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MUDCRACKS, BIRD'S-EYE, AND ANHYDRITE IN INTERTIDAL/SUPRATIDAL LATE SILURIAN KOKOMO LIMESTONE, INDIANA

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ABSTRACT. The Kokomo Limestone Member of the Wabash Formation is of late Silurian age. This member consists of about 30 m of thinly-laminated carbonates in the Logansport area of north-central Indiana. The almost complete lack of fossils throughout the member indicates a hypersaline depositional environment. Previous workers interpreted the Kokomo Limestone as a product of an intertidal and subtidal environment, or reported the presence of syneresis cracks to argue for a restricted lagoon and intertidal environment. In this paper we show that desiccation mudcracks, storm-produced intraclasts, intraformational conglomerate, and bird's-eye structures taken together indicate an intertidal and supratidal environment during deposition of the Kokomo Limestone. Microscopic supporting evidence includes microcracks, intraformational micro-breccia/conglomerate, an abundance of dolomite, anhydrite/gypsum pseudomorphs, and fenestrate structures lined with calcite, dolomite and tar. Couplets of dark and light laminae were previously interpreted as annual cycles, but we interpret them as daily tidal cycles, bimonthly spring tide deposits, and occasional storm tide deposits. We also show evidence of unconformities both at the base and at the top of the Kokomo Limestone Member.

Keywords: Mudcracks, bird's-eye, carbonates, intertidal, supratidal

The Kokomo Limestone Member of the Wabash Formation, Salina Group, is of late Silurian age, latest Ludlovian to early Pridolian (middle Cayugan) (Shaver et al. 1986). The contact with the underlying Mississinewa Shale is sharp and disconformable (Cummings & Shock 1928), but Pinsak & Shaver (1964) report lacking proofs for either disconformity or conformity. The upper contact with the Kenneth Limestone is sharp but poorly understood. According to Shaver et al. (1986), sand grains and other clastic sediments associated with this contact are not evidence of intra-Silurian unconformity but rather of pre-Middle Devonian karst. Pinsak and Shaver (1964) correlate the Kokomo Limestone to the A-2 unit of the Salina Formation of Michigan. The Kokomo Limestone is exposed in several quarries in the Logansport area of north-central Indiana. Thinly-laminated beds of the Kokomo Limestone are alternating light and dark layers less than 1 mm thick. Outcrop exposures also reveal stacking of small scale (2–5 cm) and large scale (30–100 cm) light and dark beds.

Even though most of the unit is dolomite, as noted by previous workers (Pinsak & Shaver 1964; Tollefson 1979; Nellist 1986), the Kokomo Member is still formally called a limestone rather than a dolomite. In this paper we adopt Nellist's (1986) subdivision of the Kokomo Limestone Member into the Morgan Hill Bed (Tollefson's beds A and B) and the Eel Bed (Tollefson's beds C, D, E and F). Tollefson (1979) considered the Kokomo Limestone depositional environment as a restricted, hypersaline intertidal environment on the isolated Wabash platform, which near the end of deposition changed into a more normal marine subtidal environment. Nellist (1986), however, interpreted the Kokomo Limestone depositional environment as a subtidal, restricted lagoon that near the end of deposition became shallower and, in parts, intertidal. Tollefson (1979) used the presence of broken and distorted laminae in the Morgan Hill Bed of the Kokomo Limestone as evidence of desiccation and subaerial exposure indicating presence of mudcracks, but Nellist (1986) interpreted the same features as subaqueous syneresis cracks and considered the lamination couplets to be of seasonal character. In this paper we demonstrate the presence of desiccation mudcracks not only in the outcrop, but also in thin

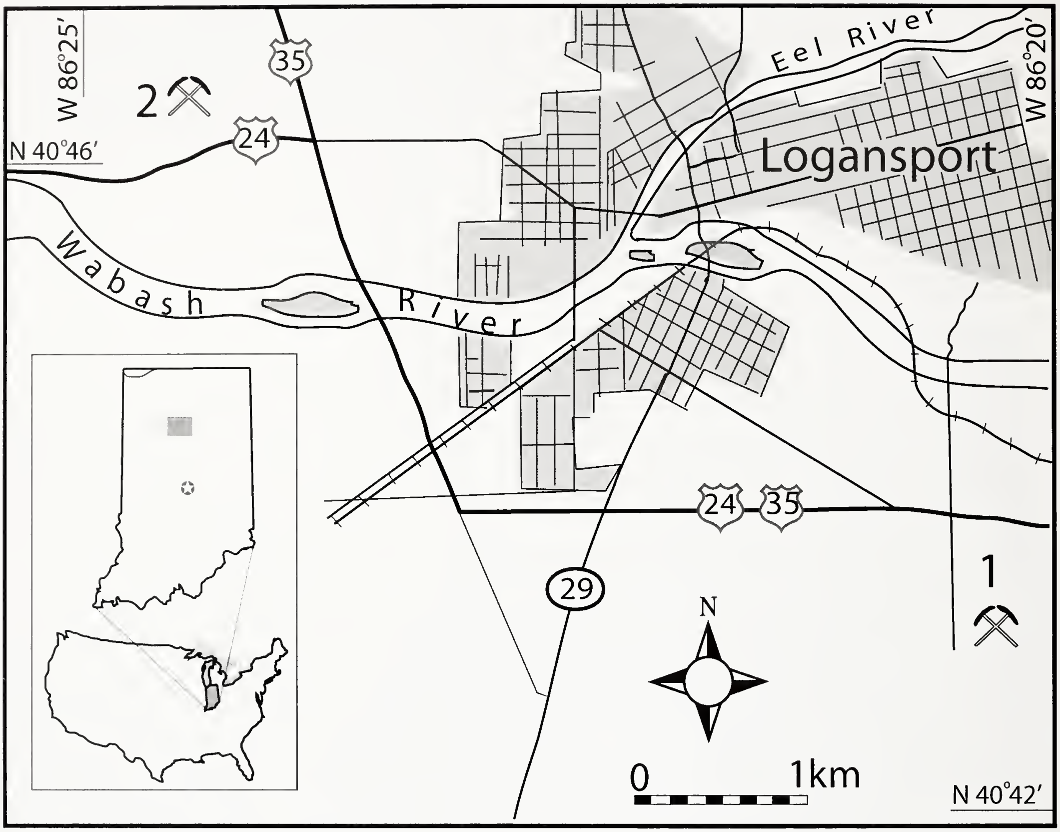

Figure 1.—Location of two quarries studied in Logansport, Indiana. The first is active Engineering Aggregates Quarry #1, and the second is now closed Engineering Aggregate Quarry #2, as referred to in the text. Drawing is based on USGS 7.5 minute series Topographic maps of Logansport, Lucerne, and Anoka Quadrangles.

sections. We argue in favor of an intertidal environment during the deposition of the Morgan Hill Bed of the Kokomo Limestone. The Eel Bed of the Kokomo Limestone contains sedimentary structures that include bird's-eye (fenestrate) structures, algal mats, gypsum/anhydrite blebs and pseudomorphs, penecontemporaneous dolomite, and intraformational storm tide deposits, that we interpret as indicative of a supratidal (Shinn 1983; Hardie & Shinn 1986) depositional environment. On a broader scale our research implies: 1) reinterpretation of Late Silurian paleotopography between the Michigan and Illinois basins, indicating partial exposure of the Wabash Platform during deposition of the Kokomo Limestone and before deposition of the Kenneth Limestone; and 2) the rejection of the subtidal syneresis hypothesis of crack formation in these carbonate sediments.

Location of the study area.—Our field work included study of two quarries in the Logansport area of north-central Indiana. Engineering Aggregates Quarry #2, now inactive, is located about 3 km west of Logansport, north of Indiana Highway 24 in E ½ of Sec. 28, T 27 N, R 1 E (Fig. 1). This quarry has been referred to as "Big Blue Hole Quarry" (Cummings & Shrock 1928) or as "Cass County Quarry" (Tollefson 1979). The uppermost part of the Morgan Hill Bed and the entire Eel Bed were studied in this quarry. Engineering Aggregates Quarry #1 is located south of town about 0.8 km south of Indiana Highway 35 in N ½ of Sec. 6, T 26 N, R 2 E. Tollefson (1979) refered to this quarry as the "South Logansport Quarry" and at the time of her work the lower part of the Morgan Hill Bed (her Unit A) was not exposed. After Nellist's (1986) study of the Kokomo Limestone in this quarry, about 5 m of the basal part of the Morgan Hill Bed was exposed. There were 52 samples of Kokomo Limestone collected and cut into thin sections for petrographic study.

SHRINKAGE CRACKS

Plummer and Gostin (1981) studied many examples of mudcracks and synaeresis cracks from the rock record and in laboratory experiments and concluded that no single feature of any shrinkage crack is useful in differentiating between the two. Evaporation of water from muddy sediment causes drying, shrinking and mudcrack formation. Shinn (1983) noted that no single sedimentary structure is more indicative of the upper intertidal and the supratidal depositional environment than mudcracks caused by shrinkage of carbonate mud. Desiccation mudcracks are generally continuous, polygonal, and often of several generations with V or U-shaped cross sections that are infilled from above. However, where desiccation has insufficient time to fully develop, an incomplete mudcrack system can form consisting of short but often intersecting cracks. Other sedimentary structures indicative of subaerial exposure and associated with desiccation mudcracks include raindrop imprints, evaporite casts, vertebrate tracks, bubbles and foam impressions (Plummer & Gostin 1981).

Syneresis cracks can form by expulsion of water from clays due to variations in water salinity at the sediment-water interface, but a majority of them are produced by compaction of clays substratally and are often associated with load structures (Plummer & Gostin 1981). Syneresis cracks are generally discontinuous, spindle, or sinuous in shape and of one generations only, with V or U-shaped cross-sections that are infilled either from above or from below (Plummer & Gostin 1981). Experiments with salinity changes (Burst 1965) produced small syneresis cracks but did not cause sediment injection. Pratt (1988) argued against deep burial and compaction and suggested dewatering of argillaceous sediment by ground motion from strong synsedimentary earthquakes as a mechanism for syneresis cracks formation. The rarity of syneresis cracks in Phanerozoic marine rocks is a consequence of greater content of organic matter in the sediment and organic binding of clay flocks in the water (Pratt 1988). Even some of the most widely cited examples of syneresis cracks from lacustrine rocks, like those of the Devonian Orcadian Basin of Scotland (Donovan & Foster 1972; Barclay et al. 1993), have recently been reinterpreted as subaerial mudcracks (Astin & Rogers 1991, 1993).

SHRINKAGE CRACKS IN THE KOKOMO LIMESTONE

We started our analysis with the older part of the Kokomo Limestone, hereinafter referred to as the Morgan Hill Bed (Nellist 1986), which is exposed in Engineering Aggregates Quarry #1, south of Logansport. The Morgan Hill Bed is a dark gray thinly-laminated dolomite that appears in small scale (2–5 cm) lighter and darker bands. The rock weathers into thin, platy chips that approximately follow the width of the colored bands. Frequently, weathering and breaking occurs along algal mat surfaces in the rock. About 3 m above the base of the Morgan Hill Bed (bottom bench in the quarry) there is a brecciated layer with disrupted lamination and numerous shrinkage cracks. Two samples (Figs. 2, 3) from that horizon were examined for this paper. Figure 2 shows deformed and broken laminae that are bent downward into a V-shape. Fracturing that affects one or two lamina couplets extends vertically 1–3 cm. Lateral spacing of cracks in some couplets is short (1 cm or less) while other couplets break in longer intervals (4 cm). Almost always, breakage starts in the dark lamina and disrupts the underlying one or two laminae. Rotation and displacement of broken parts of some laminae are evident. Overlying laminae increase in thickness in places where underlying laminae were broken. Breaking of overlying lamina occurs at places not coinciding with underlying cracks. In places where cracks were not filled with overlying laminae we saw pyrite or calcite secondary fills.

Another example (Fig. 3) showed a V-shape crack about 1 cm long in cross section. After we dislodged the rock and split it along the bedding plane, four five-sided shrinkage polygons (Fig. 4) with 3–8 cm long sides were exposed. The polygon edges are about 1 cm wide and contain calcite specks. The vertical extent of the polygon edges was about 1 cm. The bedding plane surface contains raindrop imprints. This hand sample contained three

Figure 2.—Cut and polished sample of broken laminae 3 m above the base of Morgan Hill Bed. Broken and rotated chips of laminae are visible around black arrows. Multiple generations of cracks (white arrows) do not occur along the same vertical profile. Calcite and pyrite (P) are found in the center of large crack. Anhydrite/gypsum laths are visible around gray arrow.

sets of shrinkage cracks that were independently formed because their pattern did not match vertically (Fig. 4).

At the lower bench of the quarry we examined the middle and the upper part of the Morgan Hill Bed. Numerous surfaces showed a similar pattern of shrinkage cracks with five and four sided polygons having sides ranging from 5–15 cm. A sample collected from quarry ledge 9, about 8 m above the base of the

Figure 3.—Side view shows V-shaped crack in the lower center (white arrow). Black arrows point to a lower set of polygonal cracks. Coin diameter is 2.5 cm.

Figure 4.—Split sample from the specimen shown in Fig. 3 reveals a beautiful plane view of the shrinkage polygons with triple junctions. Raindrop imprints are visible at the arrow. The hammer head is about 15 cm long.

Morgan Hill Bed, contained multiple shrinkage crack polygons along an algal mat covered bedding plane. Three sets of polygons were recognized on this surface. The largest polygons were four or five-sided with edges about 5 cm long. The width of the cracks in these polygons was about 5 mm. The second set of polygons had sides of about 2 cm length while the width of their cracks was about 3 mm. The smallest polygons had five or four sides with 5–10 mm length. The width of their cracks was 1–2 mm. No raindrop imprints were noted, but a bumpy irregular algal mat surface was obvious.

Thin section study revealed the presence of shrinkage cracks on a micro scale in both Kokomo Limestone members. We observed and measured several of these cracks that displace 11–16 couplets and extend vertically 2.5–5 mm. In all instances shrinkage began in the darker lamina at or close to the thickest couplet. An increase in the thickness of lamina above the crack was evident (Fig. 5). Sparry calcite cement and scattered quartz silt filled the micro-cracks. The thickness of dark-light couplets varied from 0.2–0.7 mm.

The Eel Bed of the Kokomo Limestone shows more variations in color than the Morgan Hill Bed. The Eel Bed contains numerous layers with vugs and bird's-eye structures and doesn't weather easily along bedding planes. In many layers vugs are filled with either calcite or tar. While the bedding plane surfaces were poorly exposed and hard to study, there are plenty of easily accessible side views with abundant vugs and disrupted and broken laminae. In its lower 3 m, the Eel Bed contains 1–3 cm structureless and vuggy beds intercalated with thinly-laminated (1–5 mm) layers of algal mats, anhydrite and dolomite. In one instance we noticed a ripple mark (Fig. 6) on top of a structureless layer with an irregular upper surface.

The Eel Bed is better exposed and easier to

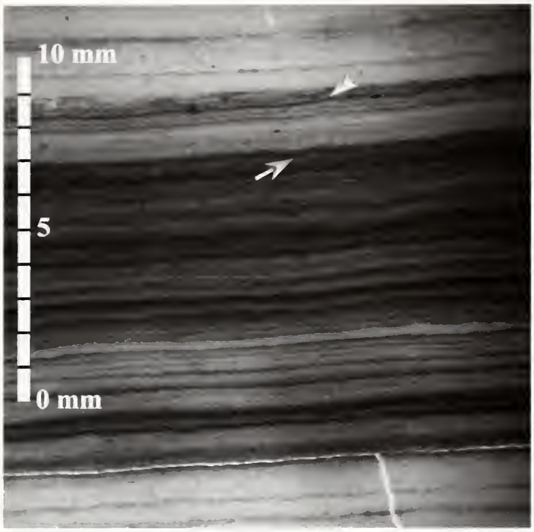

Figure 5.—Shrinkage on micro-scale (between arrows) in Eel Bed of Kokomo Limestone. Note irregular surface of dark lamina where fracture began and its increase in thickness toward left.

study in the now-abandoned Engineering Aggregates Quarry #2. About 2 m below the top of the Eel member there is a prominent 0.5 m thick tan bed that lacks lamination and contains a very porous surface full of vugs and bird's-eye structures. Several layers about 2–3 cm thick (Fig. 7) are full of mudchips that occasionally show imbrication. Mudchips range from 1–10 mm and have well-rounded edges. The bases of these layers are scoured and irregular while their tops are smooth and flat. A thin lamination with dark and light couplets resumes on top of this layer. Vugs are elongated and parallel with bedding planes.

Another common feature from the upper part of the Eel Bed is nodular anhydrite with 5–30 mm long blebs, whose lower sides are always lined with dark algal mats.

DISCUSSION

We agree with Plummer & Gostin's (1981) conclusion that no single feature of a shrinkage crack can distinguish between subaerially formed mudcracks (desiccation cracks) and subaqueously formed synaeresis cracks. However, when several features indicate similar conditions present in various parts of the same depositional environment, then the interpretation makes a valid case. We began our interpretation with samples and structures observed in the lower part of the Morgan Hill Bed (Figs. 2, 3, 4). Multiple generations of cracks break up thinly-laminated carbonate mud in Fig. 2. The V-shape of the cracks and an increase in sediment thickness over the cracks (geopetal fill) indicated subaerial exposure and the growth of algae preferentially around the mudcracks. Broken, rotated and rounded clasts are a clear indication of exposure, desiccation, and reworking during the next high tide.

The different location of the cracks along the vertical profile was an indication of multiple episodes of wetting and drying and time lapse responsible for such a pattern. During exposure, some quartz silt was brought into cracks while evaporite crystals were growing. Later, in diagenesis, dissolution of evaporites provided a source of sulphur that combined with iron to make pyrite. Reducing conditions were provided by the microbial decay of algal mats. Well-defined mud polygons (Fig. 4) with raindrop imprints further support our interpretation of subaerial exposure and the desiccation process. As in the previous example, multiple generations of cracks appear vertically stacked at various positions. Finally, we found an example with multiple generations of cracks developed on an algal mat surface. The largest polygons form first and as the drying proceeds, secondary and then tertiary sets of smaller cracks develop inside the larger polygons. The algal mats preserved some moisture, and the cracks were not very deep or wide.

We are not aware of any syneresis cracks having the properties we recognize and describe in the previous paragraphs, and with great confidence we reject the hypothesis of subaqueous crack formation in carbonate muds. The somewhat similar structures of diastasis cracks (Cowan & James 1992) may in some cases resemble our examples. However, the Morgan Hill Bed of the Kokomo Limestone is very homogenous and does not contain sediments of different competence that would cause differential mechanical behavior and crack formation.

We agree with Tollefson's (1979) interpretation of an intertidal environment for the Morgan Hill Bed based on the presence of mudcracks. Well-developed mud polygons, multiple stacking and repetition of the patterns vertically, as well as multiple generations of

Figure 6.—Lower part of the Eel Bed of Kokomo Limestone. Numerous bird's-eye structures are present (black arrows) in structureless layers. Dark bands in laminated layers are algal mats, while light bands are either dolomite or anhydrite. Grey arrow points to ripple mark on top of irregular structureless, vuggy layer. Coin is 2.5 cm wide.

mudcracks on a single bedding plane, indicate an upper intertidal zone that was under water only during extreme spring tides. On some occasions, dried mud chips were moved and reworked by the following high tide.

Examples of microcracks (Fig. 5) found at various intervals throughout both the Morgan Hill Bed and the Eel Bed show a consistent pattern of crack initiation at or near the thickest couplet. Nellist (1986) did not address these microcracks but rather interpreted our larger mudcracks as synaeresis cracks. He considered laminae couplets to be of seasonal character and suggested synaeresis as a result of seasonal changes in sea water chemistry. Scattered quartz silt that was almost exclusively found within the dark, algal mat laminae is explained by Nellist (1986) as the result of seasonal dryness and availability of silt from distant areas.

Thickening of the laminae from 0.25–0.8 mm occurs in regular intervals of 16–30 couplets. This pattern is indicative of daily and monthly tidal cycles (Brown et al. 1990; Kvale et al. 1999) rather than seasonal subtidal deposition. Spring tides deposited the thickest laminae, then brief exposure occurred 6 or 12 h later when micro-cracking occurred. An increase in thickness of subsequent laminae over the microcracks (Fig. 5) indicates their syndepositional origin and brief exposure, rather than later subsurface cracking due to loss of pore water or dewatering due to earthquake ground motion (Pratt 1988). Preferential accumulation of quartz silt in dark, algal-mat laminae can be explained either by trapping of silt by exposed algal mats, or by the settling of silt through shallow water on top of algal mats during flood tides. We interpreted intervals with microcracks as an indication of the middle intertidal zone which was exposed only during extreme low spring

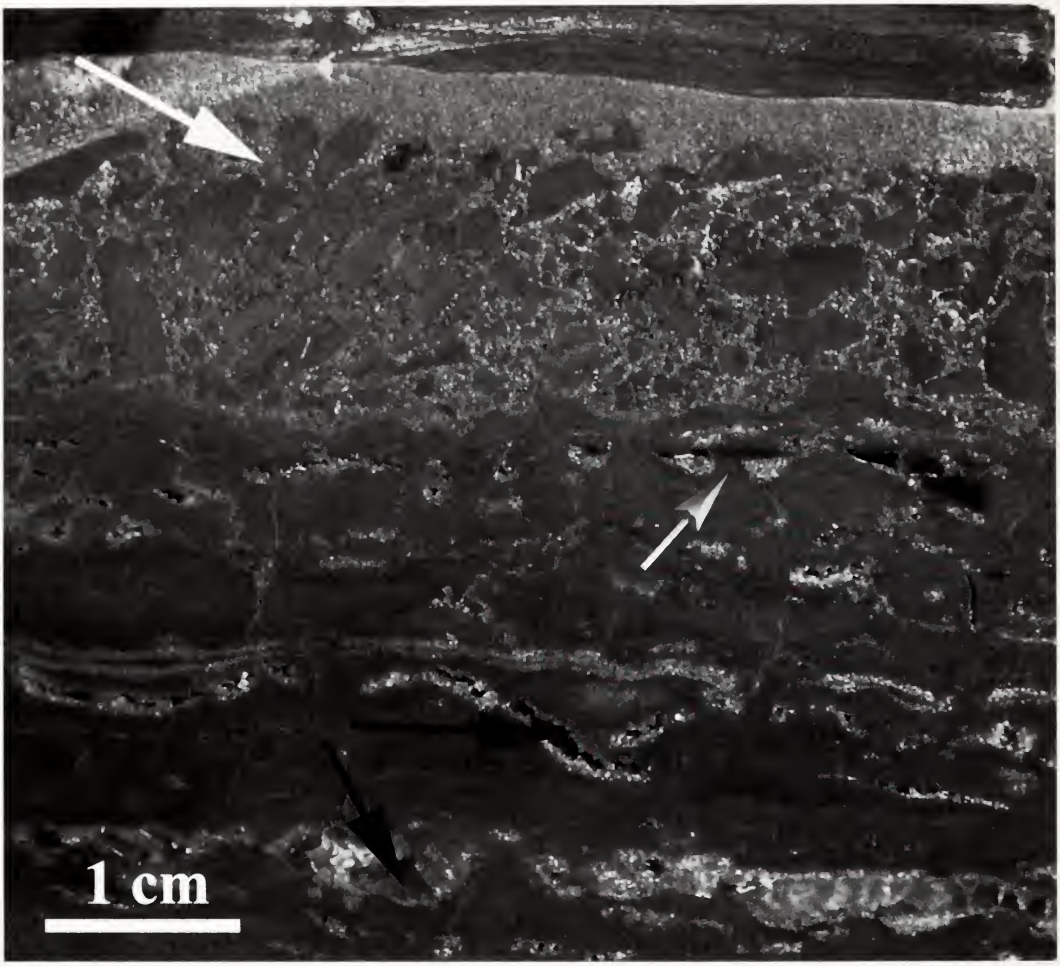

Figure 7.—Intraformational conglomerate layer (white arrow) with irregular scoured base, from the upper part of Eel Bed. Bird's-eye structures are scattered throughout the lower part of the sample. Some vugs have geopetal fill (grey arrow). Elongated vugs (black arrows) are filled with calcite and dolomite or are empty, but in other exposures contain tar or pyrite. Note lamination at the top of the sample.

tides. We correlate the Morgan Hill Bed and lower laminated parts of the Eel Bed of the Kokomo Limestone with the Salina Formation Unit A-1, lithofacies 2 (Gill 1977) representing an intertidal depositional environment that was frequently but briefly exposed to drying and desiccation.

Intraformational conglomerate, bird's-eye (fenestrate) structures, and abundant vugs (Fig. 6) are reliable indicators of supratidal depositional environment (Ginsburg 1975; Demico & Hardie 1994; Flugel 2004). During storms, highly sediment-charged water moves over supratidal flats and within a few hours layers exceeding 2 cm in thickness may be deposited (Shinn 1983). The upper part of our Fig. 7 represents one storm event which reworked dried mudchips into a 2 cm thick layer. Even though rare, ripple marks have been reported from a supratidal carbonate environment after passage of a storm (Shinn 1983).

Bird's-eye structures and vugs form in supratidal sediments as a result of shrinkage and expansion, gas bubble formation, air escape during flooding, wrinkles in algal mats or even by development of evaporites (Shinn 1968). Supratidal bird's-eye structures are preserved because of early cementation and filling with calcite, dolomite, evaporite or internal sediment (Shinn 1968, 1983). Perkins

(1963) described very similar bird's-eye structures in dolomite beds in the Devonian Jeffersonville Limestone, intercalated with laminated and mudcracked beds. Numerous bird's-eye structures and vugs in the Eel Bed of the Kokomo Limestone are filled with calcite, dolomite or geopetal fill and clearly indicate a supratidal depositional environment.

Formation of anhydrite and gypsum occurs mostly in the upper intertidal and supratidal environments, just centimeters above mean tide level. Capillary rise brings salty groundwater to the surface, where evaporation increases concentration of brines and eventually causes precipitation of gypsum or anhydrite (Shinn 1983). Gypsum may form during the dry season on humid tidal flats, such as in the Bahamas, but it is dissolved during the wet season and is not preserved in the rock record. In arid tidal flats, such as Persian Gulf sabkha, gypsum precipitates in a transitional zone between intertidal and supratidal conditions, while anhydrite precipitates in the supratidal zone (Shinn 1983).

Tollefson (1979) considers the Eel Bed to be the result of a normal marine, subtidal depositional environment, while Nellist (1986) argues in favor of an intertidal depositional environment. Most of our evidence, however, clearly suggests that during the deposition of the Eel Bed an arid supratidal sabkha was present at this part of Wabash Platform. We correlate the Eel Bed of the Kokomo Limestone with the Salina Formation Unit A-1, lithofacies 4, 5, and 6 (Gill 1977), representing supratidal sabkha depositional environment.

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