DEPOSITION OF THE CAMBRIAN EAU CLAIRE FORMATION, WISCONSIN: HYDROSTRATIGRAPHIC IMPLICATIONS OF FINE-GRAINED CRATONIC SANDSTONES

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ABSTRACT

Understanding the link between the sedimentology and the hydrogeology of the Eau Claire Formation within Dane and adjacent counties in western to south-central Wisconsin is critical to fluid flow studies. The Eau Claire is a relatively fine-grained fossiliferous sandstone unit that lies between coarser-grained, highly porous, unfossiliferous sandstone of the underlying Mount Simon and the overlying Wonewoc Formations. It consists primarily of very fine- to medium-grained, variably feldspathic, glauconitic, and dolomitic sandstone locally interbedded with argillaceous siltstone and silty mudstone that has a coarsening and thickening upward succession. On the basis of sedimentary structures, lithology, and bedding characteristics, the Eau Claire is divided into five lithofacies representing different paleowater depths of an epeiric shelf environment. The Eau Claire shallowing-upward succession is subdivided into up to five depositional cycles laid down by repetitive shoreface progradation ranging from offshore–shoreface–foreshore facies bounded at the base by a marine flooding surface. In places, sharp-based shoreface facies rest directly over offshore facies attesting to lowering of sea level. The depositional cycles and the structural contour and isopach maps suggest that the Eau Claire lithofacies deposition and distribution were controlled by the substrate, including the Wisconsin Arch and syndepositional faults, and sea level. The Eau Claire depositional facies model parallels a hydrostratigraphic model in which confining properties of the Eau Claire Formation decrease from offshore to foreshore facies. The aquitard qualities increase from the Wisconsin Arch to the western outcrop belt because the formation is more heterogeneous to the west.

INTRODUCTION

Regional aquitards, extensive layers of relatively impermeable rock units, can restrict the movement of contaminants and thus protect aquifers used for municipal water supplies. The Eau Claire Formation, which consists of fine-grained sandstones, siltstones, and mudstones, is a regional aquitard that impedes the exchange of groundwater between the Mount Simon aquifer and other main overlying aquifers in Wisconsin (Bradbury and others, 1999).

Hydrogeologic studies have been hampered by a lack of understanding of the variable thickness and lithology of the Eau Claire Formation (Krohelski and others, 2000; Gotkowitz and others, 2005). Hydraulic conductivity, a parameter describing fluid flow through rock, is a function of permeability, porosity, grain size, sorting, cementation, composition, sedimentary structures, and stratification (Freeze and Cherry, 1979). Factors such as geologic origin, depositional and post-depositional processes, and lithology can result in significant heterogeneity and preferential flow pathways within aquitards. Consequently, knowledge of the depositional environment and lithofacies distribution of the Eau Claire Formation should enhance understanding of its role as an aquitard regionally and locally.

Our study focused on the link between the sedimentology and hydrogeology of the Eau Claire Formation in southern and western Wisconsin (fig. 1).

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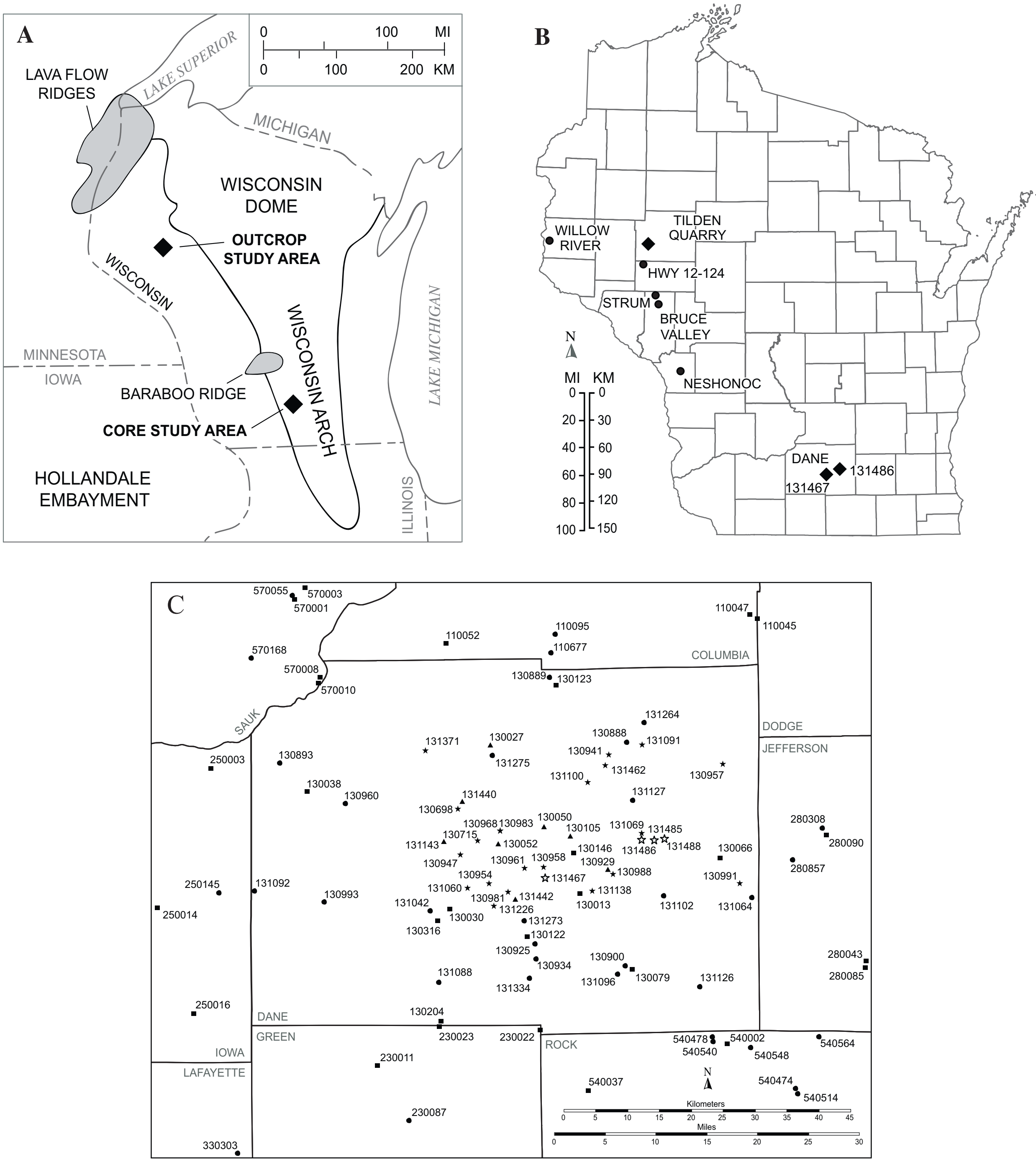

Figure 1. A. *Regional map showing early Paleozoic tectonic features and major paleotopographic highs of Precambrian rocks in the central midcontinent region. Modified from Runkel (1994).* **B.** *Core and outcrop location map. Diamonds represent the locations of the outcrop and well sections shown in figure 2.* **C.** *Locations of water wells and coreholes used in this study. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars. Well data provided by the Wisconsin Geological and Natural History Survey.*

This work may assist in predicting locations of the Eau Claire lithofacies in areas for which rock data are limited and may help explain the regional distribution of porosity and permeability, the major controls on fluid flow.

METHODOLOGY

We compiled outcrop and subsurface data within the Upper Mississippi Valley for our study. The subsurface data come primarily from Dane County in south-central Wisconsin; the outcrop information, from western Wisconsin (fig. 1). We used lithostratigraphic and sedimentologic data from outcrops, cores, cuttings, and borehole geophysical logs. Stratigraphic sections were measured and logged using a handheld natural spectral gamma-ray detector (Exploranium spectrometer, GR-320 enviSPEC). Weathered parts of outcrop faces were scraped before being measured. Four cores with gamma-ray borehole logs (Mount Sopris Instruments gamma-ray probe, 2PGA-1000) were also described. With gamma ray tools, total gamma and the amount of potassium, uranium, and thorium were measured in counts per second (cps). We studied 36 thin sections from cores and outcrops that are representative of the upper parts of the Mount Simon and Eau Claire Formations and the lower part of the Wonewoc Formation to determine mineral composition and grain size at 400 equally spaced points on each slide. In addition to the sedimentologic study, porosity and permeability of 15 samples from Tilden Quarry, West Tilden roadcut, and Willow River outcrop were measured at 400 pounds per square inch confining stress by conventional core-analysis techniques (using a Core Laboratories CMS-300 instrument) to investigate hydrostratigraphic trends.

We used subsurface data to generate structural contour and isopach maps. We reexamined 96 lithologic logs derived from cuttings that had been previously studied by Wisconsin Geological and Natural History Survey staff. We developed a continuum of reliability of well information. The most reliable information came from those wells that had cuttings with detailed descriptions supported by gamma-ray borehole logs; less reliable were wells that had detailed descriptions, but no gamma-ray measurements; next in reliability were wells that had gamma-ray logs, but poor descriptions; the least reliable were wells that had poor descriptions and no gamma-ray measurements.

EAU CLAIRE FORMATION

The Eau Claire Formation overlies the Mount Simon Formation and underlies the Wonewoc Formation. The Eau Claire Formation was deposited in a cratonic environment that included intracratonic basins and scattered arches and domes (Ostrom, 1978). During the Cambrian, the seafloor in what is now northern Wisconsin was near the Wisconsin Dome. Our core data came from Dane County, which is on the southwestern side of the Wisconsin Arch, a southeast–trending extension of the Wisconsin Dome; our outcrop data came from west of the dome (fig. 1).

The Eau Claire Formation is part of the Marjuman (*Cedaria* and *Crepicephalus* trilobite zone) to Steptoean (*Aphelaspis* trilobite zone) Stage of the Upper Cambrian Croixian Series and is predominantly very fine- to medium-grained, moderately to well sorted, variably feldspathic, glauconitic, and dolomitic sandstone with variable amounts of siltstone and mudstone. It has a distinctive gamma-ray signature that has a sharp base and up to five peaks of high gamma-ray values that decrease in magnitude up-section (fig. 2). Correlation of the gamma ray values and the lithology of the Eau Claire showed that the peaks represent greater potassium feldspar content in the very fine sand and silt than in the coarser-grained sand.

On the basis of petrographic analysis, we found two major differences between Eau Claire core and outcrop samples (fig. 3): 1) sand grains of core samples are much coarser than those of outcrop samples, and 2) potassium feldspar is a major component in outcrop samples, but almost absent in cores. These differences support the feldspar and grain-size relationship proposed by Odom (1975), who suggested that, in the Upper Cambrian rocks, feldspar is concentrated in sediments finer than 0.125 mm. We determined that the differences between cores and outcrops were influenced by the proximity to the shoreline, resulting in differences in the energy and the depth of deposition. In Dane County (core area), the Eau Claire was deposited closer to the shoreline within shallower water and higher energy conditions, so it is less feldspathic and has coarser sediments.

EAU CLAIRE LITHOFACIES

The Eau Claire Formation was first divided into lithofacies on the basis of bedding type and mudstone content by Morrison (1968) and Huber (1975) in geographically restricted investigations in west-central

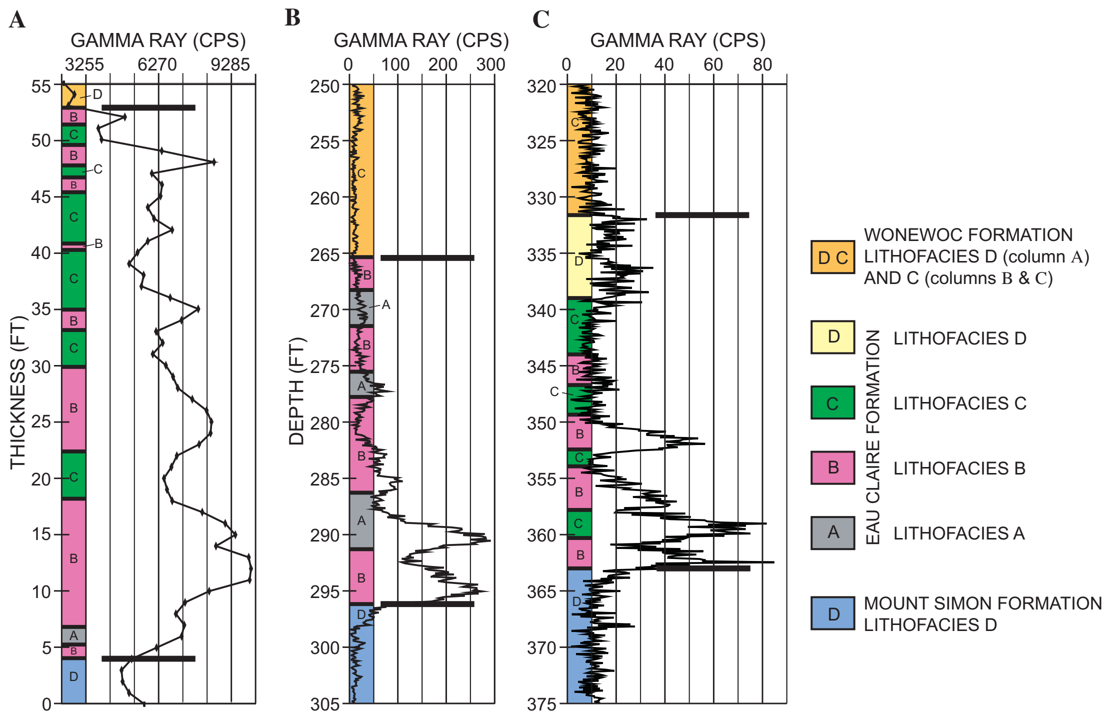

Figure 2. *Gamma-ray characteristic of the Eau Claire Formation, from outcrop:* **A.** *Tilden composite section; and from core:* **B.** *Well 131467 (Nine Springs) and* **C.** *Well 131486 (Cottage Grove MP6). See figure 1 for locations of outcrop and wells.*

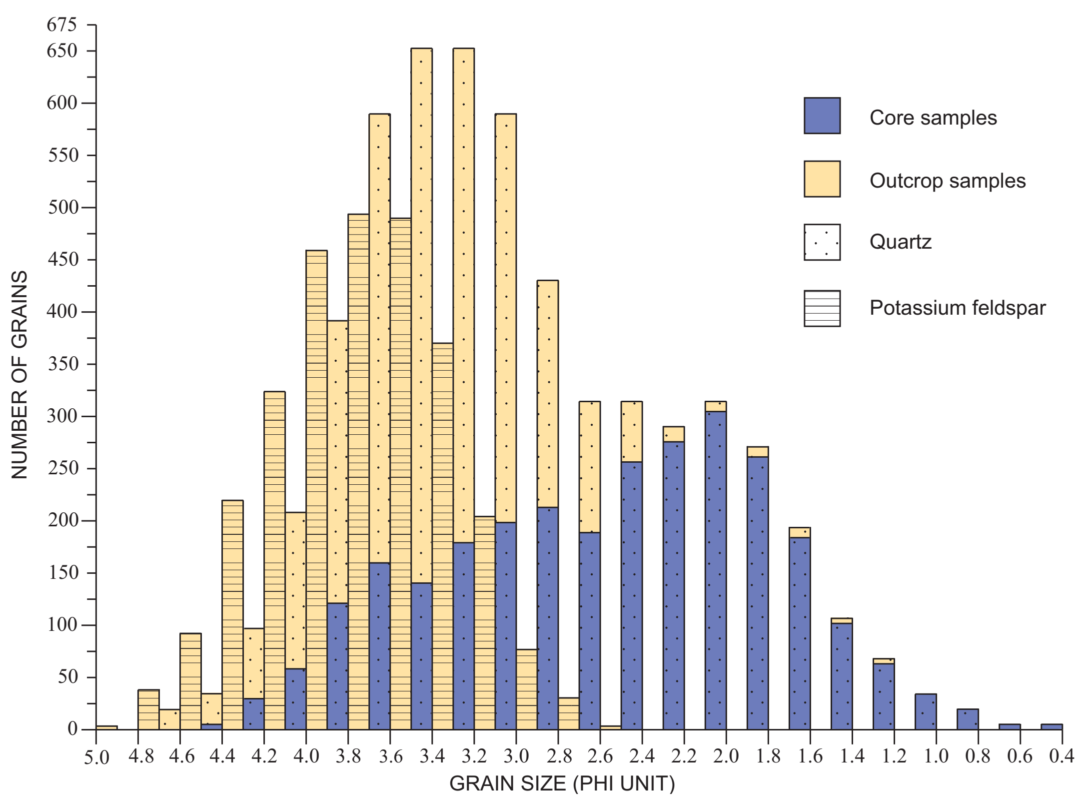

Table 1. *Eau Claire lithofacies A–E. HCS = hummocky cross-stratification; SCS = swaley cross-stratification; TCS = trough cross-stratification; FWWB = fair-weather wave base. Ichnofacies and ichnofabric index are described in Pemberton and others (1992) and Droser and Bottjer (1986), respectively.*

Lithofacies	Bedding characteristics	Sedimentary structure	Ichnofacies	Body fossil	Ichnofabric index	Contact relation with underlying lithofacies	Depositional environment
A: Mudstone and siltstone with minor sandstone	At least 1-ft interval of very thin- to thin-bedded mudstone and siltstone; very thin-bedded sandstone also present	Soft sediment deformation with loaded sandstone	*Cruziana*	Brachiopod fragments	3–4	Gradational, with lithofacies B, sharp with others	Offshore below storm wave base
B: Thin-bedded, micro-HCS sandstone with siltstone and mudstone	Sandstone beds are generally less than 2 in. thick; very thin-bedded siltstone and mudstone less than 0.1 in. thick	Microhummocky cross-stratification and ripple bed form	*Cruziana*	Brachiopod fragments	3	Gradational, with change in bedding characteristics	Offshore transition zone between storm and FWWB
C: Thick- to very thick-bedded HCS to SCS and low-angle to planar-laminated sandstone with minor siltstone and mudstone (divided into 4 sub-lithofacies: Ca, Cb, Cc, Cd)	Sandstone beds are generally thicker than 2 ft; siltstone and mudstone laminae less than 0.04 in. thick	Ripple bed forms, plus Ca: hummocky cross-stratification; Cb: hummocky cross-stratification, gutter casts and planar lamination; Cc: swaley cross-stratification; Cd: planar to low-angle lamination	*Skolithos*	Brachiopod fragments throughout; hyolithid and trilobite casts in Cb	2	Gradational and sharp-based; sharp jump in bedding style	Lower shoreface Ca: just below FWWB Cb: at FWWB Cc: just above FWWB Cd: above FWWB
D: Thick- to very thick-bedded TCS sandstone	Sandstones appear to be massive without internal breaks	Trough cross-bedding	*Skolithos*	Brachiopod fragments	1–2	Gradational	Upper shoreface below low tide
E: Very thick-bedded, planar-laminated sandstone	Massive sandstone without parting surfaces	Planar lamination	*Skolithos*	Brachiopod fragments	1	Gradational	Foreshore within intertidal zone

Wisconsin. The most recent regional study related to the Eau Claire Formation was completed by Runkel and others (1998). They divided the Eau Claire into three units on the basis of the Upper Cambrian trilobite zones, showing that the formation is a distal facies of the overlying Wonewoc Formation (*Crepicephalus* and *Aphelaspis* trilobite zones) and the underlying Mount Simon Formation (*Cedaria* trilobite zone).

◀ **Figure 3.** *Frequency diagram, showing grain-size distribution of quartz and potassium feldspar in core and outcrop samples.*

We have divided the Eau Claire Formation into five lithofacies on the basis of sedimentary structures, lithology, and bedding characteristics (table 1). Interbedding of the thin- and thick-bedded lithofacies within the formation delineates sandier-upward succes-

Figure 4. *Interbedding of thin- and thick-bedded lithofacies of the Eau Claire Formation at Tilden Quarry.*

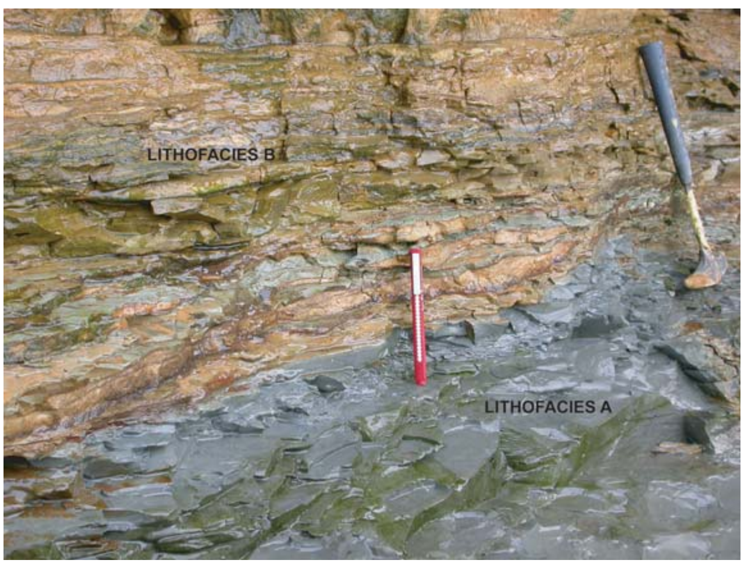

Figure 5. *Very thin- to thin-bedded silty mudstone and argillaceous siltstone of lithofacies A overlain by lithofacies B at Neshonoc Lake.*

sions (fig. 4). Because sedimentary structures are difficult to define in cores, our Eau Claire lithofacies description is mostly based on outcrop observation.

Lithofacies A is composed of 1.0- to 6.4-ft intervals of very thin to thin-bedded, relatively well cemented, silty mudstone, argillaceous siltstone, and sandy siltstone (fig. 5). Very thin-bedded, very fine-grained (fine grained in core) sandstone is common (fig. 6). The siltstone and mudstone are green to dark gray in outcrop; in core, the color ranges from green to gray, pink to maroon, and buff. The sandstone is very light gray to yellowish brown in outcrop; the sandstone in core is gray, pink, dark green, and buff. This lithofacies is locally glauconitic, dolomitic, and micaceous. Sedimentary structures are not well preserved, possibly because of the intense bioturbation.

Lithofacies B consists of 0.5- to 11.6-ft intervals of thin-bedded, very fine- to fine-grained (to medium-grained in core), variably glauconitic sandstone intercalated with substantial argillaceous siltstone and mudstone (figs. 5 and 7). The sandstone is light gray, light tan, yellowish brown, and dark green; the siltstone and mudstone are green to dark gray. In core, this lithofacies is also pink to maroon and buff. Outcrop samples are feldspathic and micaceous; cores are dolomitic. Sandstone beds pinch and swell laterally and are locally lenticular (fig. 8). They commonly display sharp, scoured bases. Mudstone and argillaceous siltstone are found in discontinuous drapes and very thin, laterally continuous beds.

The microhumocky cross-stratification is characterized by glauconite concentration and very thin-bedded siltstone and mudstone. It contains thin hummocks and swales that have wavelengths of 1.5 to 2.5 ft. Sets of laminae intersect at low angles. Low-angle to wavy lamination could be associated with the microhummocky cross-stratification. The upper surface of the sandstone beds commonly has oscillation ripples. Bioturbation obscures the original bedding in places.

Lithofacies C consists of less than 1.0-ft to 15.0-ft intervals of thick to very thick-bedded, very fine- to fine-grained (medium-grained at the top of the formation in outcrop and throughout the formation in cores), variably glauconitic sandstone intercalated with green siltstone and mudstone laminae or drapes (fig. 9). The laminae are rare compared to

A

B

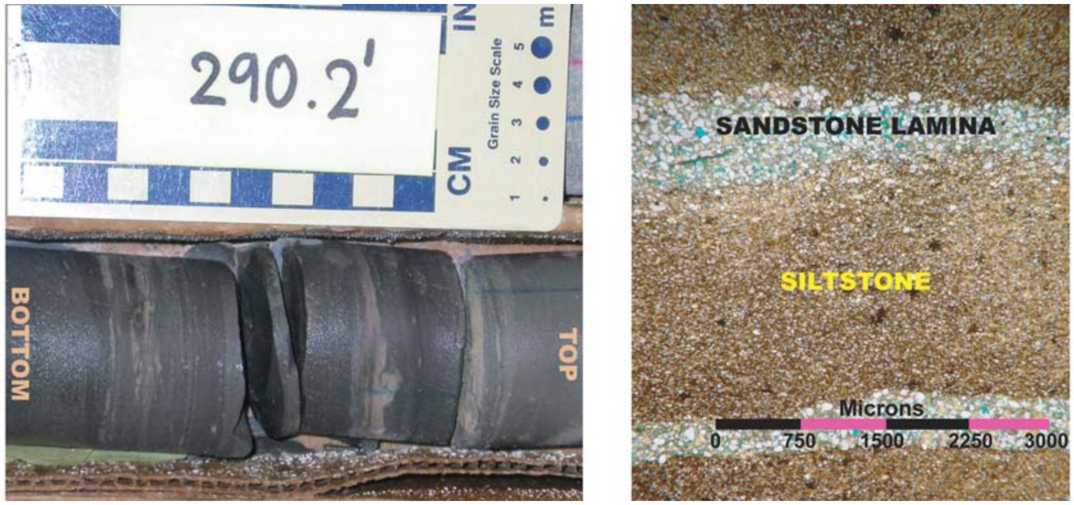

Figure 6. A. *Lithofacies A of Nine Springs core, showing presence of very thin-bedded, very fine-grained sandstone within more prominent siltstone and mudstone.* **B.** *Photomicrograph taken from sample 131467-289.8 with plane-polarized light.*

A

B

C

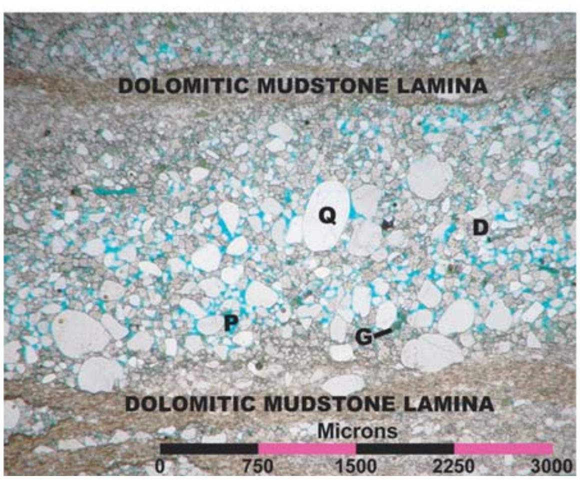

Figure 7. *Thin-bedded sandstone of lithofacies B intercalated with argillaceous siltstone and mudstone.* **A.** *Outcrop at Willow River.* **B.** *Core from well 131486 (Cottage Grove MP6).* **C.** *Photomicrograph taken from sample 131486-346.3 with plane-polarized light. Q = quartz; G = glauconite; D = dolomite; and P = pore space.*

Figure 8. *Bedding style of lithofacies B at Tilden Quarry. Sandstone beds pinch and swell laterally and locally lenticular.*

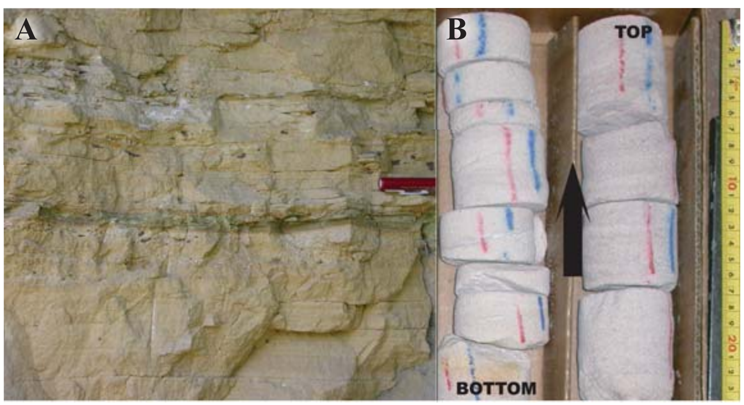

Figure 9. *Thick- to very thick-bedded sandstone of lithofacies C intercalated with siltstone and mudstone laminae.* **A.** *Outcrop at Tilden Quarry.* **B.** *Core from well 131486. The outcrop also shows amalgamated thin bedded, planar-laminated sandstone.*

those in lithofacies B. Thick sandstone beds locally compose amalgamated thin-bedded, plane parallel-laminated sandstone. Color ranges from very light gray to light tan to pink. This lithofacies is feldspathic and micaceous in outcrop and dolomitic in core.

The variation of sedimentary structures in lithofacies C in outcrop can be used to separate it into four sublithofacies. Sublithofacies Ca consists of hummocky cross-stratification; its low-angle, gently undulating laminae are formed by broad convex-upward hummocks and concave-upward swales with wavelengths of 3.0 to 5.0 ft. Sublithofacies Cb has planar lamination and less-prominent hummocky cross-stratification. Sublithofacies Cc contains swaley cross-stratification with broad, very low-angle concave-upward laminae that have some planar to low-angle internal truncation surfaces. Although the swales rarely pass laterally into hummocks, the presence of some convex-upward laminae in a swaley sandbody indicates a genetic similarity to hummocky cross-stratification. Sublithofacies Cd is dominated by planar to low-angle lamination that has a trace of swaley cross-stratification. All four sublithofacies locally display preserved asymmetric and symmetric ripple forms on top of sandstone beds.

In core, we separated lithofacies C into two sublithofacies: C1 and C2. Sublithofacies C1 is similar to sublithofacies Ca, Cb, and Cc; sublithofacies C2 is comparable to sublithofacies Cd. Sublithofacies C1 can be recognized by high- to low-angle cross-lamination and wavy lamination, which are likely to be associated with hummocky to swaley cross-stratification. Sublithofacies C2 can be defined by low-angle to planar lamination and lack of clear sedimentary structures as is sublithofacies Cd.

Lithofacies D is entirely sandstone, typified by 1.6- to 8.0-ft intervals of thick- to very thick-bedded successions of very fine- to fine-grained (up to lower medium in cores), trough cross-stratified, variably glauconitic sandstone (fig. 10). Color ranges from light tan to rusty tan, plus white to light pink in cores. Rip-up clasts of sandstone and dolomite are present. Well organized cross-sets are typically 0.3 to 1.0 ft thick. They are commonly superimposed on one another to form thick, amalgamated successions.

Lithofacies E is entirely sandstone, characterized by a 5.0-ft interval of very thick-bedded, very fine- to fine-grained, light tan to rusty tan, planar-laminated sandstone (fig. 11). Laminations dip very gently from each other.

LITHOFACIES INTERPRETATION AND DEPOSITIONAL ENVIRONMENT

Our study indicated that the lithofacies and accompanying sedimentary structures of the Eau Claire were deposited in an epeiric shelf environment ranging from offshore to foreshore facies (fig. 12). We interpreted lithofacies A to have been deposited in a quiet-water environment below the storm-wave base representing an offshore facies (Howell and Flint, 2003). Lithofacies B represents an offshore transition facies deposited by storm-generated oscillatory waves below the fair-weather-wave base, but above the storm-wave base (Dott and Bourgeois, 1982; Leckie and Walker, 1982; Duke, 1985). During storms, sands were eroded from the shoreward zone and redeposited in a microhummocky, cross-stratified sheet-like blanket across the shelf. During fair-weather periods, clays and silts were deposited from suspension and covered the sheet of sand laid down during the storms. We interpreted lithofacies C to represent lower shoreface facies deposited by storms in water depths close to the fair-weather-wave base, where the seabed was constantly agitated and clays and silts were rarely deposited (Howell and Flint, 2003). The sublithofacies Ca–Cd indicate slightly different settings: from a deeper and lower energy environment of sublithofacies Ca to a shallower and higher energy environment of sublithofacies Cd (Leckie and Walker, 1982; Walker, 1985; Duke, 1990). We interpreted the trough cross-bedded sandstone, lithofacies D, and planar-laminated sandstone, lithofacies E, to be upper shoreface and foreshore facies, respectively. The sedimentary structures and the lack of mica suggested conditions of high flow velocity and shallow water depth (Collinson and Thompson, 1989). Lithofacies D and E are rare in the Eau Claire, but common in the Wonewoc and Mount Simon Formations. This is consistent with flooding of the shoreline (Mount Simon–Eau Claire contact), followed by shallowing upward and progradation of the Wonewoc over the deeper-water Eau Claire.

Figure 10. *Thick- to very thick-bedded, trough cross-stratified sandstone of lithofacies D at Willow River. The broomstick is marked every 6 in.*

Figure 11. *Very thick-bedded, planar-laminated sandstone of lithofacies E at Willow River. The broomstick is marked every 6 in.*

Lithofacies D and E were deposited within an energetic nearshore environment, close to the arch, in a

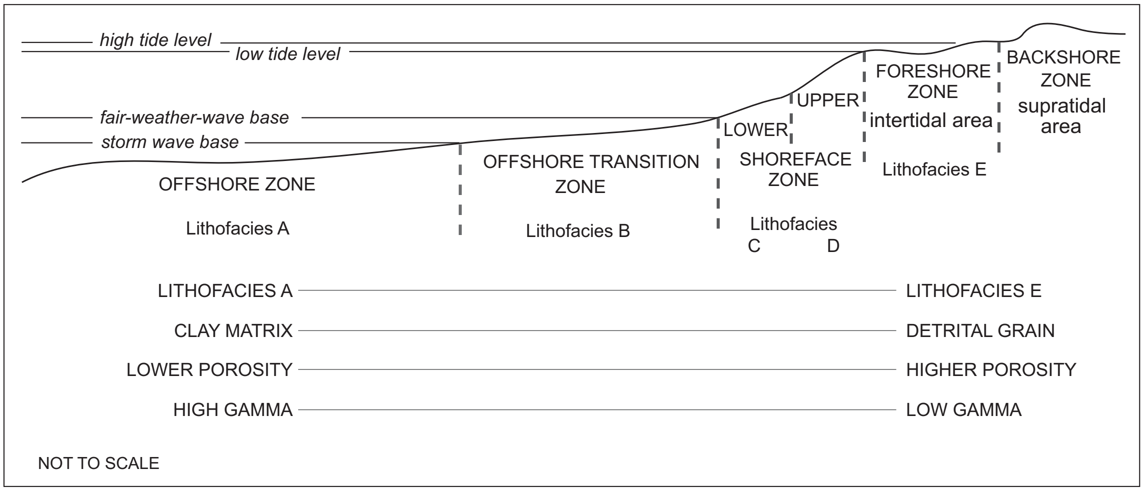

Figure 12. *Shallow marine profile, showing the typical succession of the Eau Claire Formation. (Modified from Coe and Church, 2003.)*

storm-dominated shoreface and in an intertidal zone, respectively. The lower shoreface sediment (lithofacies C) was transported by storm-enhanced currents—along the shore by longshore currents and away from the shore by rip currents (Runkel, 1994; Byers and Dott, 1995; Runkel and others, 1998) following topographic differences on the seafloor. Immediately seaward, lithofacies B sediment was buried during storms and graded basinward to the mudstone of lithofacies A.

The lithofacies of the Eau Claire Formation are also distinctly expressed in the relationship between the Eau Claire sediments and the total gamma of these sediments as measured in outcrop and in the subsurface. The total gamma-ray measurements of the Wonewoc and Mount Simon Formations (table 2) are for the base and the top, respectively. Figure 2 and table 2 show that the gamma decreases from lithofacies A to lithofacies D. On the basis of the subsurface data, the Eau Claire lithofacies of some intervals can be identified with the total gamma. The highest total gamma mostly corresponds to the lithofacies A (>100 cps) or B (<100 cps) of the second depositional cycle from the base of the formation. If the highest gamma represents lithofacies A, the peak of the bottom depositional cycle can be interpreted as representing shallower-water facies because the highest gamma-ray values of each depositional cycle decrease in magnitude up-section. If the highest total gamma of the bottom cycle is more than 200 cps, this interval consists of lithofacies B. If it is less than 200 cps, then lithofacies C composes this interval. Notably, lithofacies D and E never corresponded to the peaks of any cycles, except the uppermost cycle of the Cottage Grove MP6 core (well 131486).

STRATIGRAPHIC SUCCESSIONS AND CYCLICITY OF THE EAU CLAIRE

Correlation of a composite section based on outcrops in Chippewa County and the descriptions of two cores in Dane County demonstrates cyclicity and lithofacies repetitions within the Eau Claire stratigraphic successions (fig. 13). Note that the two cores show more proximal facies than the Tilden section, which represents more distal deposits.

The overall vertical stacking of the Eau Claire lithofacies represents shallowing-upward successions and internally can be subdivided into depositional cycles characterized by repetitions of lithofacies. The cycles are defined by deeper-water facies overlying shallower-water lithofacies. In outcrop it is possible to recognize up to eight lithofacies repetitions; the cores show no more than six lithofacies repetitions. With respect to subsurface correlations based on total gamma ray measurement, each Eau Claire depositional cycle is bounded at its base by a relatively high gamma count; we interpreted this to be a marine flooding surface, which is marked by an abrupt change from shallow- to deeper-water facies. We interpreted the intervals that have lower gamma counts to be grading into a shallowing-upward succession. The outcrop shows at least five cycles, but the cores show only four cycles. It is important to note that the cores and outcrop

Table 2. *Total gamma-ray measurements showing geophysical trends within the Eau Claire Formation. The difference between core and outcrop measurements is due to the different tools used in the study. W = Wonewoc Formation; MS = Mount Simon Formation.*

Lithofacies/ formation	Outcrop		Core	
	Total gamma (cps)	Average total gamma (cps)	Total gamma (cps)	Average total gamma (cps)
W	1,431–2,587	2,182	1.7–14.0	8.4
E	2,121–2,991	2,724	—	—
D	3,187–3,617	3,407	4.2–14.1	8.7
C	3,259–6,833	4,972	1.7–196.3	26.5
B	3,909–10,101	6,565	1.6–273.2	57.3
A	4,125–9,738	7,259	12.1–289.4	105.7
MS	2,973–5,784	4,638	7.2–37.4	20.4

are separated by approximately 150 miles and that part of this variability can be explained by changes in lithology and stacking along depositional strike. On the other hand, the cores are separated by only 12 miles; the variability between them may be a result of deposition at different locations in relation to the Wisconsin Arch.

Generally, the contacts between lithofacies are gradational, with two exceptions. The basal contact of each cycle reflects an abrupt change from shallow- to deeper-water facies that we interpreted as marine flooding. Cementation and faunal lags are common at these surfaces. In some places, sharp-based shoreface sandstone (lithofacies C and D) rests directly over lithofacies B (Willow River section), interpreted by Walker and Plint (1992) to be the result of progradation due to a relative sea level fall. In other places, the microhummocky cross-stratified sandstone of lithofacies B is overlain by hummocky cross-stratified sandstone of sublithofacies Cb; the contact is marked by gutter casts (Bruce Valley Quarry), which Aswasereelert (2005) interpreted as being formed by wave scour on the bed. Lithofacies Cc and Cd are present only in the sharp-based successions; we interpreted local wave-base erosion during regression to have led to sharp and, in some locations, erosive contacts between the offshore transition microhummocky strata and the shoreface sandstones.

Morrison (1968), Ostrom (1970), DiStefano (1973), and Huber (1975) suggested that erosive contacts and sudden changes in lithology between the Eau Claire and the Wonewoc Formations may be associated with a significant unconformity. However, Havholm (1998) and Runkel and others (1998) described the Eau Claire–Wonewoc contact as gradational and becoming younger to the west, which would likely be the result of the nearshore marine Wonewoc prograding across the Eau Claire sediment. Our outcrop investigation showed that local wave-base erosion resulted in sharp contacts between offshore transition strata and shoreface sandstones and in turn could be responsible for the thickness variability of the Eau Claire Formation. Therefore, we concluded that the unconformity-like feature between the Eau Claire and the Wonewoc Formations was due to local wave-base erosion and facies changes, not to any significant period of nondeposition or extensive erosion of previously deposited sediment.

REGIONAL CONTROLS ON EAU CLAIRE DISTRIBUTION

The amount of data from outcrops and cores (high-quality data) was insufficient to allow us to adequately define the regional distribution of the Eau Claire Formation; therefore, we used subsurface logs derived from cuttings (generally lower quality or more interpretive data) from the Wisconsin Geological and Natural History Survey to interpolate between high-quality data points.

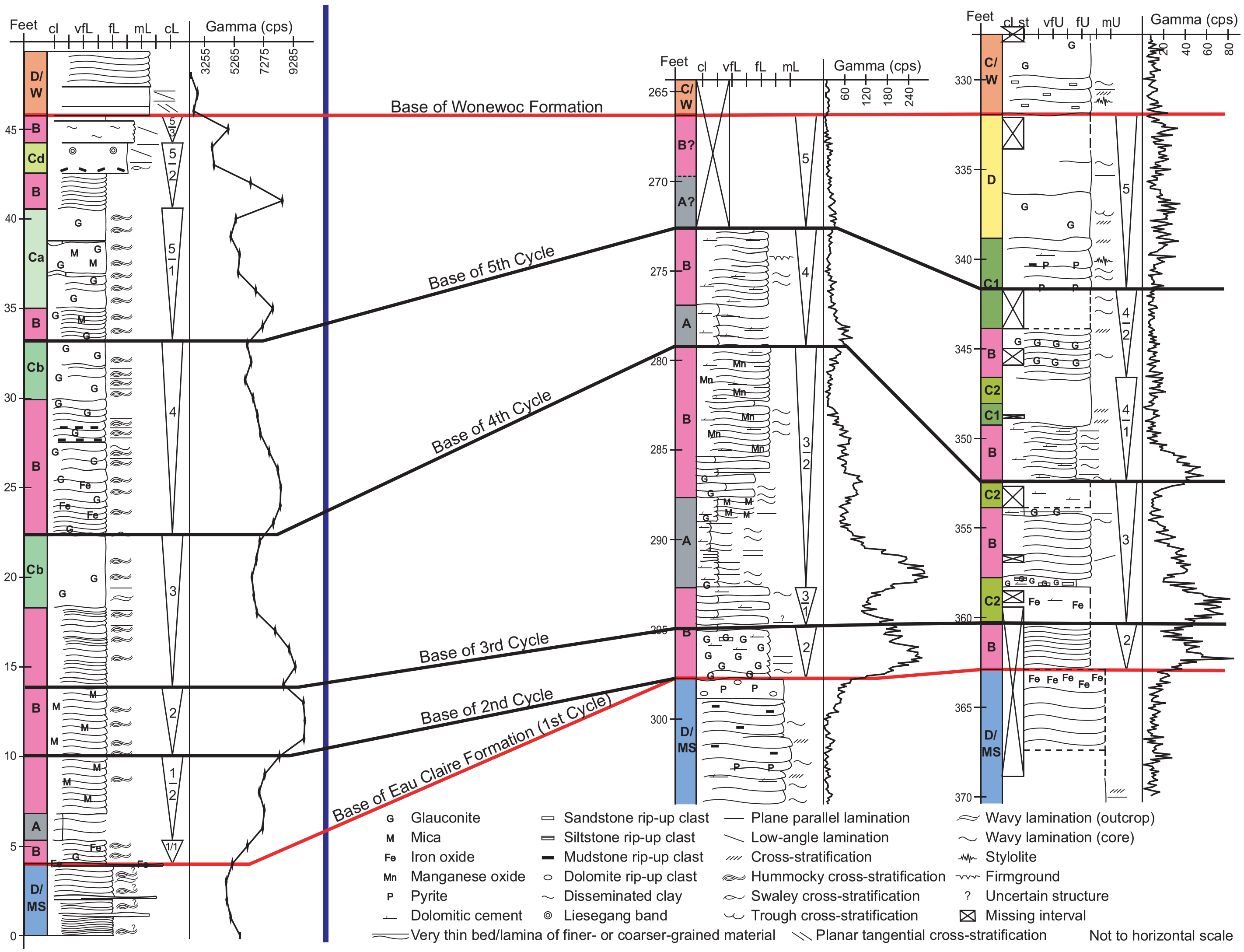

Figure 13. *Outcrop–core correlation and comparison. Notice that the Eau Claire Formation in Tilden outcrop composite section (left) is thicker and represents more shallowing-upward successions than in well 131467 (middle) and well 131486 (right); see figure 1 for locations of outcrop and wells.*

We used the relative amounts of sandstone and mudstone to define the Eau Claire lithofacies in the cuttings. Cuttings composed of shale and siltstone were interpreted to represent lithofacies A. When sandstone dominated, depending on the amount of shale and siltstone present, that interval could be lithofacies B (large amounts of clay- to silt-sized sediments), C (trace amount of clay- to silt-sized sediments), or D and E (no sediments finer than sand were present).

The structural contour map of the Precambrian basement in Dane County shows a north–south trending high and three east–west trending faults (fig. 14A). The high and the faults are also reflected in the structural contour maps of the base of the Eau Claire Formation and the Tunnel City Group (fig. 14B and 14C). The isopach maps of the Eau Claire and the combined Eau Claire–Wonewoc (fig. 14D and 14E) reflect the fact that the Eau Claire Formation progressively thins from 110 ft in southwestern Dane County to 40 ft in central Dane County; it is absent in northeastern Dane County. This is consistent with the interpretations of Twenhofel and others (1935), Odom (1975), and Runkel and others (1998), who suggested that the Eau Claire is thinned by virtue of its upper and lower parts grading laterally into the progressively thicker Mount Simon and Wonewoc Formations toward the Wisconsin Arch.

The Eau Claire and the combined Eau Claire–Wonewoc isopach maps (fig. 14D and 14E) demonstrate that faulting is a major control on the thickness variation and the stratigraphic boundaries of the Eau Claire Formation (fig. 14D and 14E). The faults were identified in areas where the contour lines were close to each other or where the elevations of the Eau Claire structural contour map and the thickness of the Eau Claire isopach map changed so abruptly that it could be evidence of displacement. The thickness contours of the Eau Claire Formation are substantially influenced by the faults; the faults have relatively less effect on the combined Eau Claire–Wonewoc thickness. Cross sections on the regional surface at the base of the Tunnel City Group show that the Wonewoc Formation (fig. 15) thins across faults corresponding to abrupt changes in the Eau Claire–Wonewoc boundary elevations, and the elevations change abruptly at the base of the Eau Claire across the faults. Consequently, we interpreted the faults to be active during the deposition of the Eau Claire and the Wonewoc.

The structural contour and isopach maps show a north–south trending structural high (fig. 14). This high is evidence that the Eau Claire deposition was also influenced by the north–south trending positive feature of the Precambrian substrate associated with the Wisconsin Arch, which modified the paleocurrents and sediment distribution. These maps indicate the shape of the north–south trending high was modified by syndepositional faults. In addition to the influence of the bedrock substrate varying over time, the cyclicity within the Eau Claire Formation can be reasonably attributed to relative sea-level fluctuations that forced shorelines to move seaward and landward.

HYDROSTRATIGRAPHIC IMPLICATIONS

The permeability contrast between lithofacies and between depositional cycles, the vertical and lateral trends in porosity and permeability, and the amount, thickness, and continuity of mudstones are particularly important to fluid flow through the Eau Claire Formation. The Eau Claire is a heterogeneous and anisotropic aquitard due to the discontinuity and vertical stacking pattern of the lithofacies within the formation. The aquitard nature of the Eau Claire Formation is defined primarily by two components: low permeability mudstone and siltstone and higher permeability sandstone.

Some of the best evidence for the Eau Claire being an aquitard comes from test well 131467 at the Nine Springs site, where a packer slug test was used to measure horizontal hydraulic conductivity (Kh) and static head of the Eau Claire (Bradbury and others, 2006; fig. 16). A significant drop in hydraulic head—approximately 30 ft across the Eau Claire–Mount Simon contact—shows that the Eau Claire Formation acts as a major aquitard. The Kh values for the Eau Claire fall into the clay–silt category, even though the sandstone dominates lithofacies B; this is consistent with our outcrop investigation, which showed that the mudstone and siltstone strata of this lithofacies are generally more laterally continuous than the sandstone beds (Aswasereelert, 2005). This continuity along with the thickness of the mudstone and siltstone is likely to be significant to fluid flow through the aquitard. The vertical hydraulic conductivity is very difficult to measure directly; we inferred it to be low because the aquitard holds up about 30 ft of hydraulic head.

The mudstone and siltstone of the Eau Claire For-

A

B

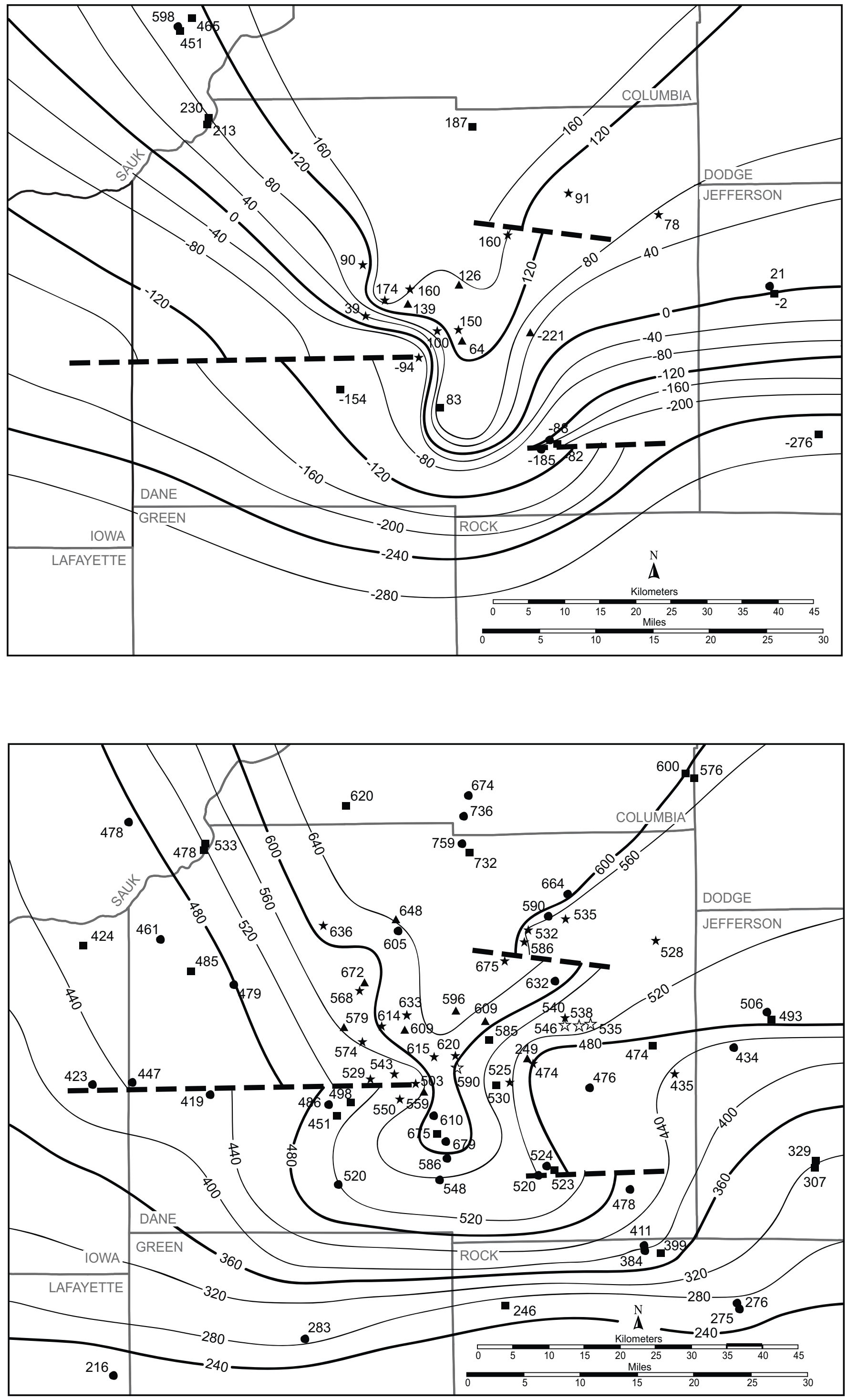

Figure 14. *Structural contour maps:* **A.** *Precambrian basement;* **B.** *Base of the Eau Claire Formation. Faults (dashed line) based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars.*

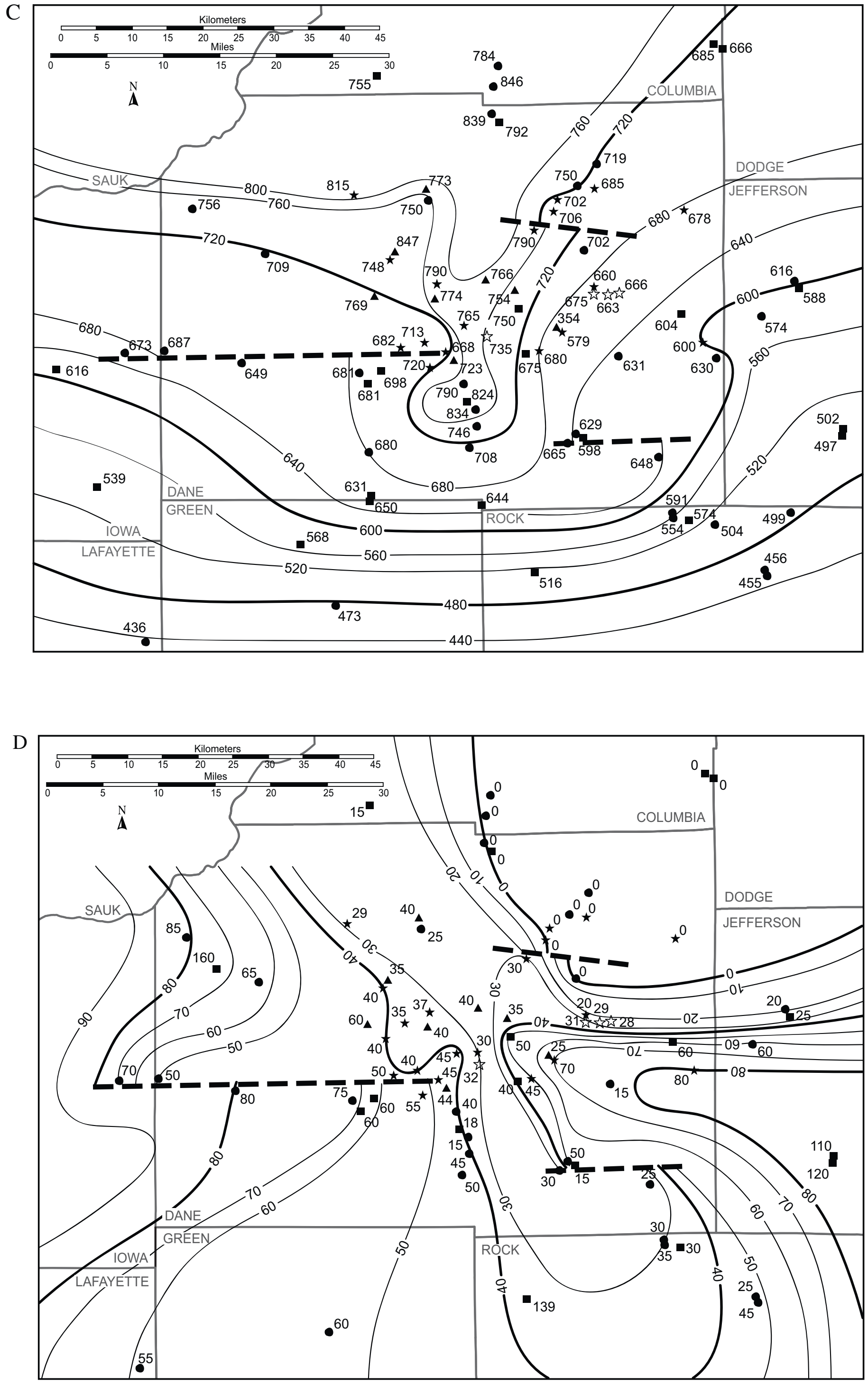

Figure 14 (continued). **C.** *Base of the Tunnel City Group. Isopach maps:* **D.** *Eau Claire Formation. Faults (dashed line) based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars.*

E

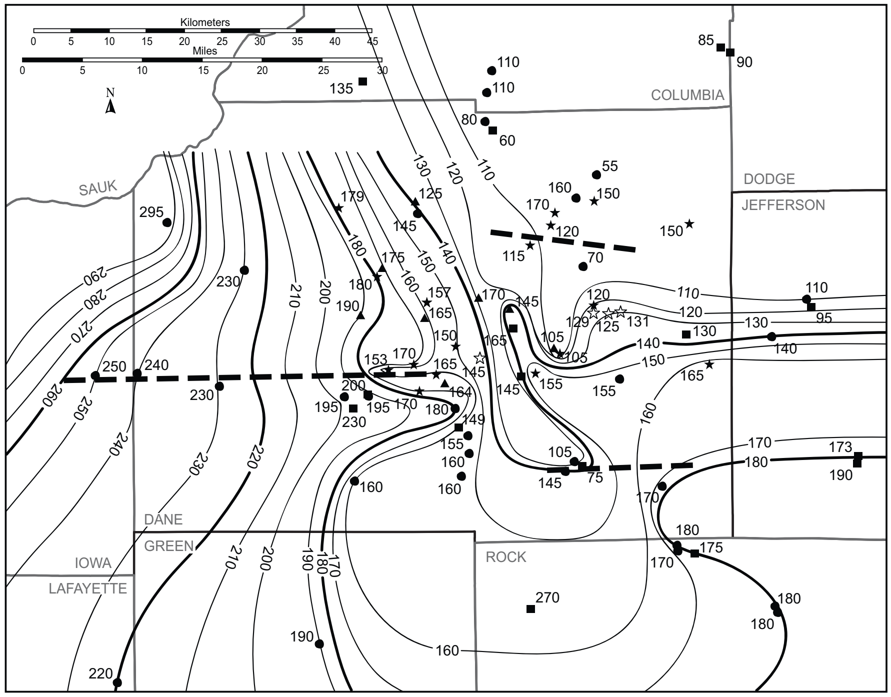

Figure 14 (continued). **E.** *Combined Eau Claire and Wonewoc Formations. Faults (dashed line) present in all maps based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Faults (dashed line) based on Eau Claire structural contour map. Elevation (in feet) based on sea level. Solid stars, circles, triangles, and squares represent more reliable to less reliable control points, respectively. Cores represented by open stars.*

mation, which are interpreted to act as a major barrier to fluid flow, dominate lithofacies A and lithofacies B. On the basis of Kh values (Bradbury and others, 2006) and lithofacies distribution, the amount, thickness, and continuity of mudstone and siltstone are particularly important to fluid flow through the Eau Claire aquitard. The thickness of the least permeable strata, lithofacies A, can vary from approximately 2 ft up to 25 ft. The distribution of lithofacies A shows the most irregularity: It can be present in one well, but absent in another less than 10 miles away. Lithofacies A might have been preserved as either extensive strata or discontinuous patches; lithofacies B, which is present in all the wells (fig. 15), comprises much of the Eau Claire Formation.

The stacking pattern of the Eau Claire succession is also significant to fluid flow. The Eau Claire depositional cycles, bounded above and below by flooding surfaces, represent the building block of the Eau Claire aquitard being separated by a surface of high permeability contrast between the offshore (lithofacies A) or offshore transition (lithofacies B) facies and the various shoreface facies (lithofacies C, D, and E) of the underlying strata. The difference in facies above and below the cycle boundaries can result in flow-unit boundaries that have significant permeability differences. For instance, the permeability and porosity of the Tilden Quarry sandstones studied in outcrop in Chippewa County increase from 328.3 millidarcies (md) and 28.1 percent (lithofacies B) to 811.1 md and 29.4 percent (lithofacies C); the samples are only 3 ft apart (fig. 17).

The most porous and permeable strata are the relatively high depositional energy lower and upper shoreface and foreshore sandstones (lithofacies C, D, and E; fig. 12). The increase in porosity and permeability can be tied to an increase in depositional energy, which resulted in 1) better grain sorting and an associated decrease in the amount of fine-grained sediment within pore spaces; 2) fewer and thinner mudstone layers; and 3) a decrease in cementing materials. As a result, porosity and permeability are lower from upper

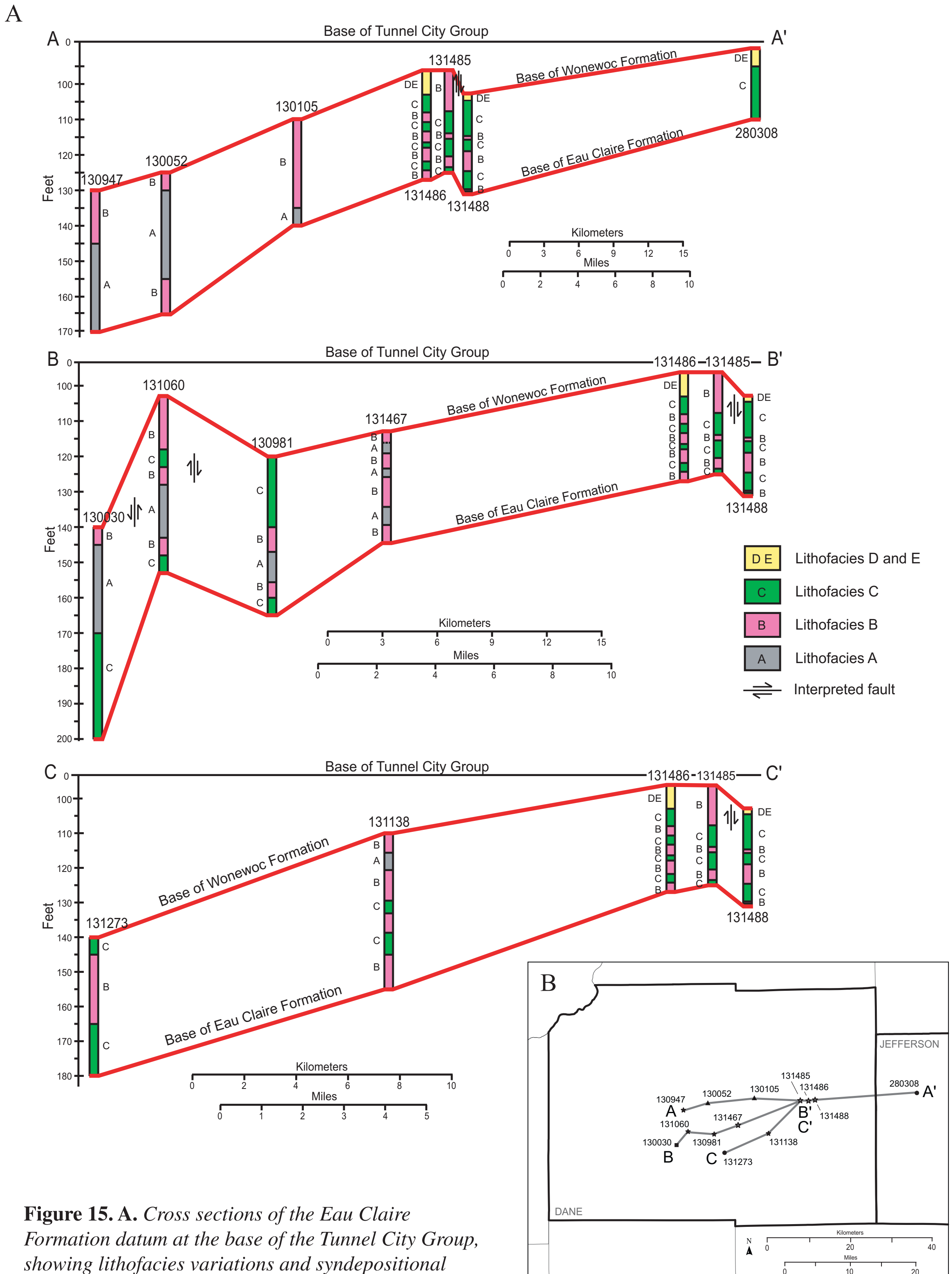

Figure 15. A. *Cross sections of the Eau Claire Formation datum at the base of the Tunnel City Group, showing lithofacies variations and syndepositional faults.* **B.** *Lines of cross sections.*

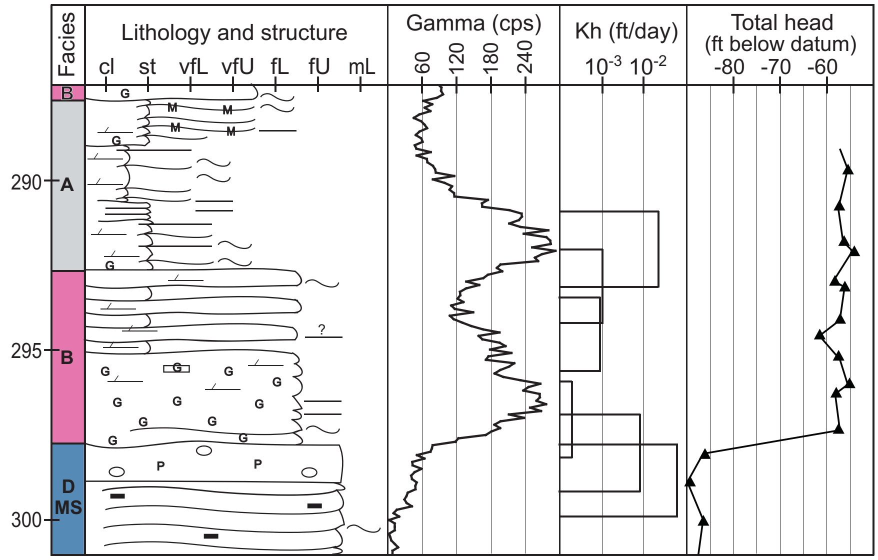

Figure 16. *Stratigraphic section of an Eau Claire interval, showing results from a packer-slug test at the Nine Springs site (well 131467). Bars show horizontal hydraulic conductivity (K_h) derived from slug test using inflatable straddle packers to isolate various sections of the borehole. Width of bars represents width of packed intervals. Hydraulic heads were measured using pressure transducers; K_h and hydraulic head data from Bradbury and others (2006). MS = Mount Simon Formation.*

shoreface sandstones to offshore mudstones. This corresponds to the previously mentioned increase in gamma-ray values from lithofacies D to lithofacies A. We concluded that the greater the permeability, the lower the gamma-ray values and the higher the depositional energy.

The relationships among the various lithofacies imply that the hydraulic properties of the aquitard are directly related to the geometry and distribution of lithofacies, which are a function of the depositional environment. Therefore, it should be possible to relate trends in the distribution of hydraulic properties to the distribution of lithofacies in the aquitard system. Regionally, more depositional cycles and more shallowing-upward successions are present along the western outcrop belt than in the area near the Wisconsin Arch. As a consequence, the Eau Claire Formation becomes more of a barrier to fluid flow from the Wisconsin Arch to the west.

SUMMARY

We have divided the Eau Claire Formation into five lithofacies based on sedimentary structures, lithology and bedding characteristics representing a shallow marine depositional shelf deposit ranging from offshore-shoreface-foreshore facies. In general, the formation thickens to the south and the west. The number of vertical stackings, potassium feldspar grains and sediments finer than fine sand increase from eastern Dane County to the western outcrop belt due to the proximity to the shoreline or the Wisconsin Arch. The structural contour and isopach maps and the cyclicity of the Eau Claire Formation suggest that the Precambrian substrate (Wisconsin Dome and Arch), syndepositional faulting, and sea level fluctuation are major controls on the Eau Claire lithofacies deposition and distribution. The Eau Claire aquitard is likely to retard fluid flow to the west from the arch to the western outcrop belt.

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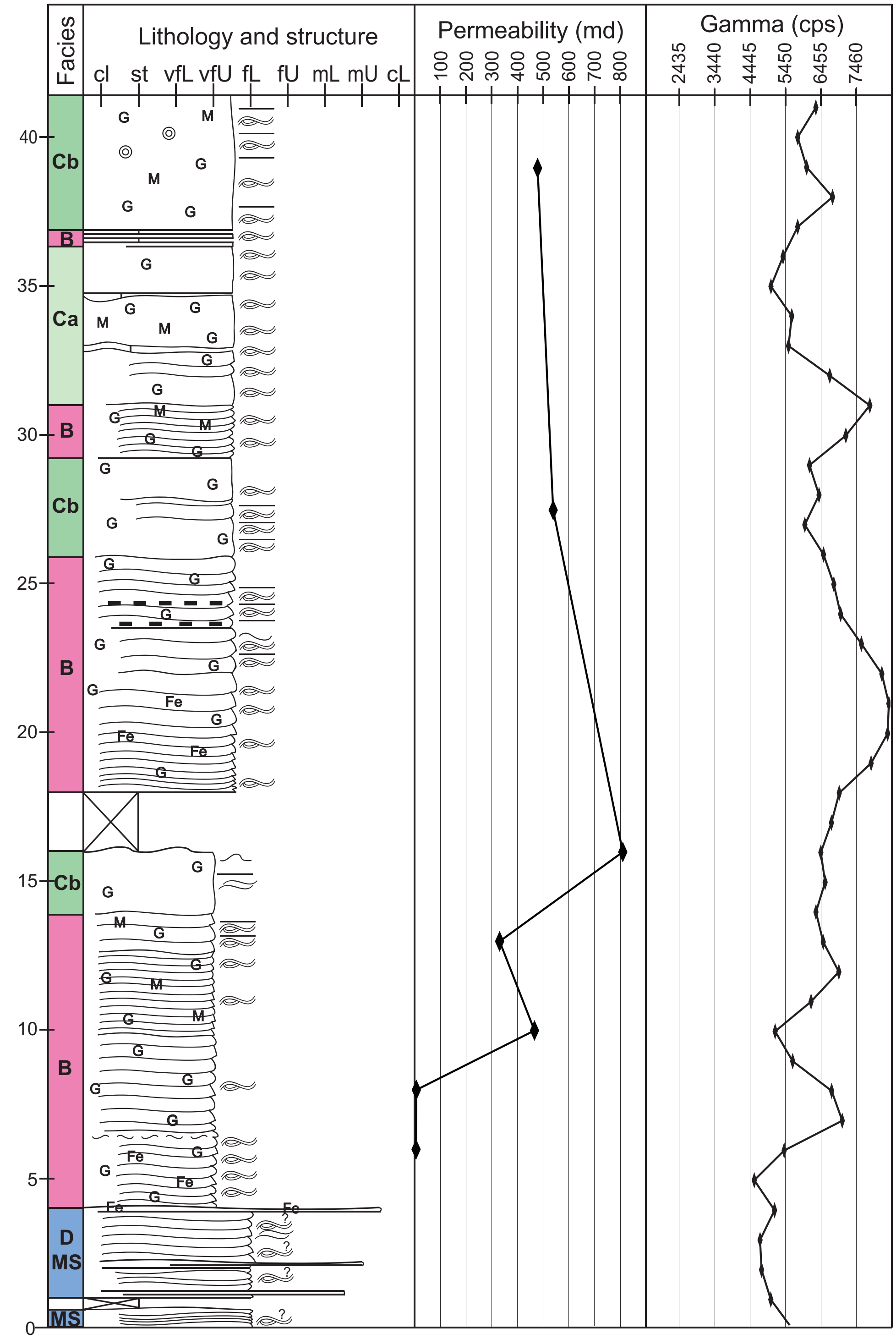

Figure 17. *Stratigraphic section at the Tilden Quarry (location 90516), showing the relationship between the Eau Claire lithofacies, total gamma, and permeability. Permeability was measured by conventional core analysis techniques, using Core Laboratories CMS-300 instrument. MS = Mount Simon Formation.*

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