. The dips on these faults range from 55° to 85° in the north, southeast, and southwest directions. Beds less than 1 m from the faults appear deformed in the direction of movement with approximately 10 to 50 cm of displacement (fig. 3A). The entire Shakopee Formation shows local tilting in the study area. These stratal undulations appear to have no preferred direction (Simo and others, 1996). Two types of tilted strata are in the area: strata truncated by the intra-Shakopee unconformity (fig. 3A, right side), and strata above and below the intra-Shakopee unconformity (fig. 3A, left side).

Valley fill and associated deformation

Convoluted siliciclastic beds and many dipping dolostone blocks compose the thick sandstone wedge (referred to in the *Sandstone facies* section above). This wedge fills an incised valley cutting into beds in the underlying dolostone at Michaels Quarry–Ben Carrie (fig. 4A and 4C). The incised valley fill has a basal drape of shale that has thin lenses of sandstone. Figure 5 illustrates the shape, thickness, and orientation of the incised valley fill. The axis of the incised valley fill is oriented east–west. The facies in the incised valley are truncated above by an erosional surface and are bound below by an erosional surface with a minimum of 8 m of vertical relief. Some shale beds are truncated by the upper erosional surface, some are truncated by the dolostone blocks, and others have a

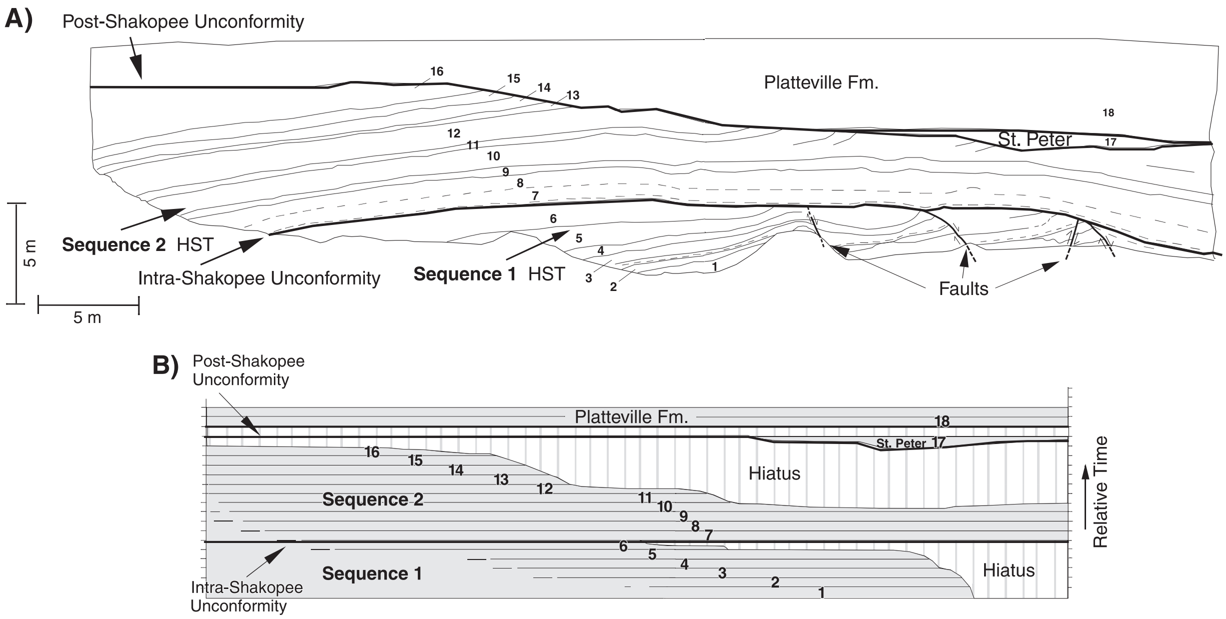

Figure 3. *Cross section and Wheeler diagram from Ripon Lime and Materials Quarry.* ***A.*** *Cross section illustrating the unconformities, strata, truncation, congruent and incongruent tilting, and normal faulting.* ***B.*** *Wheeler diagram illustrating depositional sequences 1 and 2, hiatus periods of no deposition, and the two unconformities.*

conformable contact with the dolostone blocks (fig. 4A and 3C). We did not determine whether the surface between the siliciclastics and dolostone blocks was erosional or non-erosional. The dolostone blocks are 3 to 20 m wide, angular with broken surfaces oriented perpendicular to bedding, and preferentially dip 4° to 30° into the center of the incised valley from both sides (fig. 4C). The facies of the dolostone blocks is grainy dolostone.

Unconformity surfaces

Two unconformity surfaces are recognized in the Shakopee Formation in the study area: the regionally recognized post-Shakopee unconformity, which is the boundary between the Sauk and Tippecanoe Supersequences of Sloss (1963), and a previously undocumented intra-Shakopee unconformity (figs. 3, 4, and 5).

The post-Shakopee unconformity is the upper bounding surface of the entire Shakopee Formation. This unconformity is characterized by a sharp lithologic contact between the Shakopee and St. Peter or Platteville Formations. The St. Peter Formation is absent in two of the four quarries in the study area and apparently pinches out from paleo-topographic highs on the Prairie du Chien Group (Simo and others, 1996). This surface is flat and laterally continuous; however, it undulates 1.5 m down into the incised valley fill of the Shakopee Formation below (fig. 5A).

The intra-Shakopee unconformity is characterized by the following:

- 8 m of erosional relief truncating dolostone beds below (fig. 4A);
- high-angle normal faults truncated by the unconformity above (fig. 3A);
- a regionally laterally continuous shale drape on the erosional surface; and
- a thick sandstone wedge that fills an incised valley above the intra-Shakopee unconformity. Figure 5 illustrates the features of the incised valley.

Regional correlation of the intra-Shakopee unconformity and post-Shakopee unconformity was possible because both were found at all four quarries in the study area. We did not observe the basal Shakopee unconformity (Shakopee–Oneota contact) in any of the quarries (fig. 6).

DISCUSSION

Depositional environment

The Shakopee Formation is a mixed siliciclastic–

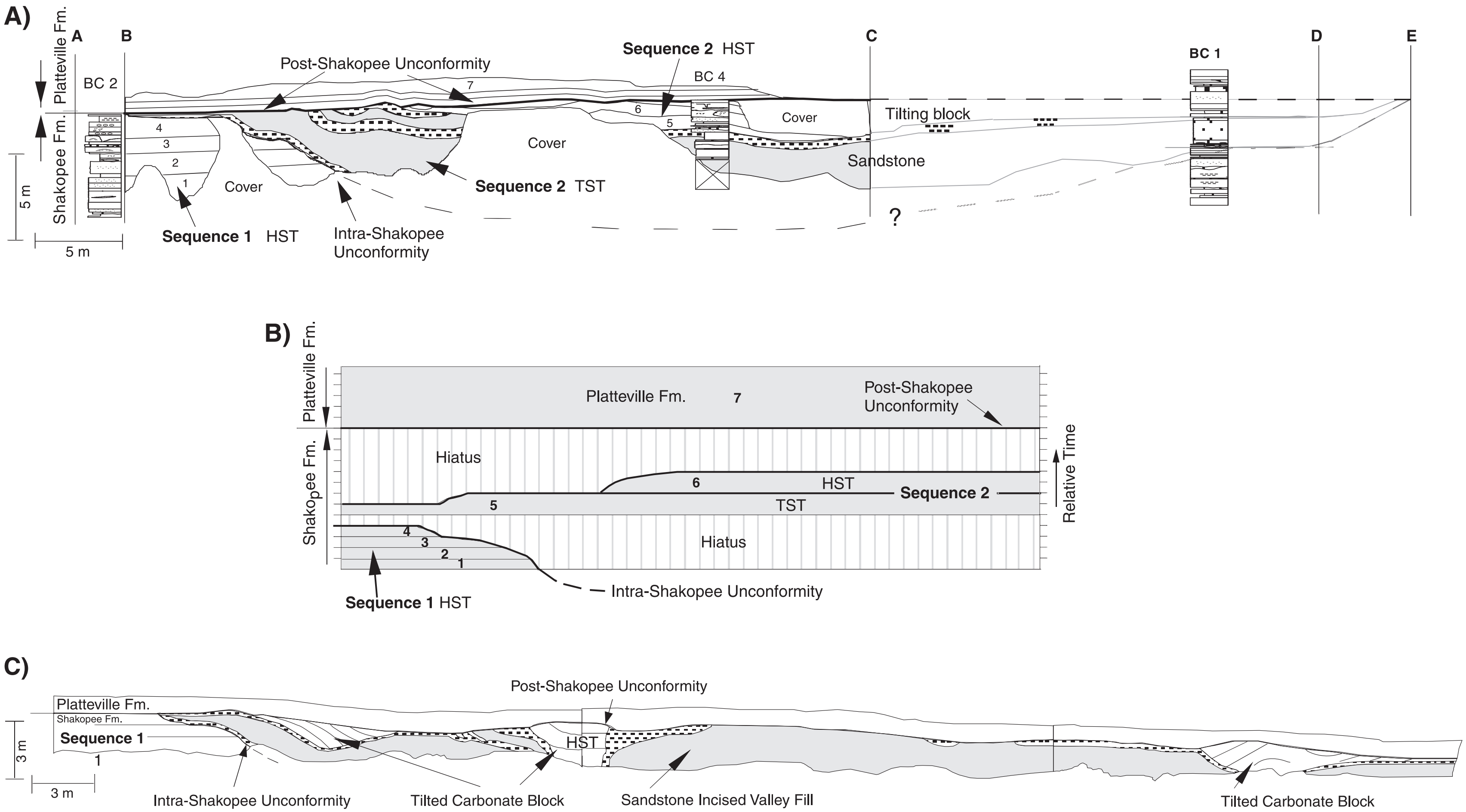

Figure 4. *Cross sections and Wheeler diagram from Michaels Quarry–Ben Carrie.* ***A.*** *Cross section with stratigraphic sections illustrating the west axis of the incised valley system.* ***B.*** *Wheeler diagram illustrating depositional sequences 1 and 2, hiatus periods of no deposition, and the two unconformities.* ***C.*** *Cross section illustrating east axis of the incised valley, tilted carbonate blocks, and convoluted shale beds.*

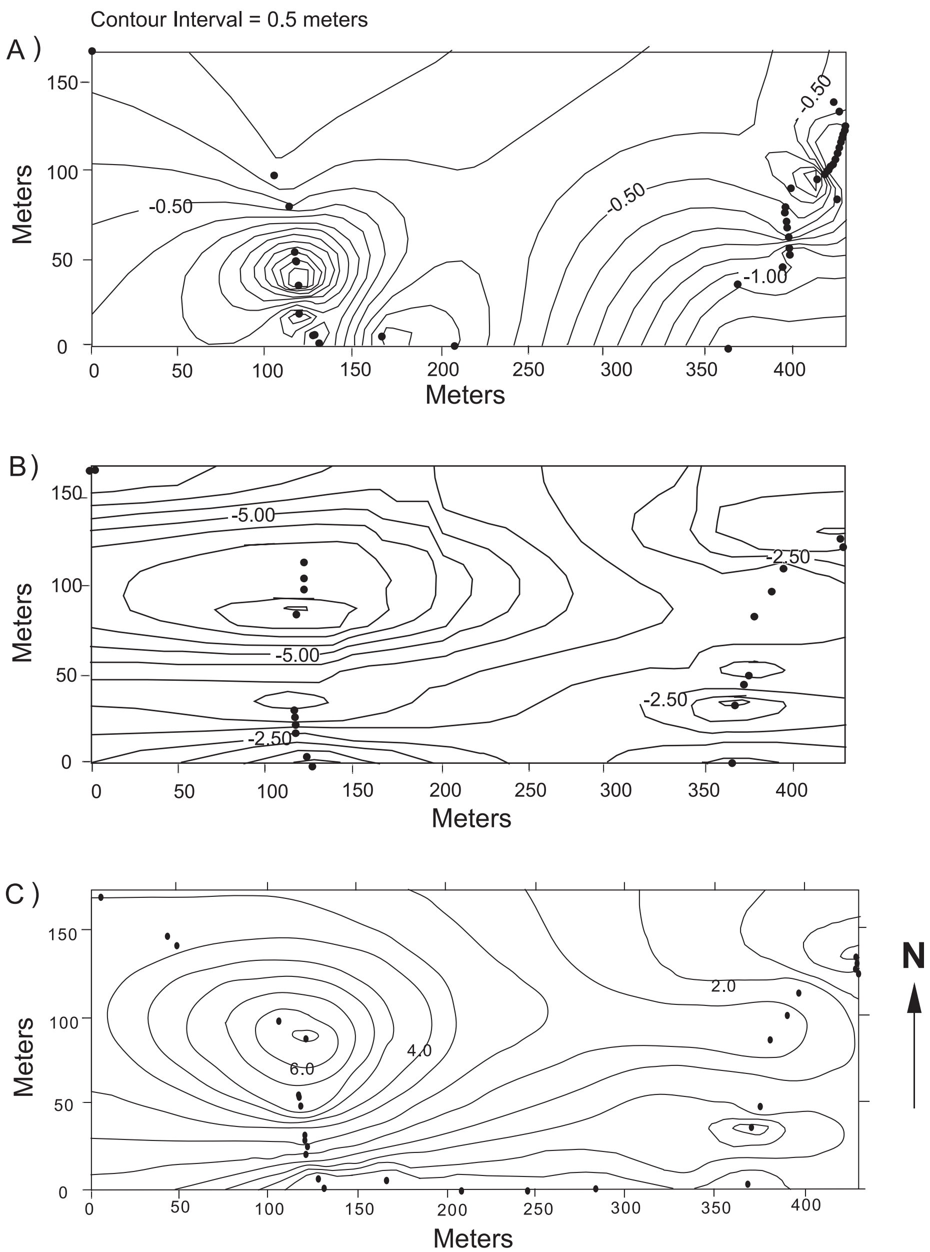

Figure 5. *Contour and isopach maps created with a total station at Michaels Quarry–Ben Carrie.* ***A.*** *Contour map of St. Peter–Platteville unconformity.* ***B.*** *Contour map of the intra-Shakopee unconformity, illustrating the east-west axis orientation of the incised valley.* ***C.*** *Isopach map of sequence 2, illustrating the shape of the incised valley fill.*

carbonate system deposited in a restricted, peritidal environment that was punctuated by erosion and incision of a valley network. This incised valley filled with siliciclastics and later carbonates. The grainy and stromatolitic–algal boundstone facies were deposited in a subtidal to supratidal environment (fig. 7). The muddy dolostone, sandstone, and shale facies were deposited in a subtidal environment.

The features of the grainy dolostone facies indicative of a subtidal environment are the presence of a small amount of carbonate mud, which suggests winnowing by waves (Enos, 1983), and the presence of peloids, bioturbation, mottled textures, and fossils, which suggest the ability to sustain life (Shinn, 1983;

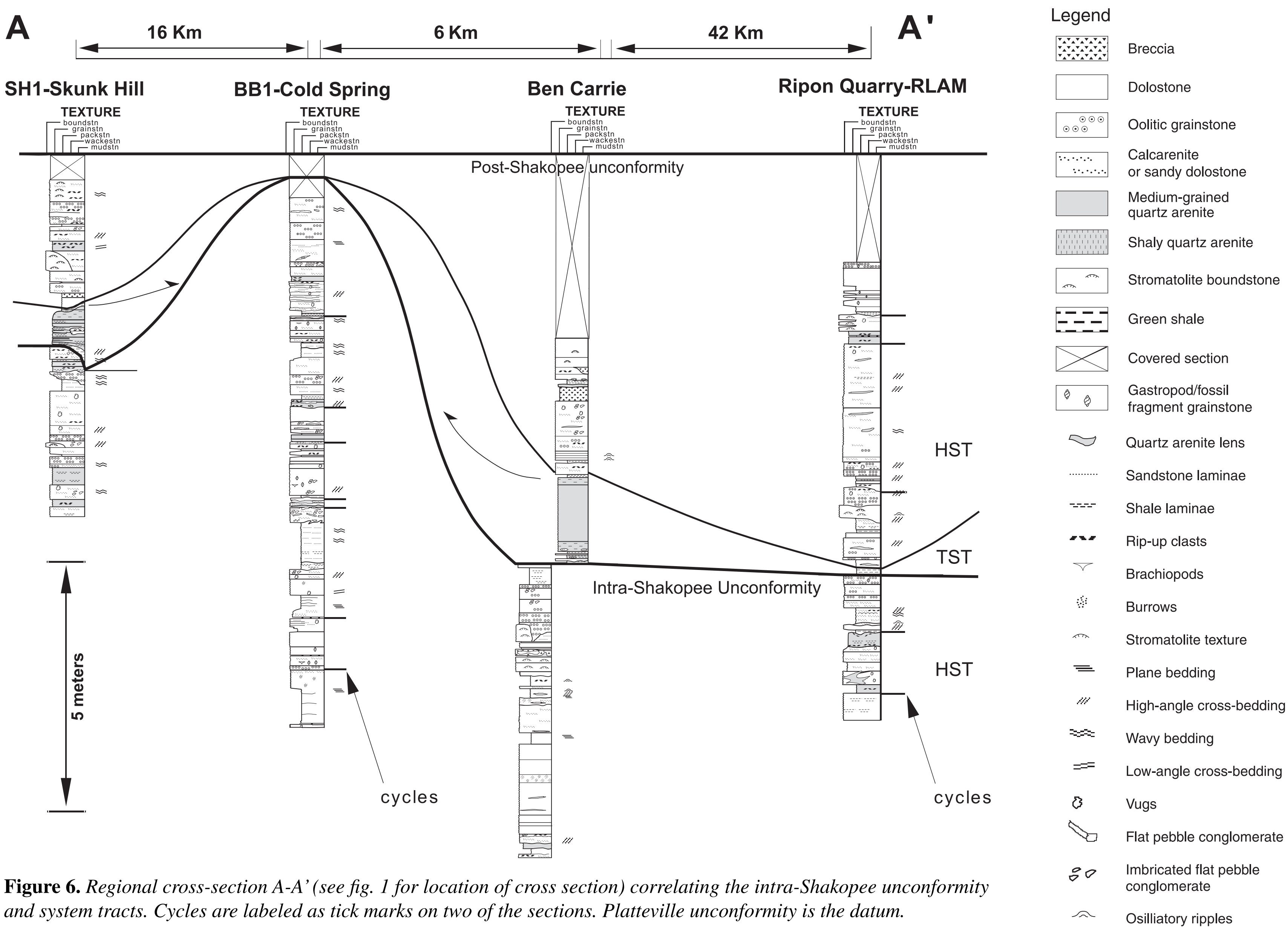

Figure 6. *Regional cross-section A-A' (see fig. 1 for location of cross section) correlating the intra-Shakopee unconformity and system tracts. Cycles are labeled as tick marks on two of the sections. Platteville unconformity is the datum.*

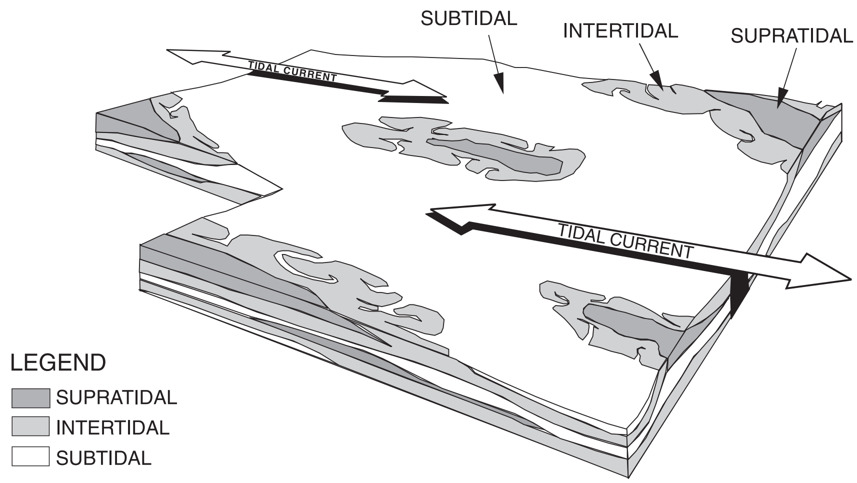

Figure 7. *Hypothetical block diagram of the peritidal island facies model of Pratt and James (1986), showing an epeiric sea and laterally discontinuous sub-, inter-, and supratidal deposits.*

Enos, 1983; James, 1984). The presence of ooids suggests constant wave agitation, which is common in the shallow subtidal realm (Enos, 1983). Features of the stromatolitic boundstone and grainy facies that suggest an intertidal setting are stacked hemispherical stromatolites that have generous spaces between hemispheres (Logan and others, 1964; Ginsburg, 1975), algal mats, preserved sedimentary structures, and mudcracks (Shinn, 1983).

The features of the muddy dolostone, sandstone, and shale facies indicative of a subtidal environment are siliciclastic and carbonate fines, which suggest little winnowing by waves, and massive textures, which indicate profuse bioturbation (Enos, 1983). Restrictive, highly saline, marine conditions are supported by the presence of stromatolites and gastropods (Enos, 1983), the location far inland on a shallow epeiric sea, and the presence of a facies mosaic (Laporte, 1967).

The small size of the incised valley, its channel-like shape, steep flanks, orientation perpendicular to the paleoshoreline, and location on the inner shelf of a wide epeiric sea suggest that it was eroded by fluvial processes. The siliciclastic facies filling the incised valley lack fluvial indicators such as a basal conglomerate and traction bedforms. The deposit has a basal shale drape and massive texture in the sandstones, suggesting the deposits are marine in origin. The shale was probably deposited as the relative sea level rose and a revinement surface removed fluvial deposits.

The source of the quartz sand in the Shakopee Formation probably was the emergent Wisconsin Dome because the sand decreases in abundance from the Wisconsin Dome to the Michigan Basin (Smith, 1991). Davis (1966) interpreted the shale to be from granite on the Wisconsin Dome. This concentration of sand in the Wisconsin Dome in relation to that of the Michigan Basin implies that the sand source is older Wisconsin Dome Paleozoic sandstone (Davis, 1966; Mai and Dott, 1985; Smith and others, 1993, 1996). The Shakopee, Oneota, and Jordan Formations show formation-scale thinning toward the Wisconsin Dome from the Michigan Basin and Minnesota (Ahlen, 1952; Smith, 1991; Smith and others, 1993, 1996; Starke, 1949). This thinning suggests that the Wisconsin Dome was a topographically positive structure and siliciclastic source in the Lower Ordovician.

Cyclicity

Meter-scale, mixed siliciclastic–carbonate, shallowing-upward (coarsening-upward) cycles are exposed in Ripon Lime and Materials Quarry in Ripon and Michaels Quarry–Cold Spring. Similar cycles have been described in the literature (Smith, 1991; Smith and others, 1993, 1996; James, 1984). The cycle boundaries are recognized on the basis of erosional surfaces evidenced by a sharp lithologic contact of contrasting facies. These surfaces are recessive and in places laterally continuous in outcrop.

The cycles are defined by a basal erosional surface overlain by shale or sandstone that has a gradational contact upward to muddy carbonate facies. The middle section is dominated by oolitic, peloidal, and quartz-sandstone grainy carbonate subfacies with lesser amounts of the muddy carbonate facies. The lower

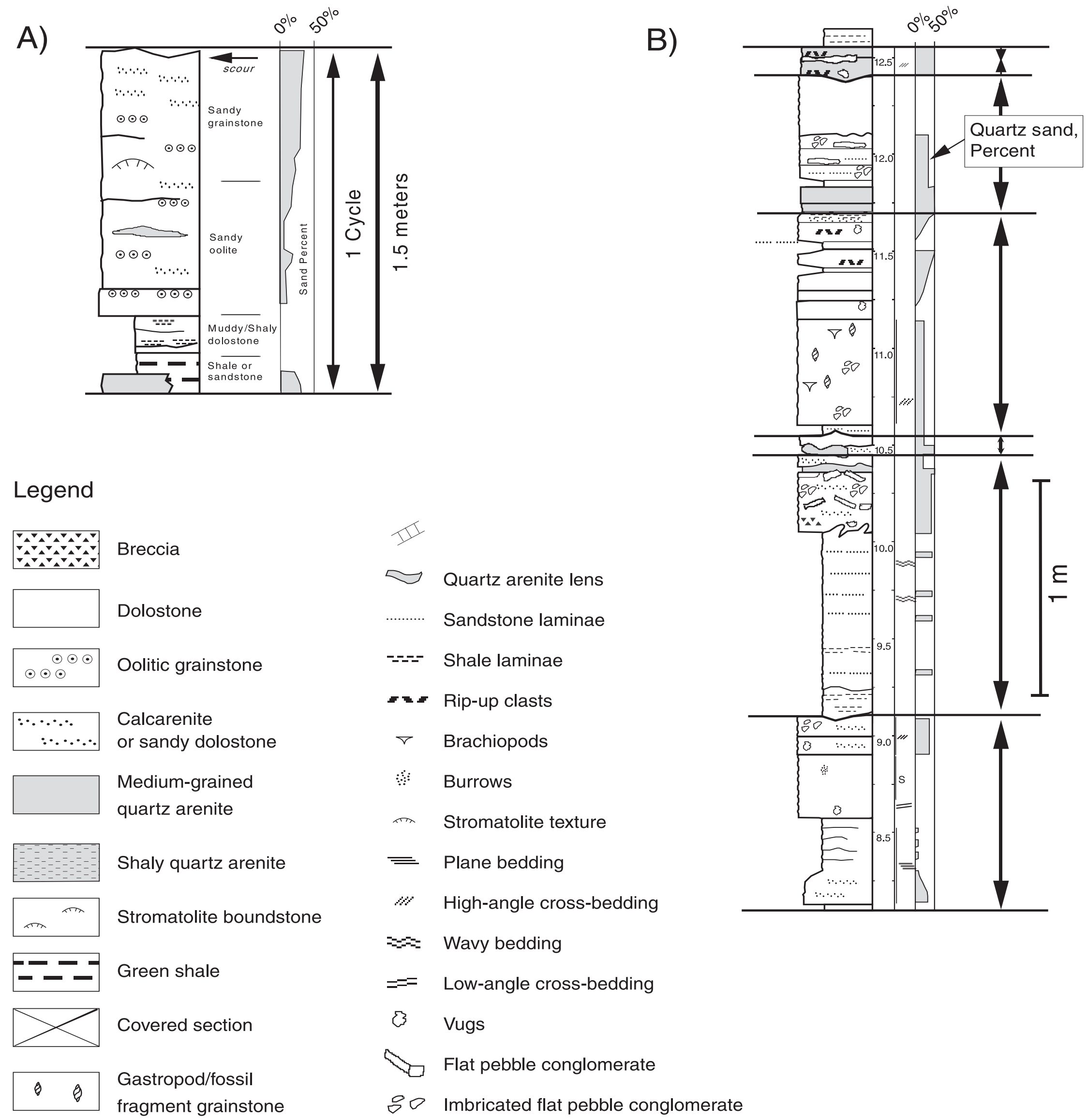

Figure 8. *Shallowing-upward cycles within the Shakopee Formation.* ***A.*** *Idealized cycle showing bounding erosional surfaces, shale and sandstone, argillaceous muddy carbonate, sandy oolite, stromatolites and sandstone lenses, and sandy grainstone.* ***B.*** *Cycle examples from Ripon Lime and Materials Quarry: Thick lines are cycle boundaries and individual cycle interval marked by arrows.*

and middle sections typically have wavy laminations, plane bedding, and low- to high-angle cross-bedding. The upper section of the cycle is characterized by mudcracks and increasing quartz sand up-section in the grainy carbonate facies. This description can be seen in the ideal cycle (fig. 8A) and cycle examples (fig. 8B). The cycles are laterally continuous only in places.

Similar meter-scale shoaling-upward cycles in the Shakopee Formation in western Wisconsin and the Michigan Basin have been interpreted by Smith (1991) and Smith and others (1993, 1996) to have formed in low-energy intertidal environments that have prograding tidal flats and migrating tidal channels. The “muddy sequences” and “stromatolite sequences” of James (1984) and the cycles of Smith (1991) and Smith and others (1993, 1996) have basal grainy carbonate facies or pebble lag supporting the tidal channel migration interpretation. In contrast, the Shakopee cycles in our study are characterized by basal sandstone and shale beds.

Two autocyclic models have been proposed by James (1984) to explain small-scale peritidal carbonate cycles in cratonic epeiric seas: the lateral progradation of a tidal-flat wedge model and the peritidal island facies model (fig. 7; Pratt and James, 1986). The peritidal island facies model originated from work in the St. George Group (Lower Ordovician) in western Newfoundland, Canada (Pratt and James, 1986). Due to the absence of laterally continuous cycles and the presence of shallowing-upward cycles, the peritidal island facies model is a better explanation than the prograding tidal-flat wedge model, although the prograding tidal-flat wedge model has not been disproven.

Sequence boundaries and sequences

Sequence boundaries

We characterized two bounding surfaces in quarries in Middle and Lower Ordovician strata in east-central Wisconsin. The two sequence boundaries are the intra-Shakopee unconformity and the post-Shakopee unconformity. The intra-Shakopee sequence boundary is an emergent surface indicating a relative fall in sea level. The post-Shakopee sequence boundary is a well established sequence boundary (Winchell, 1874; Chamberlin, 1877; Dott and others, 1986; Smith, 1991; Smith and others, 1993, 1996) representing the final regression of the Sauk epeiric sea in the study area. Both of the sequence boundaries are illustrated in Wheeler diagrams (figs. 3B and 4B).

Sequences

Smith and others (1993, 1996) interpreted the Shakopee Formation to be subdivided into three sequences (Sauk C2 2.1, 2.2, and 2.3, following Schutter, 1992, nomenclature). Smith and others (1993, 1996) interpreted the New Richmond Member (Sauk C2 2.1 and 2.2) to consist of a transgressive systems tract and a highstand systems tract and the Willow River Member (Sauk C2 2.3) to be only a highstand systems tract. The sequences in our study are not correlated to the sequence stratigraphic nomenclature of Schutter (1992) or Smith and others (1993, 1996) (fig. 2).

We identified two sequences in the Shakopee Formation in east-central Wisconsin: Sequence 1 is bounded on the bottom by the Oneota–Shakopee contact and on the top by the intra-Shakopee unconformity; sequence 2 is bounded at the bottom by the intra-Shakopee unconformity and on the top by the post-Shakopee unconformity. The upper part of sequence 1 is interpreted as the highstand systems tract; sequence 2 is interpreted to contain a transgressive systems tract represented by the siliciclastic incised valley fill and a highstand systems tract represented by carbonate strata and blocks (fig. 4A, 4B, and 4C). The shape and thickness of sequence 2 are illustrated in the isopach map in figure 5C.

The transgressive systems tract is supported by marine siliciclastics and a partially truncating surface that separates the siliciclastics from the carbonates in the incised valley. Sarg (1988) speculated that this is a marine flooding surface. The highstand systems tract in each sequence is supported by shallowing-upward cycles, a facies mosaic, apparent aggradation due to consistent stacking of peritidal deposits, and preservation of peritidal sediments, which suggest no reworking by a wave revinement surface (Sarg, 1988). The Wheeler diagrams from two localities illustrate the sequence stratigraphic concept explained above (figs. 3B and 4B).

Interpretation of the stratal geometries

Faulting and stratal tilting

We interpreted the tilting of Lower Ordovician beds below unconformities to have resulted from the collapse of underlying cave systems (for example, Smith, 1991). The cave system would form from exposure and karstification associated with dissolution. Later, deposition of strata above the exposure surface would increase lithostatic pressure, causing cave roof collapse and normal faulting in the underlying strata and tilting of the overlying strata. This mechanism is hypothetical because cave collapse has not been documented in any of the field studies.

Deformation in incised valley fill

In the incised valley, convolution of siliciclastic deposits is associated with the collapse of overlying carbonate blocks. This collapse (fig. 4A and 4C) is explained by differential compaction of shale in relation to carbonates and/or de-watering of siliciclastics from overburden pressures created by lithified carbonates above. Peloids, intraclasts, and flat-pebble conglomerates suggest early lithification of the carbonate facies, resulting in a differential rate of lithification of carbonate facies to siliciclastic facies (Shinn, 1983). Differential rates of lithification are speculated to be the cause of differential compaction. The partial conformity of shale layers to the overlying carbonate blocks suggests a synchronous deformational origin of the convolute strata and dipping carbonate blocks (fig. 4A and 4C). We speculate that undulations in the Platteville Formation above the incised valley fill were caused by post-Lower Ordovician compaction of the shale facies.

CONCLUSIONS

1) Facies in the study of the Lower Ordovician, Shakopee Formation, are alternating grainy dolostone, muddy dolostone, sandstone, shale, and stromatolitic–algal mat boundstone. Overall, the alternation is cyclic, representing variations in paleo-water depth within a restricted peritidal environment. The grainy dolostone and stromatolitic–algal boundstone facies were deposited in a subtidal to supratidal environment. The muddy dolostone, sandstone, and shale facies were deposited in a subtidal environment.

2) The previously undocumented intra-Shakopee unconformity is an emergent sequence boundary separating sequences 1 and 2. This sequence boundary corresponds to an incised valley filled with siliciclastic sediment and is regionally continuous. The surface truncates beds below and postdates normal faults. Strata overlying the incision consist of a shale drape and thick siliciclastic wedge.

3) The Shakopee Formation consists of two sequences. Sequences 1 consists of a highstand systems tract; sequence 2, a transgressive systems tract and a highstand systems tract. The highstand systems tract is composed of shallowing-upward cycles and peritidal dolostones in both sequences. The transgressive systems tract is composed of deformed siliciclastic deposits on top of the intra-Shakopee unconformity and in the incised valley. Above the incised valley fill the transgressive systems tract is overlain by a marine flooding surface and a highstand systems tract.

4) Associate strata to the intra-Shakopee unconformity are tilted and faulted, probably as a result of the overburden pressure of strata above paleocaves and differential compaction. Paleocaves associated with karstification from dissolution may have caused roof collapse. Differential lithification of carbonates in relation to siliciclastics caused differential compaction, resulting in convoluted siliciclastic deposits in the incised valley.

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