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STRATIGRAPHIC CONTROLS ON DISTRIBUTION OF HYDRAULIC CONDUCTIVITY IN CARBONATE AQUIFERS

Final Report to the Wisconsin Department of Natural Resources

by

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CONTENTS

Figures

Tables

Plates

INTRODUCTION

Background

Carbonate rocks underlie forty percent of the United States east of the Mississippi River (Quinlan, 1990) and are quite variable in their flow characteristics, ranging from low-permeability confining units to highly-transmissive karstic aquifers (LeGrand, 1977; Brahana and others, 1988). In Wisconsin, the fractured Silurian dolomite and Ordovician Sinnipee Group are important, but vulnerable, aquifers. The dual-porosity nature of these aquifers-- high-permeability fractures transmit the majority of the water while the lower-permeability matrix blocks provide the storage capacity -- make them exceedingly susceptible to contamination, challenging to characterize, and difficult to model.

Accurate knowledge of hydraulic conductivity is necessary for most groundwater investigations including design of monitoring and remediation systems, wellhead protection studies, groundwater recharge studies, and numerical models of flow and transport. The three-dimensional distribution of aquifer heterogeneities, however, is difficult to characterize with sparse borehole data. Researchers are starting to recognize that sedimentological and stratigraphic models provide a method of incorporating geologic variability into models of fluid flow in sedimentary aquifers (e.g., Fraser and Davis 1998). Evaluating hydraulic conductivity in relation to stratigraphic framework has proved quite useful for the Pleistocene units of the state (e.g., Rodenbeck, 1987; Muldoon and others, 1988; Simpkins, 1989).

In carbonate aquifers, the porosity and permeability structure is dependant on both matrix properties and the development of secondary porosity. Matrix properties are controlled by lithostratigraphic variability and diagenetic processes; the distribution of secondary fractures is controlled by stress history and mechanical stratigraphy which reflects lithostratigraphic variations. Because carbonates are relatively soluble, both primary and secondary porosities can be enhanced by dissolution. The complex porosity distribution in carbonates is reflected in the hydraulic conductivity distribution. Fractured-carbonate aquifers typically have a bimodal hydraulic conductivity distribution of both low-conductivity matrix blocks and high-conductivity fracture and dissolution zones. Carbonate lithostratigraphy has been used as a predictor of permeability distributions in petroleum reservoirs (e.g., Fogg and Lucia 1990). This approach, however, is less common in groundwater investigations. In the few studies that have incorporated facies analysis of carbonate aquifers (e.g., Rovey and Cherkauer 1994), the scale of the hydraulic testing has typically precluded the characterization of the properties of discrete high-permeability features. Recent work on the Silurian dolomite in northeastern Wisconsin (Muldoon and Bradbury, 1994; Gianniny and others, 1996; Muldoon, 1999a) has indicated that high-conductivity zones in carbonate aquifers are laterally continuous at regional scales and appear to follow and be controlled by the stratigraphy. This is in contrast to other aquifers in which high-permeability discontinuities are discontinuous and controlled by depositional geometries (e.g., channels, deltaic lobes, outwash fans, or eskers) and facies. It is our hypothesis that high-conductivity zones in carbonates deposited on shallow marine shelves can be predicted by understanding the history of deposition or sequence framework.

We have used detailed stratigraphic analysis coupled with geophysical and hydrogeologic data to characterize the hydraulic conductivity distribution of the Silurian and Sinnipee dolomite aquifers in northeastern Wisconsin. These two units exhibit very different lithologies. The Silurian sequence is a pure dolomite, with very minor amounts of shale, that was deposited in shallow subtidal to tidal settings. The Ordovician Sinnipee Group consists entirely of subtidally deposited carbonate rocks, predominantly of dolomite with shale disseminated throughout the dolomite or as thin layers and partings. Three study areas (Figure 1) were chosen to encompass the range of lithologic variability seen in these units. The vertical variability of hydraulic conductivity was characterized by short-interval (< 1 m) packer tests that provided data on both matrix and fracture hydraulic conductivities. High-flow features in existing domestic and high-capacity wells were identified using fluid temperature/resistivity and flowmeter logs.

Groundwater investigations in fractured sedimentary rocks can be exceedingly expensive and time-consuming. The integrated approach used in this study is a powerful and cost-effective way to characterize the geologic heterogeneities that control flow and transports in fractured

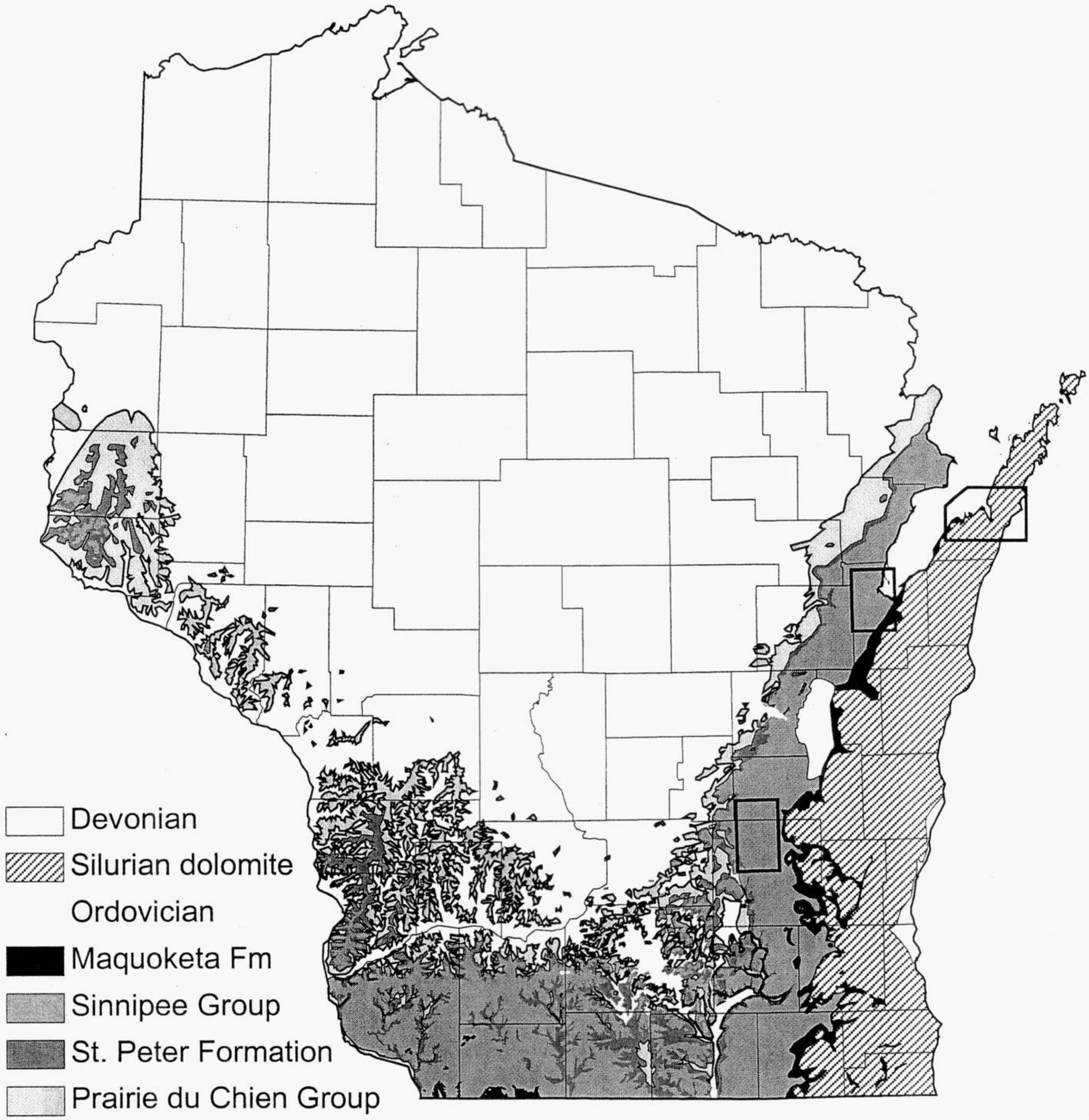


Figure 1. Bedrock geologic map of Wisconsin (modified from Mudrey and others, 1982) showing distribution of units Ordovician in age and younger. The boxes indicate the study areas in the Silurian dolomite and Sinnipee dolomite where stratigraphy and hydraulic conductivity of the dolomite units were characterized.

sedimentary rocks. Combining stratigraphic data with detailed, quantitative hydrogeologic data from a small number of coreholes can be used to define the relationships between lithologic facies and transmissivity. Facies have characteristic geophysical signatures which can be correlated on a regional basis using geophysical logs. Hydraulic conductivity distributions, determined at a limited number of coreholes, can then be predicted on a regional scale based on the defined facies relationships and geophysical correlations. These predictions are strengthened when combined with qualitative hydrogeologic data concerning the location of discrete high-flow features from a larger number of wells. This approach is applicable as a model for studies of other carbonate aquifers.

Purpose and Scope

The objective of this project was to characterize the hydraulic conductivity distribution of carbonate aquifers in the Silurian (Niagaran) and Ordovician (Sinnipee) dolomites in eastern Wisconsin (Figure 1) by integrating sequence stratigraphy with geophysical and hydrogeologic data. The integration of methodologies and approaches from reservoir geology and hydrogeology has led to a better understanding of the controls on the distribution of hydraulic conductivity in carbonate rocks. Specific objectives varied for the different aquifers. More hydrogeologic data were available for the Silurian (Sherrill, 1978; Bradbury and Muldoon, 1992; Gianniny and others, 1996; Muldoon and Bradbury, 1998; Bradbury and others, 1998); for this aquifer the objective was to further refine the sequence stratigraphic framework and determine its relationship with previously mapped high-permeability zones and hydrostratigraphic units. Relatively few data were available on the hydraulic conductivity of the Sinnipee, however, the sequence stratigraphic framework was well developed (Simo and others, 1995; Choi, 1995). For the Sinnipee, the specific objectives were to 1) define hydrostratigraphic units in the Fox River Valley and other parts of eastern Wisconsin where it is the uppermost bedrock unit and 2) determine if these zones could be correlated on a regional scale. In addition to the above, specific objectives applicable to both aquifers included: 1) construction of cross-sections illustrating hydrostratigraphic units, stratigraphic discontinuities, and discrete high-permeability zones; 2) correlation of high-permeability zones with stratigraphic discontinuities/zones; and 3) compilation of databases of hydraulic conductivity values for both the Silurian and Sinnipee dolomites that can be used by individuals and agencies interested in groundwater flow and transport in fractured carbonates.

SETTING

Silurian

Lower Silurian facies on the North American craton was dominated by a broad carbonate platform that probably extended across the continent from Mexico to the Arctic (Johnson, 1987). Lower Silurian Niagaran rocks of the Great Lakes region form an arcuate escarpment that trends northwestward from Niagara Falls through Ontario to the Bruce Peninsula (Figure 2). The escarpment emerges again on Manitoulin Island and extends westward along the upper peninsula of Michigan and into the Door Peninsula of Wisconsin. To the south, the rocks are poorly exposed due to overlying glacial deposits along the western edge of Lake Michigan to Chicago, Illinois. The Silurian outcrop in Wisconsin is the western edge of a broad carbonate platform that dips gently to the east under Lake Michigan. The western edge is an erosional boundary marked by the north-south trending escarpment known as the Niagaran Escarpment. The outcrop belt extends north-south approximately 350 km from Washington Island to the Illinois border and has an east-west extent of approximately 65 km at its widest points; just south of the town of Mayville the outcrop belt is buried beneath glacial drift.

The Door Peninsula, located in northeastern Wisconsin between Green Bay and Lake Michigan, is underlain by Lower Silurian dolostones which dip gently into the Michigan basin to the east-southeast at approximately 0.5 degrees or 8 to 9 m per kilometer and are underlain by Ordovician-aged shale, which forms a regionally extensive confining unit (Sherrill, 1978). The dolomite is more than 150 meters thick along the eastern shore of the peninsula and thins to the southwest. Surficial deposits in Door County consist of unlithified Pleistocene sediments, which range in thickness from zero to about 10 m. In general, the upland areas have very thin (< 1 m) unconsolidated deposits and the low-lying areas have thicker (> 2 m) deposits.

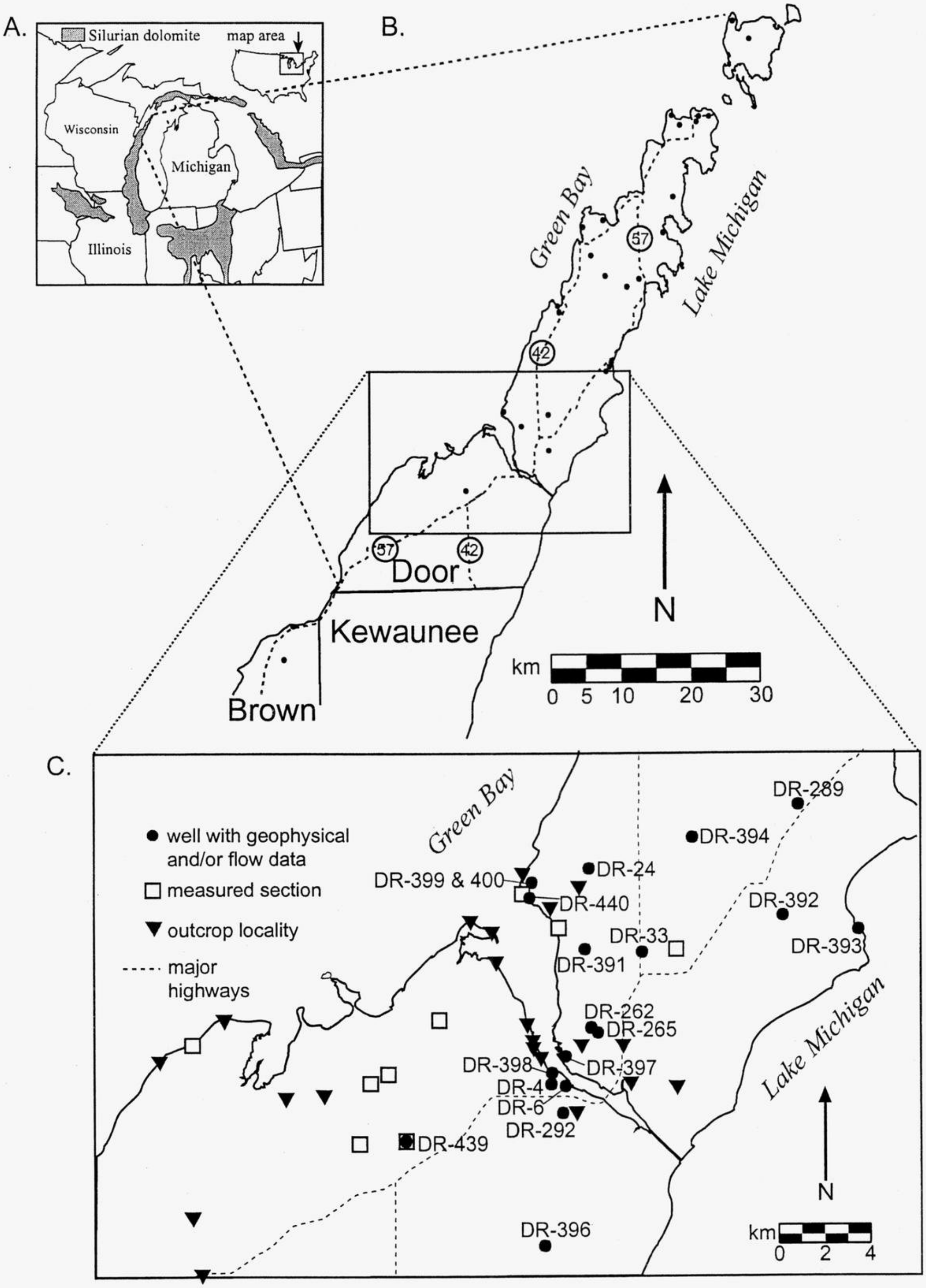


Figure 2. Location of Door County including **A)** map of generalized Silurian subcrop shown as shaded area (modified from Shaver and others, 1978), **B)** location of quarry sections measured by Waldhuetter (1995) and **C)** map showing location of wells used in the regional correlation of high-permeability zones, additional measured stratigraphic sections, and outcrop localities where lithologies and stratigraphy were field checked.

In the Door Peninsula, the Silurian aquifer is a self-contained unconfined aquifer system, bounded on three sides by surface water and beneath by the Ordovician Maquoketa Shale. The dolomite is the primary aquifer for the Door Peninsula, providing over 99% of all water used for agriculture, industry, and drinking-water supply (based on data in Ellefson and others, 1987). The area receives about 76.5 cm/yr of precipitation, including both rain and snow. Due to the thin soils and permeable bedrock, runoff is negligible over much of the study area and approximately 24 cm/yr recharges the groundwater (Bradbury, 1989). Groundwater recharge does not occur uniformly throughout the year; the primary recharge period is during spring snowmelt and additional recharge usually occurs in the fall of the year when vegetation has gone quiescent.

The dolomite is densely fractured and secondary dissolution has enlarged both fracture apertures and primary porosity. Groundwater flow is characterized by recharge through vertical fractures and rapid lateral movement along horizontal high-permeability zones (Sherrill, 1978; Bradbury and Muldoon, 1992) that appear to be laterally continuous on the scale of kilometers (Gianniny and others, 1996). Figure 3 shows near-vertical fracture expression in an alfalfa field in the northern Door study area. The photo shows two predominant joint sets with fractures spaced approximately 5 to 10 m apart. The major joint sets are oriented approximately N45°W (azimuth 135°) and N70°E. Each fracture, if open, can provide a direct route for infiltrating water to recharge the groundwater system. Most fractures, however, are at least partially filled with clayey or silty sediment near the land surface.

Water-table maps for Door County (Sherrill, 1978; Bradbury and others, 1991; Bradbury and others, 1998) indicate potentiometric highs in the center of the peninsula both north and south of Sturgeon Bay. Regional flow is primarily away from these potentiometric highs towards Lake Michigan to the east and Green Bay to the west. Accounts of contaminant releases suggest that groundwater flow rates can be very rapid in the dolomite aquifer. Bradbury and Muldoon (1992) reported groundwater velocities of 64 and 116 m/day based on elevated nitrate levels in two domestic wells after a nitrate release during manure pit construction.

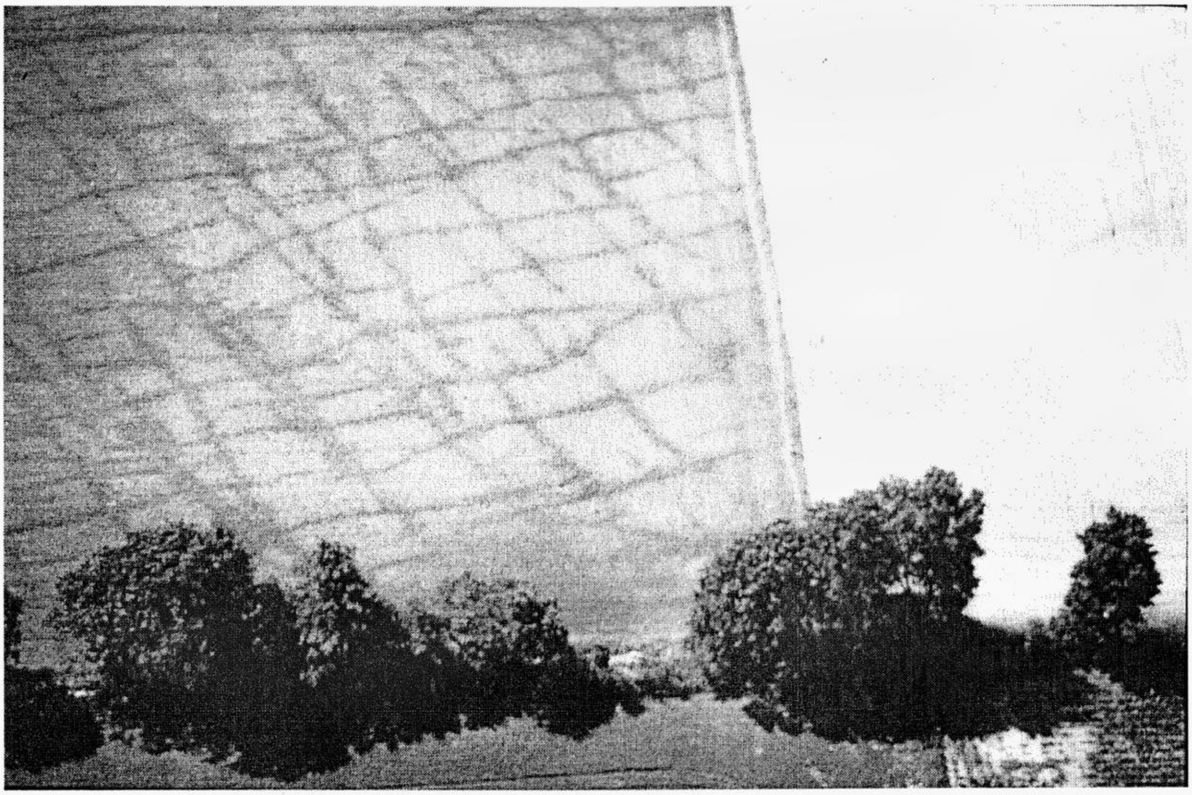


Figure 3. Oblique airphoto of fracture traces in an alfalfa field in north-central Door County (photo by Bradbury).

Sinnipee

The Ordovician Sinnipee Group carbonate aquifer system (Figure 1) is used as a drinking-water supply throughout the heavily populated Fox River Valley and other parts of eastern Wisconsin where it is the uppermost bedrock unit (Drescher, 1953; Knowles and others, 1964; Knowles, 1964; Devaul and others, 1983). This shallow aquifer has a high risk for contamination throughout much of its subcrop area (Feinstein and Anderson, 1987). The stratigraphy of this carbonate aquifer is well defined by Choi (1998). In eastern Wisconsin, the Ordovician Sinnipee Group (OSG) ranges in thickness from 50 to 80 meters and consists of the Platteville and Galena Formations. Ordovician strata dip to the east-southeast at approximately 0.5 degrees. The OSG exhibits significant facies changes from northeast to southwest (Choi, 1995, 1998). The northern and southern study areas were chosen in order to characterize the hydraulic properties of the end-members facies of the OSG. The southern study area encompassed portions of Dodge and Fond du Lac Counties and the northern area encompassed a portion of Brown County (Figure 4). Both du Lac Counties and the northern area encompassed a portion of Brown County (Figure 4). Both regions were approximately 15 miles in length and 5 miles in width.

Hydrogeologic Setting

The diagrams in Figure 5 illustrates that the regional direction of groundwater flow in eastern Wisconsin is towards Lake Michigan, the regional discharge point, and flow generally follows the dip of the formations. Local flow systems exist in the uppermost aquifer, which has been defined differently by various researchers. Knowles and others (1964) include only the Pleistocene and younger unconsolidated deposits, Batten and Bradbury (1996) include the unconsolidated deposits plus the upper weathered portions of the Sinnipee, and Weaver and Bahr (1991) include the unconsolidated deposits plus both the Galena and Platteville formations. The local flow direction is generally downward through the uppermost aquifer, recharging the deeper aquifer system which consists of the Prairie du Chien Group, the St. Peter Sandstone, and the Jordan Formation. To the south, there are strong upward gradients near the transition from an unconfined to a confined system where the Maquoketa Formation subcrops. In the north, general gradients are also downward, however, local groundwater flow paths move upward, discharging to the surface-water systems of the area. Downward gradients are also present within the cone of depression centered on Green Bay.

METHODS

Stratigraphic Characterization

For both the Silurian and Ordovician study areas, surface outcrops and subsurface cores were characterized in terms of lithologies, textures, and depositional cycles. Geophysical logs, primarily the natural gamma log, were used to correlate the lithostratigraphic units within each study area. Although the both the Silurian and Sinnipee sections have been dolomitized, the original textures are preserved well enough to allow recognition of original textures. Lithologic descriptions use Dunham's (1962) classification system for carbonate textures which is illustrated in Figure 6. Stratigraphic interpretations, including interpretation of depositional cycles, are based on standard methodology such as that outlined in Kerans and Tinker (1997).

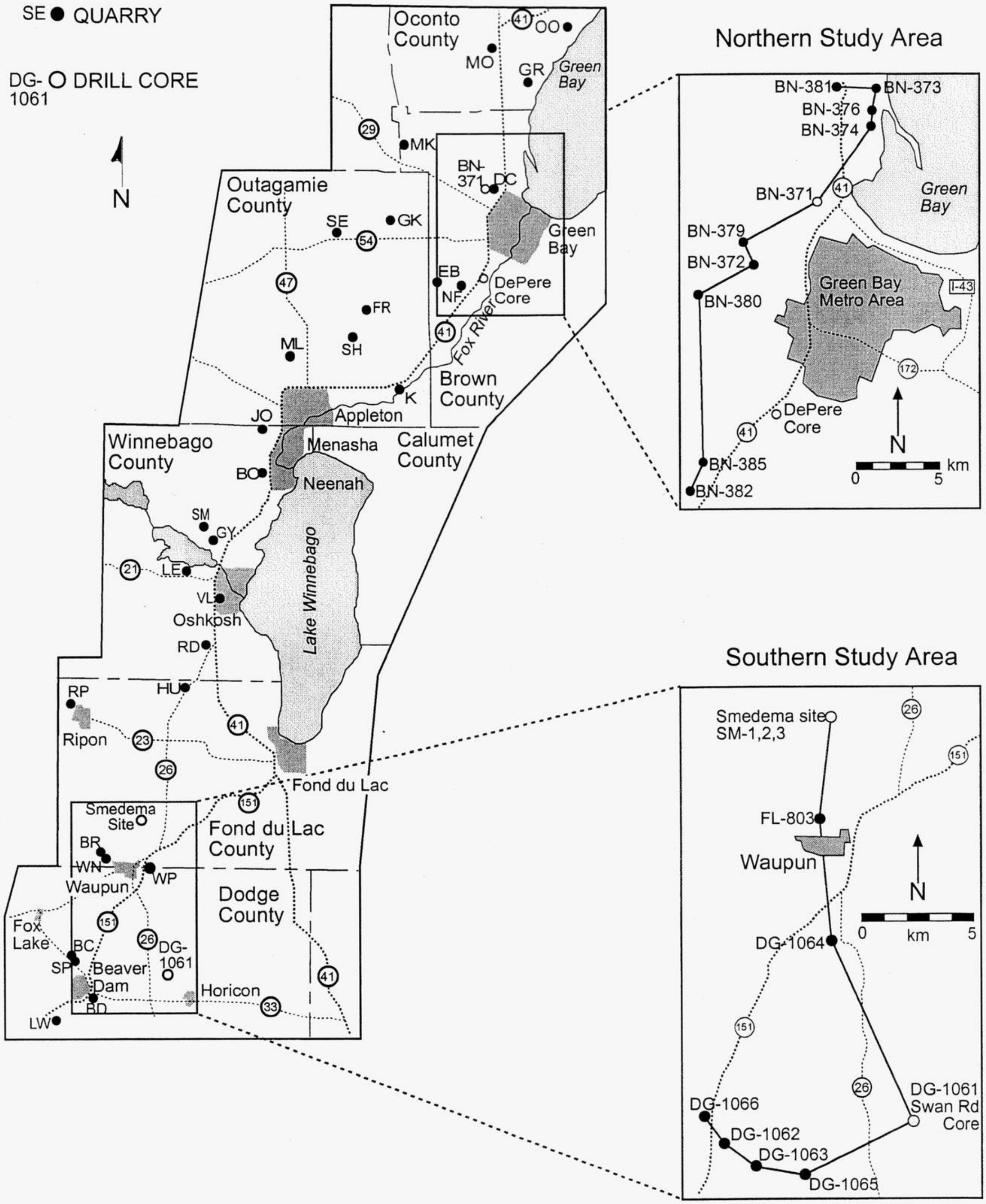
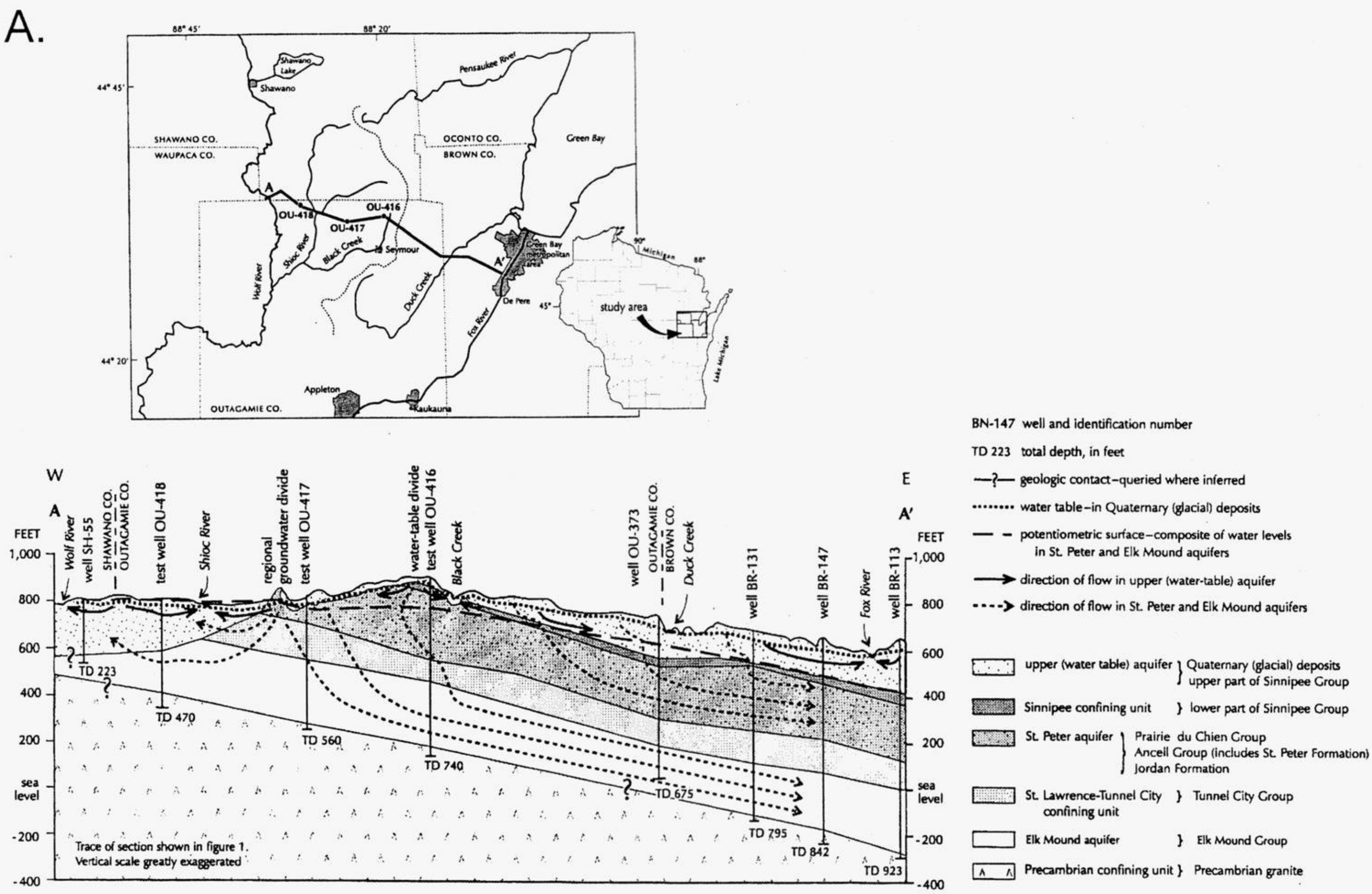


Figure 4. Maps showing locations of measured quarry sections and Ordovician study areas including coreholes, and wells. Names and locations for measured quarry sections can be found in Simo and others (1996), Choi (1996, 1998); core locations can be found in Stocks (1998a).

A.



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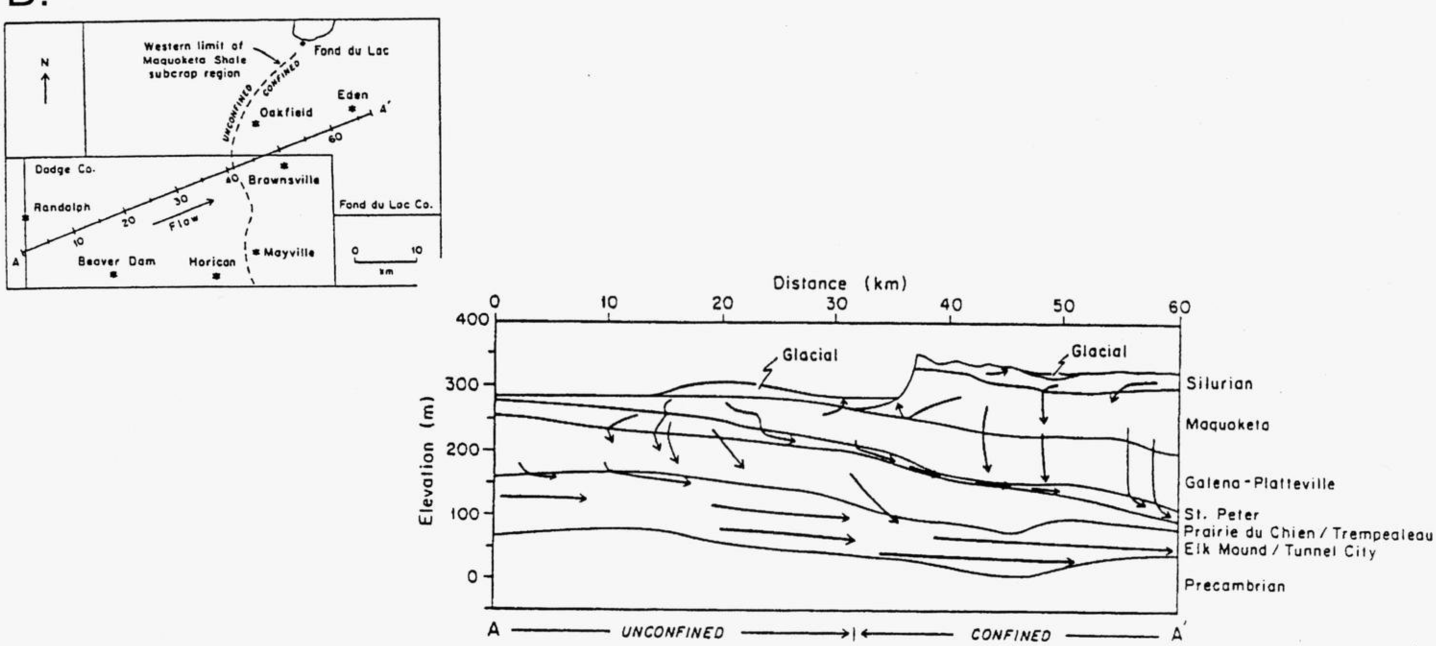


Figure 5. Diagrams illustrating groundwater flow paths in the A) area west of Green Bay (modified from Batten and Bradbury, 1996) and near Beaver Dam and Horicon (from Weaver and Bahr, 1991).

Geophysical logs provided information on the lithologic characteristics of the stratigraphic units as well as an independent method of stratigraphic correlation. Logs include caliper, which measures borehole diameter and can help identify fractures and dissolution zones; natural gamma, which measures natural radiation and can be used for stratigraphic correlation as well as to identify zones with shale or clay; and single-point resistivity and spontaneous potential, which are useful for stratigraphic correlation. Borehole video logging, performed on selected wells, provided a continuous image of the borehole wall.

Silurian Study Area

Surface stratigraphic data collected by Gianniny and others (1996) and Muldoon and others (in review) include nine measured sections and 21 descriptions of lithologies in smaller outcrops (Figure 2). Waldhuetter (1994) measured 26 quarry sections throughout the Silurian outcrop area and these locations are also shown in Figure 2. Subsurface lithologic data within the study area include description of cores from holes DR-394, DR-439, and DR-440. Existing geophysical data used in this investigation include logs from Sherrill (1978), Bradbury and Muldoon (1992), Gianniny and others (1996), Muldoon and Bradbury, (1998), and Bradbury and others (1998). Additional data were collected from DR-399, DR-439, and DR-440. Table 1 summarizes the

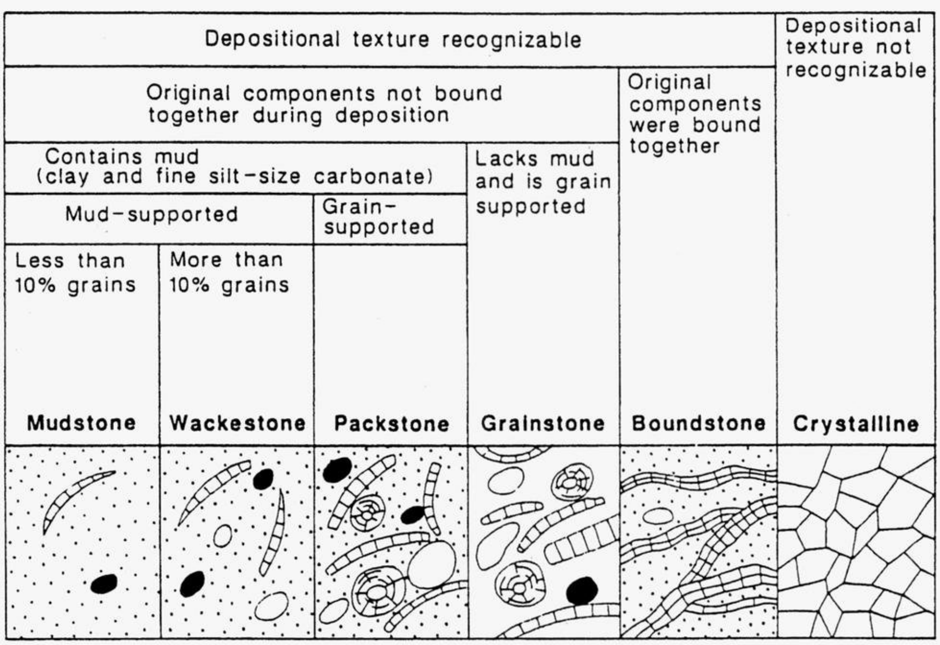


Figure 6. Classification of carbonate textures (from Dunham, 1962).

TABLE 1. Data Compiled for Wells in the Silurian Study Area

Well ID	Gamma	SP/ resistivity	Caliper	Fluid Temp/Res	Flowmeter	Hydraulic Testing*
<u>Sherrill (1978)</u>						
DR-24	X	X		X		
DR-33	X	X				
DR-262	X					yield data
DR-265						yield data
DR-289	X					
<u>Bradbury and Muldoon (1992)</u>						
7 boreholes, same location as DR-394						
	X	X	X	X	X	slug tests
<u>Gianniny and others (1996)</u>						
DR-4	X	X	X	X	X	
DR-6	X	X	X	X	X	
DR-24			X	X		
DR-391	X		X	X		
DR-392	X	X	X	X	X	
DR-393	X	X	X		X	
DR-394	X	X	X	X	X	slug tests
DR-396	X	X	X		X	
DR-397	X	X	X	X	X	
<u>Muldoon and Bradbury (1998)</u>						
18 boreholes, same location as DR-439						
	X	X	X	X	X	slug tests
<u>Bradbury and others (1998)</u>						
DR-265	X	X	X	X	X	pump tests
DR-292	X	X	X	X		
DR-398	X	X	X	X	X	pump tests
<u>New Data</u>						
DR-399	X	X	X	X		
DR-400	X	X	X			
DR-439	X	X	X	X		slug tests
DR-440	X	X	X	X	X	

*All hydraulic tests were conducted over discrete-intervals. Straddle-packer assemblages were used in most holes, however, the slug tests by Bradbury and Muldoon (1992) were conducted in piezometers.

geophysical and hydrogeologic data available from the wells in the Silurian study area. The majority of these logs can be found in Gianniny and others (1996) and are also available from the Wisconsin Geological and Natural History Survey's (WGNHS) Subsurface Lab.

Sinnipee Study Areas

Surface stratigraphic data for the Sinnipee include measured sections from 27 quarries collected by Simo and others (1996) and Choi (1995, 1998). Subsurface lithologic data include description of cores from holes DG-1061, BN-371, and the USGS Smedema site (Waupun, WI) and the Better Brite Superfund site (DePere, WI). Figure 4 shows the two Sinnipee study areas along with locations for measured sections, core holes, and wells with geophysical and/or hydrogeologic data. Geophysical data used in this investigation include existing logs on file in the WGNHS Subsurface lab, the USGS Smedema and Better Brite Superfund sites, as well as logs collected from 15 available open domestic and high-capacity wells in two study areas. Table 2 summarizes the geophysical and hydrogeologic data available from the wells in the two Sinnipee study areas. These geophysical logs can be found in Stocks (1998a, 1998b) and are also available from the WGNHS Subsurface Lab.

Hydrogeologic Characterization

Two approaches were used to characterize the hydraulic properties of the Silurian and Sinnipee dolomites. Vertical variability of hydraulic conductivity was determined from discrete-interval slug tests in coreholes and was compared to stratigraphic variability. High-flow features were identified using fluid temperature/resistivity logs, flowmeter logs, and short-interval packer tests. Natural gamma logs were used to identify the stratigraphic position of flow features in each well and to correlate flow features between wells.

Short-interval Packer Tests

Permeability tests conducted on discrete sections of a borehole provide a quantitative method of characterizing the hydraulic conductivity of both high-permeability features and the matrix portion of the aquifer. Discrete intervals can be isolated by installing piezometers screened over short intervals or by using inflatable packers. These zones can then be tested either by pumping

TABLE 2. DATA Compiled for Wells in the Sinnipee Study Areas

Well #	Gamma	SP/sptRes	Caliper	Fluid T/R	Heatpulse			Fluid Cond.	Slug	Core
					Static	pumping	injection	logging	Tests	
Northern Study Area										
BN-371	X	X	X	X	X		X		X	X
BN-372	X			X						
BN-373	X									
BN-374	X	X	X	X	X					
BN-376	X	X	X	X	X					
BN-379	X	X	X	X	X					
BN-380	X	X	X	X	X					
BN-381	X	X	X	X	X					
BN-382	X		X	X	X					
BN-385	X		X	X	X					
DePere										X
Southern Study Area										
FL-803	X	X		X						
SM-1	X	X	X	X	X	X	X	X		X
SM-2	X	X	X	X	X					
SM-3	X	X	X	X	X		X			
DG-1061	X	X	X	X	X				X	X
DG-1062	X	X	X	X	X					
DG-1063	X	X	X	X	X					
DG-1064	X	X	X	X	X					
DG-1065	X	X	X	X	X					
DG-1066			X	X						

tests or slug tests in order to quantify hydraulic properties. A straddle-packer assemblage was to complete rising-head slug tests in four coreholes. Two of the cores (DR-394 and DR-439) were located in the Silurian study area (Figure 2) and one corehole was located in each of the two Sinnipee study areas (Figure 4). The open interval for the DR-394 tests was 0.85 m and tests were completed at 0.46-m increments. The open interval was shortened to 0.64 m and tests were completed at 0.6-m intervals in holes DR-439, DG-1061 and BN-371.

Water-levels were monitored using pressure transducers and recorded with a datalogger. Tests were initiated 10 to 15 minutes after packer inflation and recovery was monitored for 10 to 15 minutes. Recoveries varied from 2 to 100%. Tests were analyzed using the Hvorslev (1951) method. The geometry of coreholes and the packer assemblage allowed use of the simplified version of the Hvorslev equation which is applicable when the length of the open interval is more than eight times the radius of the borehole (L/R > 8):

$$K = \frac{r^2 \ln(L/R)}{2LT_o}$$

where K is hydraulic conductivity,

r is the radius of the standpipe,

R is the radius of the borehole,

L is the length of the open interval,

T_0 is the time is takes for the water level to recover to 37% of the initial change.

A best-fit line, fit to the recovery data, was used to calculate T_0. Repeated tests on specific intervals yielded hydraulic conductivity values that varied within an order of magnitude. Additional details of the test procedure are provided in Stocks (1998a). Test data can for the Sinnipee coreholes can be found in Stocks (1998b) and for the Silurian coreholes in Muldoon (1999b).

While the short measurement intervals were designed to isolate and test individual fractures and to minimize the averaging inherent with most packer tests, this methodology has limitations. Resulting hydraulic conductivities are still averaged over the length of the test interval; for matrix-dominated test intervals this is probably appropriate. For fracture-dominated test intervals, the bulk of the flow is carried through an individual fracture or a small number of fractures, yet the apertures of the fractures are a minor percentage of the overall test-interval length. As a result, the actual conductivity of the fracture(s) will be underestimated by this method, and the amount of underestimation will vary somewhat with the length of the test interval. We were primarily interested in comparing the relative permeabilities of the fractures and matrix. Given that the measured hydraulic conductivities range over five orders of magnitude, the variation due to differing test-interval length is considered insignificant.

Identification of High-permeability Features

High-flow features in the coreholes and in existing domestic and municipal wells within the three study areas were identified using fluid temperature/resistivity logs, flowmeter logs, and short-interval packer tests. Data were compiled from previous reports and additional data were collected as part of this study. Fluid temperature and resistivity/conductivity data can be acquired easily and rapidly in any open borehole. Sharp changes in these profiles, within a given borehole, provide a qualitative method of locating discrete high-permeability features where water of differing chemistry or temperature is flowing into or out of the borehole. Temperature profiles have been used by other workers as a means to identify bedding-plane fractures and estimate their aerial extent (Trainer, 1968) or determine the interconnectivity of fractures between boreholes (Silliman and Robinson, 1989). If there is no vertical flow in the borehole, the temperature will show a gradual increase with depth due to the geothermal gradient (approximately 0.75 degrees Celsius per 30 meters of depth). Fluid resistivity is partly a function of temperature, so these logs must be interpreted together (Keys and MacCary, 1971).

Both spinner and heat-pulse flowmeter logging can be used to quantify the amount of water entering a borehole at various depths. These two logging methods differ both in terms of logging method and in terms of the effective flow rates that they measure. Spinner logging is most effective at detecting larger flow rates (approximately 75 l/m or more) and continuous profiles of flow rates are typically collected while a well is being pumped. Sharp changes in flow rate indicate the location of discrete high-permeability zones that contribute the majority of water being pumped from the hole. We attempted to use a spinner tool in several holes in the Silurian study area and found that we were not able to generate measurable flow rates using a submersible pump rated at 30 gpm.

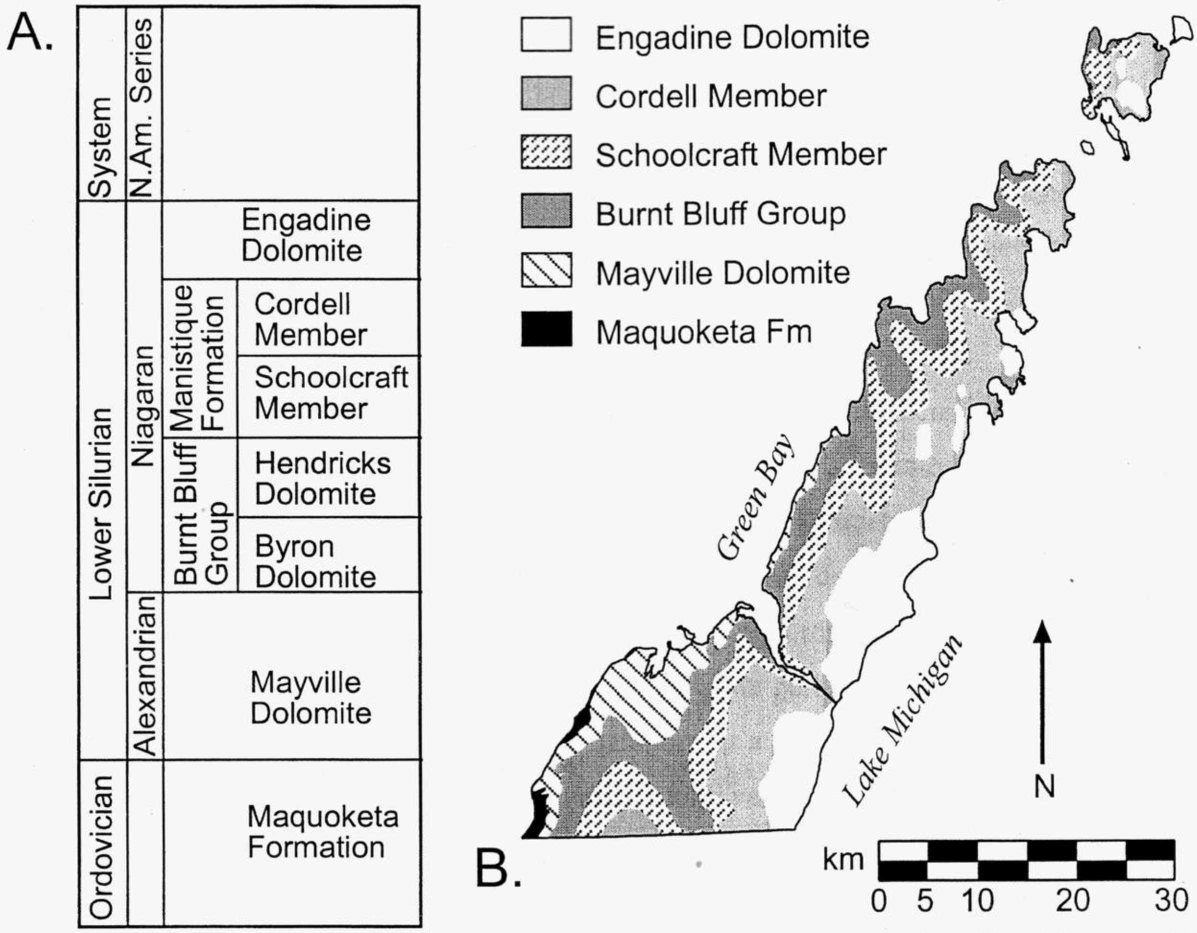
The heat-pulse flowmeter is only effective at flow rates less than four to six liters per minute (1 to 1.5 gpm). The heat-pulse meter consists of a heating element with two thermistors; one located above the heating element and one below it. A flexible rubber centralizer, located near the heating element, serves to center the tool in the borehole and focus flow through the meter. A heat pulse is generated and as the water flows either up or down the borehole, it is detected by one of the thermistors. The time from generation of pulse, until it is recorded by one of the two thermistors, is then used to calculate a flow rate. Measurements are taken at specific depths and any change in flow rate or flow direction from one measurement point to the next indicates that water is either entering or leaving the borehole within that interval. A general overview of flow-meter logging techniques in fractured rocks is given by Cohen (1995) and Paillet and others (1993) provide an example of heat-pulse logging to identify secondary-permeability features in a fractured-dolomite aquifer.

Heat-pulse measurements intervals were somewhat variable for wells in the Silurian study area but in the Sinnipee wells, measurements were made at 1.5 meter intervals. Interpretation of test results were complicated by limitations due to the detection limits of the meter and the head distribution within the aquifers. In many wells, the ambient vertical flow rates were below the detection of the meter. When possible, the head distribution was stressed, by either injection or pumping, to impose steeper vertical gradients and higher flow rates (Morin and others, 1988; Paillet and others, 1987). This was done in only a few wells because of power- and water-supply limitations. Tests run under stressed conditions were used primarily to identify additional transmissive zones that were not noted in the static log.

STRATIGRAPHY

Silurian

The Silurian strata of the Door Peninsula were first described and mapped by Chamberlin (1877) who subdivided the dolomite into five formations. Stratigraphic nomenclature and bedrock geology are summarized in Figure 7. Overviews of Door County stratigraphy are provided by Kluessendorf and Mikulic (1989) and Steiglitz (1989). Harris and Waldhuetter (1996), Hegrenes (1996), and Simo and others (1998) provide a sequence stratigraphic interpretation of the Silurian section.



Engadine Dolomite: The Engadine Dolomite (~11 m thick) is a light-gray, thickly-bedded dolostone with poorly preserved fauna, no chert nodules, and vuggy porosity.

Manistique Formation: The Manistique Formation (27 m thick) consists of subtidal facies, and represent a transgressive package over the restricted-marine facies of the Hendricks Dolomite. The Manistique Formation is subdivided into two members, with the upper Cordell Member richer in chert that the lower Schoolcraft Member.

Hendricks Dolomite: Similar to the upper Byron, the Hendricks Dolomite records a cyclic succession of subtidal and supratidal facies, with cycles of 1-3 m thickness, and a total thickness up to 28 m.

Byron Dolomite: The Mayville-Byron contact records a change from the coral-brachiopod-rich rocks (Mayville Dolomite) to a laminated, mud-cracked mudstone (Byron Dolomite). Most of the Byron Dolomite consists of restricted shallow-subtidal to supratidal facies, and is 23-25 m thick. In Door County, the Byron Dolomite culminates in an argillaceous, bluish-gray, mudstone.

Mayville Dolomite: The Mayville Dolomite (approximately 62 m) consists of deep- to shallow-subtidal facies arranged into two shallowing-upward successions interpreted as deposited in moderate- to high-energy, subtidal, open-shelf environment. Bedding is typically massive or wavy, and occasionally is rippled; thickness varies from thin to medium beds. Chert is very abundant in the lower part of the section.

Maquoketa Formation: In Door County, the Maquoketa is a poorly exposed shale succession that is thinly laminated and greenish-gray in color.

Figure 7. Summary of bedrock geology of Door County; **A)** stratigraphic nomenclature and description of units (modified from Simo and others, 1998) **B)** geologic map of Door County (digitized from Chamberlin (1878) by Roffers (1996)).

Geophysical Signature

These facies associations have characteristic geophysical signatures that are easily recognized and correlated throughout the study area. A composite stratigraphic column for the Door Peninsula, based on core and outcrop descriptions, is shown in Figure 8 along with the natural gamma, spontaneous potential (SP), and single-point resistivity (sptRes) logs for corehole DR-394. Caving of the hole limited data collection to the upper 132.5 m. In general, the Middle Shelf Facies Association (color-coded white in Figure 8) is characterized by a low to moderate natural gamma signature and when sptRes and SP are available they show low sptRes signal, and higher SP.

In the gamma-ray logs, two distinct packages of predominantly Inner Shelf and Inner-Middle Shelf Facies Association (color-coded black and gray respectively in Figure 8) are present from 94 to 62.5 m in the Byron and Hendricks dolomites). Each of these packages (94-76 m, and 76-62.5 m; Figure 8) is characterized by a distinctive high in natural gamma, associated with argillaceous and organic-rich laminites, at the base of the package that generally decreases upward. This decreasing upward trend is also seen in the SP log while sptRes increases upward. The Inner Shelf Facies Association package near the top of the Mayville Dolomite has a different signature that those of the Byron and Hendricks Dolomites. The overall gamma-ray is slightly higher that the Middle Shelf Facies Associations below and above the package. Two sharp peaks in the gamma signal (106 and 110 m) are due to thin layers (3-20 cm) of greenish laminated clay. Similar layers in the Ordovician are composed of bentonite.

Correlation

The geophysical logs, particularly the natural gamma logs were used to correlate selected wells and measured quarry sections (Simo and others, 1998). Plate 1 illustrates this correlation and the similarities between stratigraphic and lithofacies patterns observed in cores and quarry sections throughout the Sturgeon Bay area. A more extensive correlation of gamma logs from throughout the study area can be found in Gianniny and others (1996).

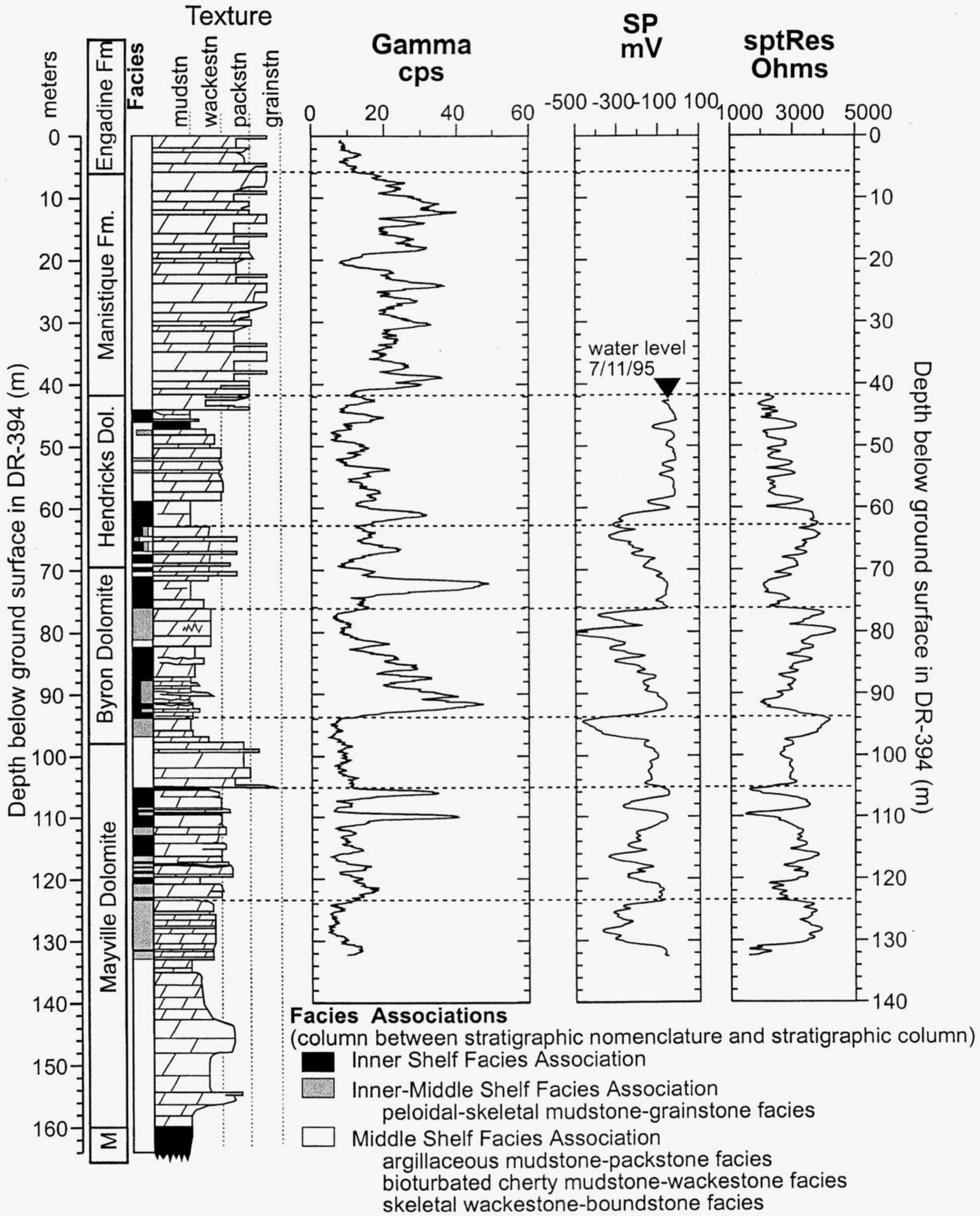


Figure 7. Summary of Silurian stratigraphy for the Door Peninsula. From left to right the figure includes the following: depth scale (meters); stratigraphic nomenclature; facies associations (color-coded white to black, legend is included at bottom of figure; composite stratigraphic column (brick pattern is dolomite, black is shale); the natural gamma, spontaneous potential (SP), and single-point resistivity (sptRes) logs from corehole DR-394. Correlatable geophysical units are delineated by dashed lines.

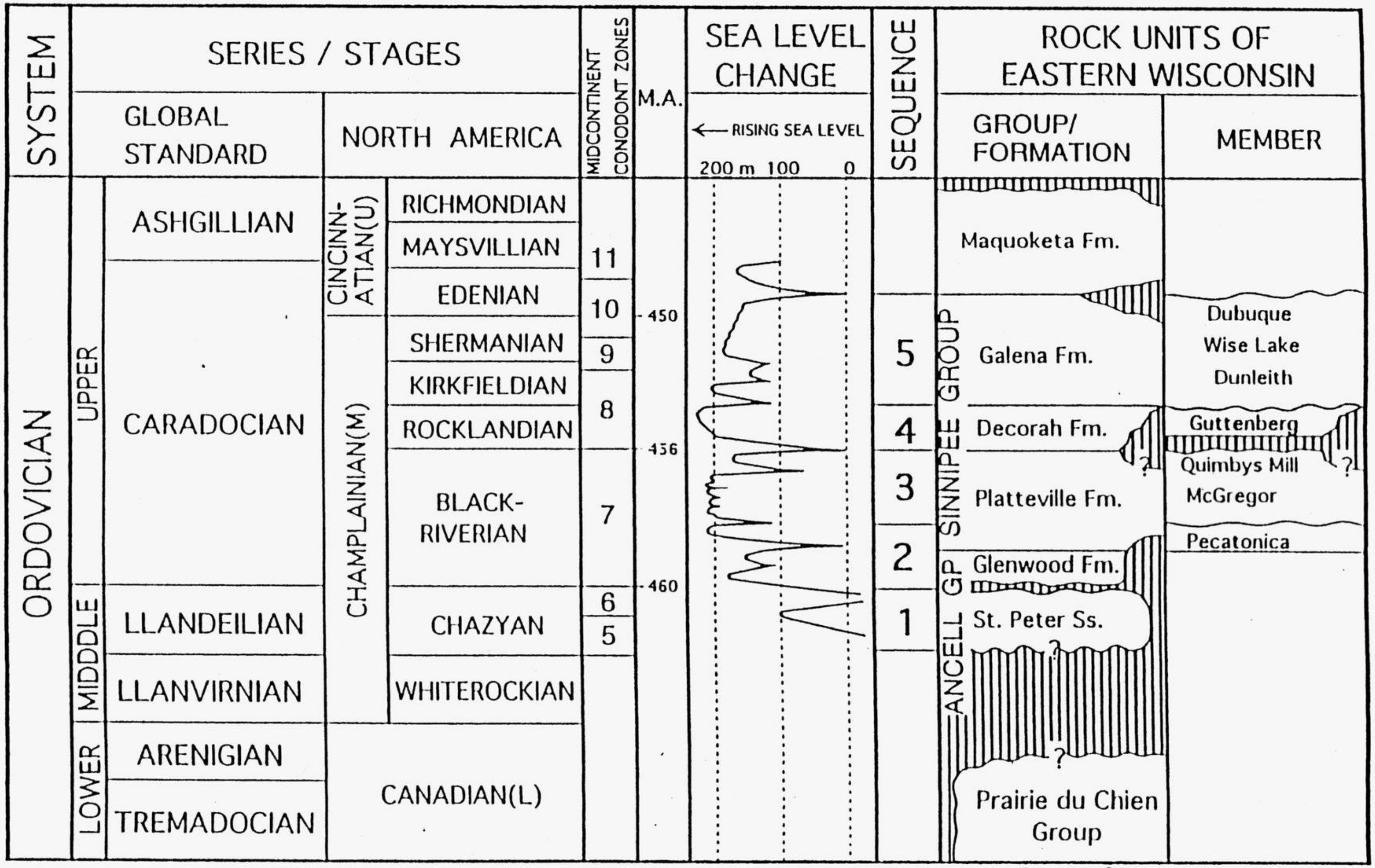


Figure 3. Chronostratigraphy, lithostratigraphy, and sequence stratigraphy diagram for Ordovivian rocks in Wisconsin. From Choi, 1998.

Figure 9. Chronostratigraphy, lithostratigraphy, and sequence stratigraphy diagram for Ordovician rocks in Wisconsin.

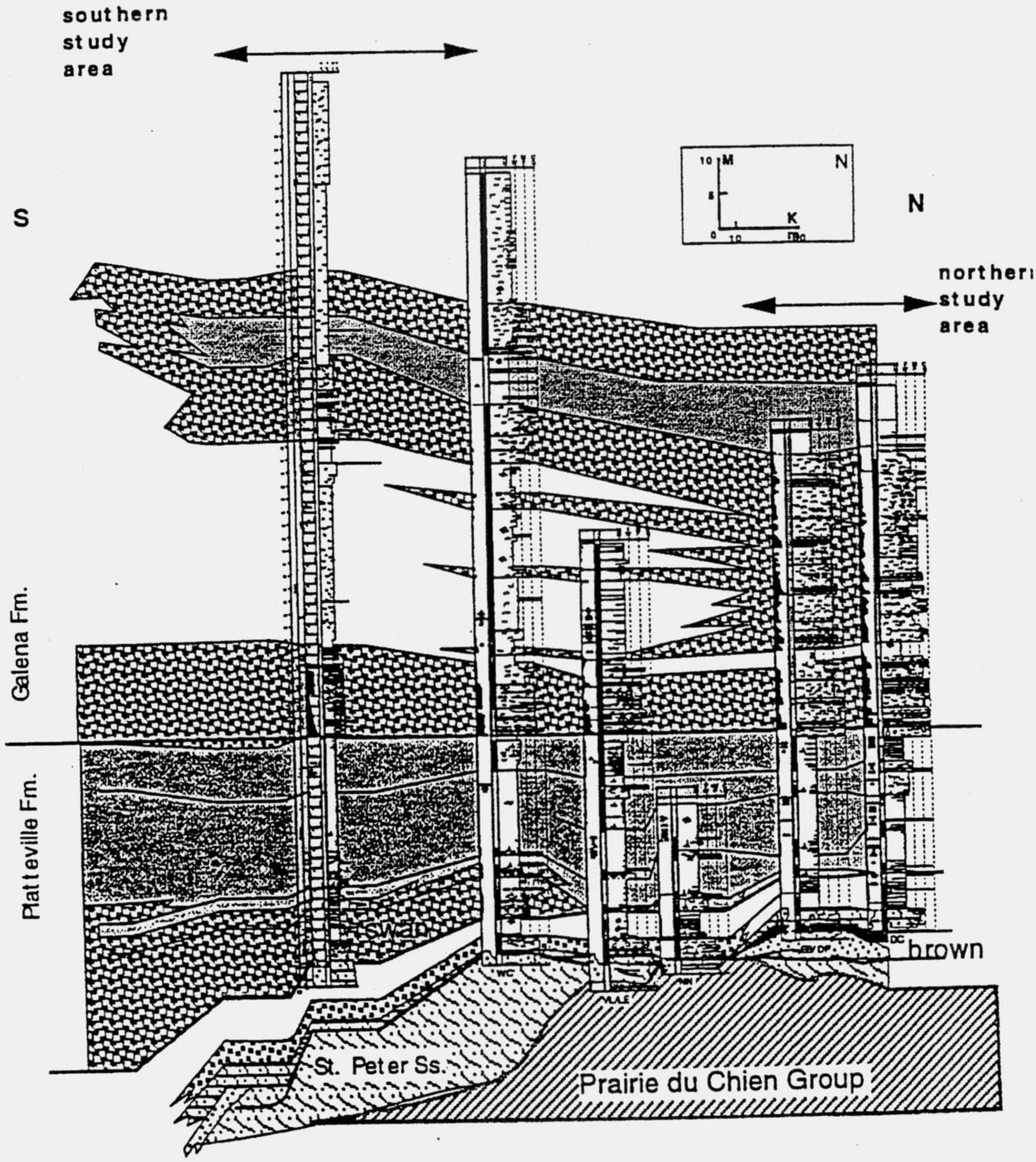


Figure 10. Lithologic cross section showing south to north facies and thickness changes for the Ordovician Sinnipee Group.

The Ordovician Sinnipee Group consist of three facies: inner ramp, mid-ramp, and outer ramp facies. These facies contain eighteen lithofacies described in detail by Choi (1998). Figure 10 illustrates the vertical and lateral facies changes in the study area. The inner ramp facies represent shallow-water environments above fair-weather wave base delineating migrating shoal bars and back shoal protected environments or low energy shallow-water environments without shoals. The dominant lithologies are mottled argillaceous mudstone to wackestone and non-mottled non-argillaceous mudstone to wackestone. The mid-ramp facies consists of skeletal-rich carbonates, with open marine fauna such as brachiopods, crinoids, pelecypods, bryozoans, trilobites, corals, and nautiloids. The open marine fauna, pervasive bioturbation, good sorting of fragmented and abraded skeletal grains in the skeletal wackestone to packstone lithofacies indicate deposition influenced by frequent storm reworking. The mid-ramp facies may contain abundant clay. The clay-rich, mid-ramp facies consists of interbedded grainstone/shale and interbedded nodular carbonate/grainstone lithologies. The outer ramp facies, in the study area, consists of carbonate mud-rich sediments such as bioturbated mudstone to wackestone and crinoidal wackestone, and was deposited in the deepest paleowater-depth.

Lithostratigraphy

The Platteville and Galena formations in cores DG-1061 and BN-371 were subdivided into three lithostratigraphic packages based on fine-scale changes in lithology, texture, and clay content described in the cores and finer-scale trends in the geophysical logs. The basal package (A) consists of the siliciclastic sandstones, dolomitic sandstones, and green clays of the St. Peter Sandstone and Glenwood Formation. Package B consists of the dolomites and argillaceous dolomites of the Platteville Formation. Package C consists of the dolomites and argillaceous beds of the Galena Formation. Packages B and C were further subdivided into five (B1-B5) and six (C1-C6) lithostratigraphic units respectively. Table 3 summarizes the characteristics and Figures 11 and 12 the vertical distribution of the lithostratigraphic units recognized.

The lithostratigraphic unit nomenclature is consistent for both stratigraphic sections (i.e. C1 in the Swan Road core (DG-1062) is the same as C1 in the Brown County core (BN-371)). South to north lithologic variations are noted by the presence or absence of a given unit and changes in

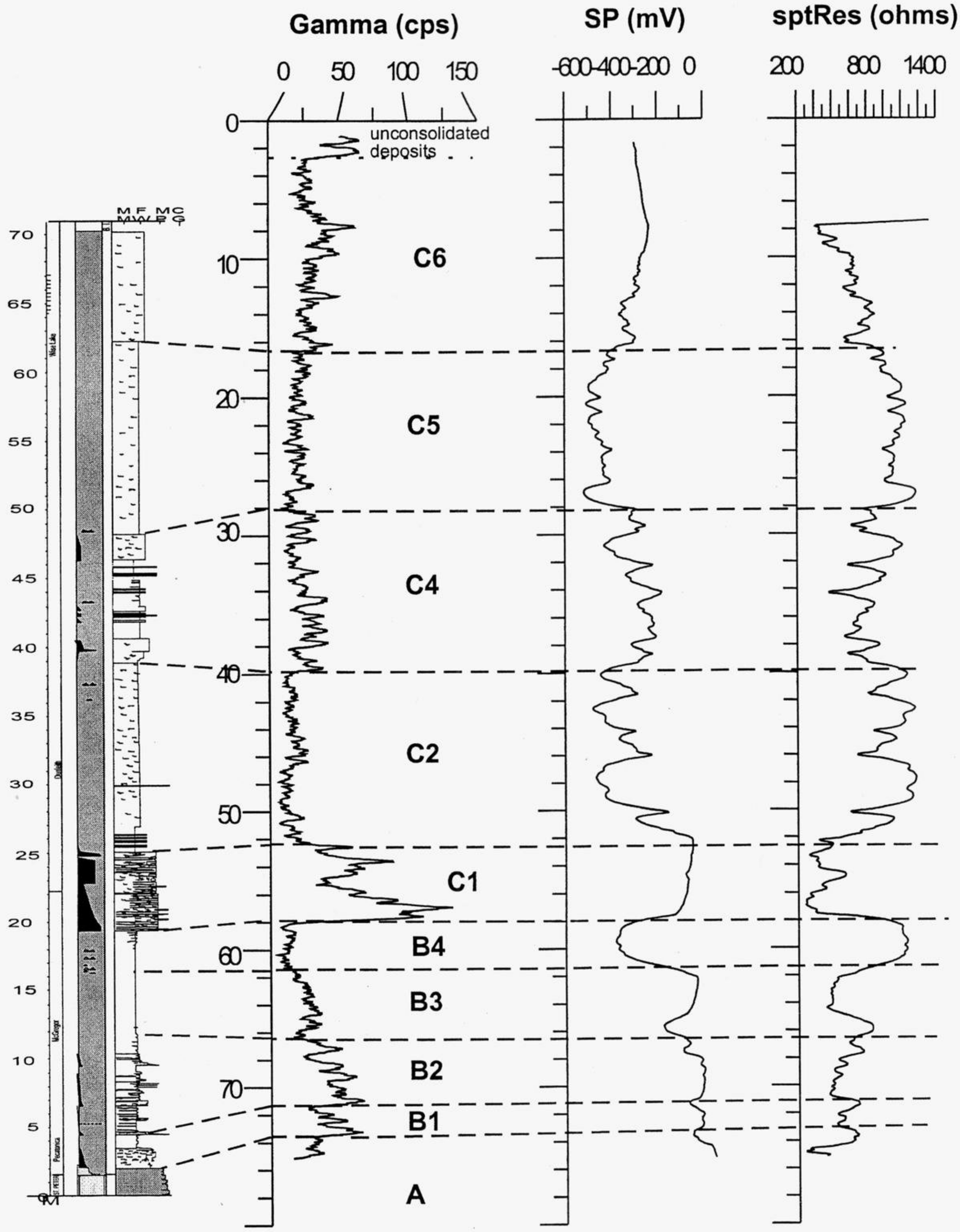


Figure 11. Summary of Ordovician stratigraphy in the southern study area. Swan Road stratigraphic column (DG-1061), natural gamma, spontaneous potential, and single-point resistivity logs with lithostratigraphic units delineated. Legend for stratigraphic column can be found in Appendix A.

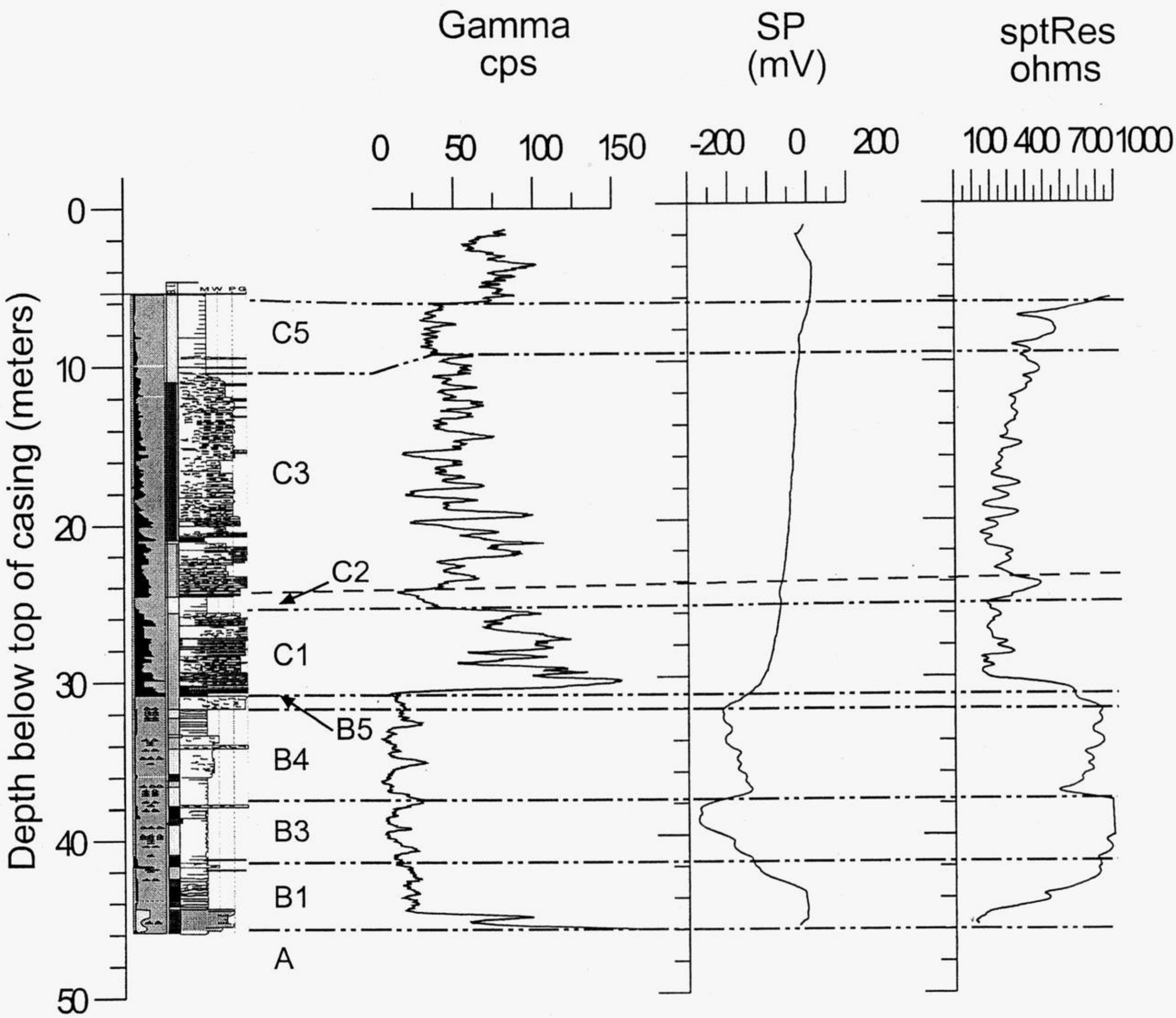


Figure 12. Summary of Ordovician stratigraphy in the northern study area. Brown County stratigraphic column (corehole BN-371), natural gamma, spontaneous potential, and single-point resistivity logs with lithostratigraphic units delineated. Legend for stratigraphic column can be found in Appendix A.

Table 3. Summary of Lithostratigraphic Units for the Ordovician Sinnipee Group

Lithostratigraphic Units	C1	C2	C3	C4	C5	C6
Swan Road Lithologic Description	Mudstones to packstones with interbedded green shales	Thinly bedded mud- and wackestones grading into thick-bedded, fossiliferous mud-wackestones. Abundant clay seams, moderate bioturbation	Absent	Moderately bioturbated fossiliferous wacke- to packstones overlain by interbedded mud- and wackestones with coarser interbeds	Moderately bioturbated fossiliferous mud- to wackestone. Clay seams, vugs, and secondary porosity present	Moderately bioturbated fossiliferous wackestone. Clay seams, vugs, and secondary porosity common
Brown County Lithologic Description	Pack-grainstones interbedded with green shales	Mudstone, little to no clay, bioturbation, or fossil content	Alternating wacke-, pack-, and grainstones with variable clay content and high bioturbation	Absent	Moderately bioturbated fossil-poor mudstone	Absent
Swan Road Thickness	6 meters	14 meters	N/A	9 meters	14 meters	8 meters
Brown County Thickness	5 meters	1 meter	14 meters	N/A	4.5 meters	N/A
Swan Road Gamma, SP, and sptRes signatures	Gamma up to 125 cps SP increase of 250 mV relative to B5 sptRes decrease of 1100 ohms relative to B4	Gamma signal of 15 to 25 cps SP decrease of 350 mV relative to C1 sptRes increase of 800 ohms relative to C1	N/A	Gamma signal of 15 to 40 cps SP increase of 200 mV relative to C2 sptRes decrease of 400 ohms from C2	Gamma signal of 15 to 25 cps SP decrease of 200 mV relative to C4 sptRes increase of 400 ohms relative to C4	Gamma signal of 25 to 50 cps SP increase of 200 mV relative to C5 sptRes decrease 400 ohms relative to C5
Brown County Gamma, SP, and sptRes signatures	Gamma up to 150 cps sptRes decrease of 450 ohms relative to B5	Gamma decreases from 25 to 15 cps sptRes increase of 200 ohms relative to C1	Gamma varies between 25 and 100 cps sptRes increases 200 ohms upward	N/A	Gamma signal of 35 cps sptRes increase of 200 ohms relative to C3	N/A

unit thickness. Disparities between the thicknesses of the lithostratigraphic units in the stratigraphic sections are attributed to facies change from an area closer to the Ordovician landmass to the north. Lithostratigraphic units A, B3, B4 and B5 correspond to inner-ramp facies; units B2, C1, C3 and C4 to mid-ramp facies; and units C2, C5 and C6 to outer-ramp facies. Unit B1 correspond to both mid-ramp and outer-ramp facies. The lithostratigraphic units were correlated in regional wells based on their characteristic geophysical signatures. Plate 2 shows the correlated gamma logs for the southern region and Plate 3 shows the correlated gamma logs for the northern region. One gamma log is used to represent all three Smedema wells due to their proximity (approximately 30 meters apart). The Galena-Platteville contact is the datum for well-log correlation. Figures 13 and 14 show the structure-contour maps of this surface for the southern and northern study areas respectively. Data for these maps were obtained from the geophysical logs from this research and existing geophysical and geologic logs of wells on file at the Wisconsin Geologic and Natural History Survey.

Geophysics

Geophysical logs were collected from the core sites DG-1061, BN-371, and SM-1,2,3 (the DePere corehole had been previously abandoned and was unavailable for logging), and new domestic and municipal wells. In total, 20 wells were logged. Table 2 lists the geophysical logs performed in each well and Table 3 summarizes the lithologic and geophysical characteristics. Figures 11 and 12 show the stratigraphic sections, natural gamma logs, spontaneous potential (SP) logs, and single-point resistivity (sptRes) logs for the Swan Road (DG-1061) and Brown County (BN-371) cores. Appendix A contains a complete legend for the stratigraphic sections.

The Platteville Formation has a natural gamma signal of approximately 25 to 50 counts per second (cps) and moderate spontaneous potential and single-point resistivity signatures. The lower Galena Formation has a distinct, high natural gamma signal of 125 to 150 cps, a high spontaneous potential, and a low single-point resistivity. The upper Galena Formation has two different geophysical signals. In one, the natural gamma signal is around 25 to 50 cps and the spontaneous potential and single-point resistivity is moderate. In the other, the natural gamma

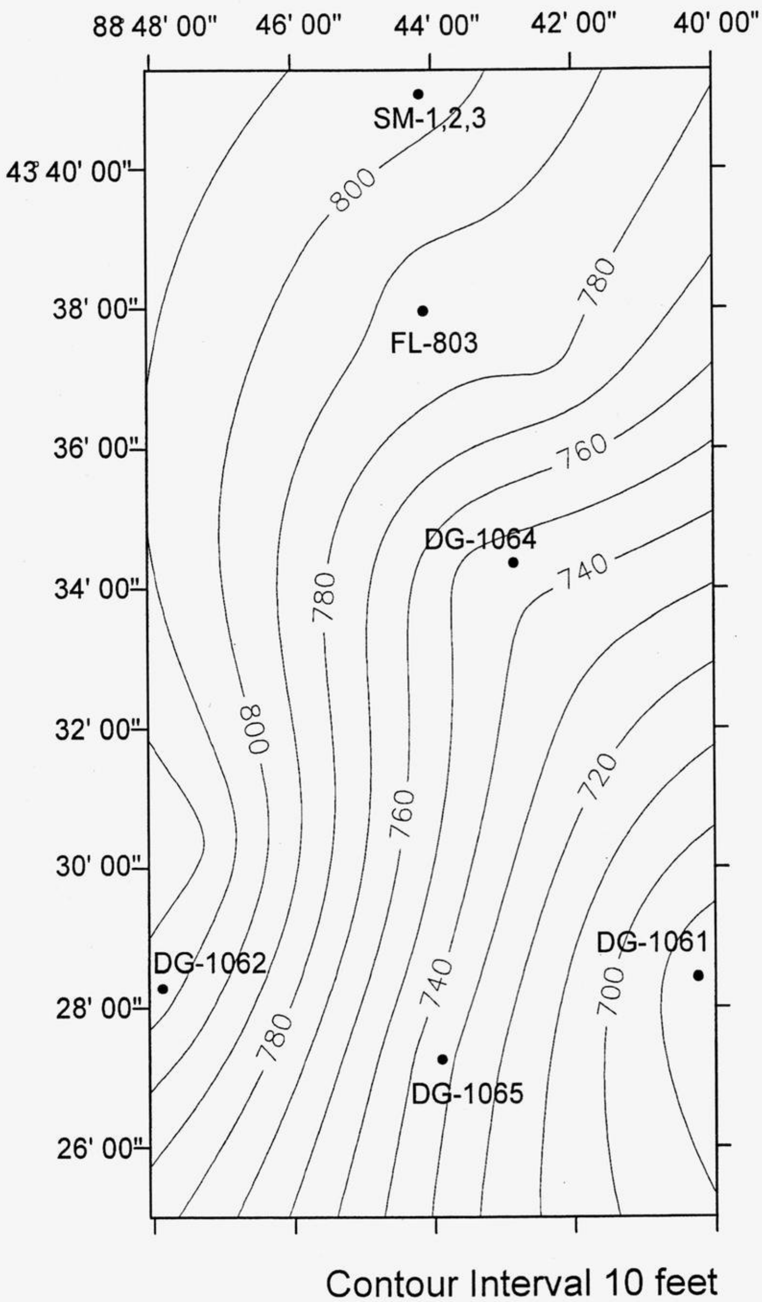


Figure 13. Structure-contour map of the Galena-Platteville contact for the southern study area.

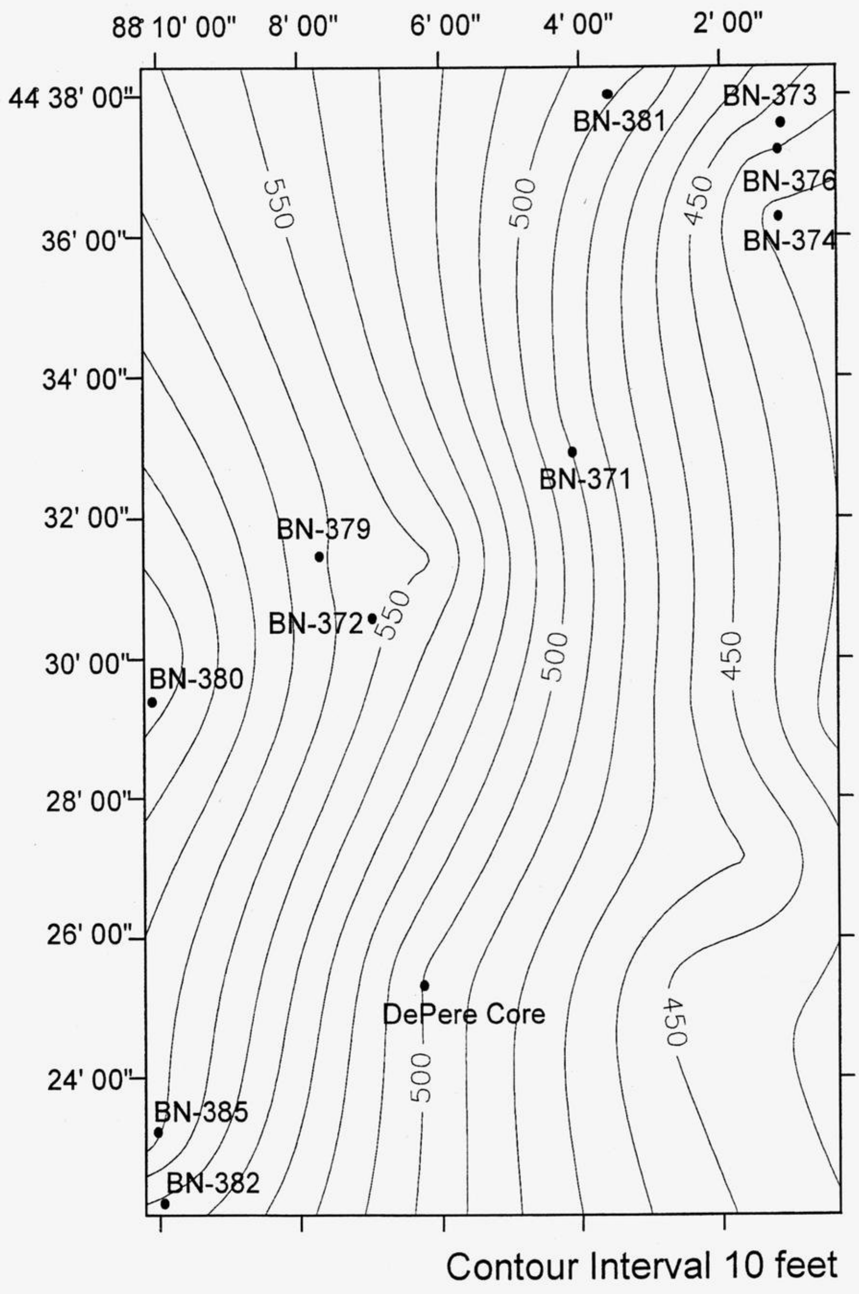


Figure 14. Structure-contour map of the Galena-Platteville contact for the northern study area.

signal is around 50 to 100 cps, the spontaneous potential is high, and the single-point resistivity is low.

HYDROSTRATIGRAPHY

Silurian

Vertical Distribution of Hydraulic Conductivity

Short-interval packer tests were used to characterize the vertical variability of hydraulic conductivity in coreholes DR-394 and DR-439. The hydraulic conductivity profiles from these holes (Figure 15) provide data on the relative permeabilities of the matrix as well as high-permeability features. The two profiles were correlated using the natural gamma logs.

Measured hydraulic conductivity values range over five orders of magnitude in hole DR-394 from 1.5×10^{-1} to 2.0×10^{-6} cm/sec. Hole DR-439 exhibits less variability, with values ranging from 4.5×10^{-2} to 1.5×10^{-4} cm/sec. It is not clear why the two holes exhibit different ranges of measured hydraulic conductivity values. Hole DR-439 was developed more completely than DR-394 and this may explain some of the difference. Despite the difference in absolute values, the two profiles are generally similar in shape and they suggest that there are several distinct populations of measured hydraulic conductivity values which are related to lithologic variations. The profiles were divided into nine segments based on variations in hydraulic conductivity and lithology. More detailed discussion of the variations between segments follows; histograms of hydraulic conductivity values for the different segments are presented in Figure 16.

Segment 1 of the hydraulic conductivity profile (128 - 123.8 m) is composed of bioturbated wackestones of the Inner-Middle Shelf Facies Association (Figure 15). Slug test data suggest a relatively uniform matrix hydraulic conductivity of approximately 10^{-5} cm/sec in this bioturbated, mud-rich facies (Figure 16). The transition at 123.8 m to a package of alternating laminites of the Inner Shelf Facies Association and Inner-Middle Shelf Facies Association is marked by subtle changes in the hydraulic conductivity distribution.

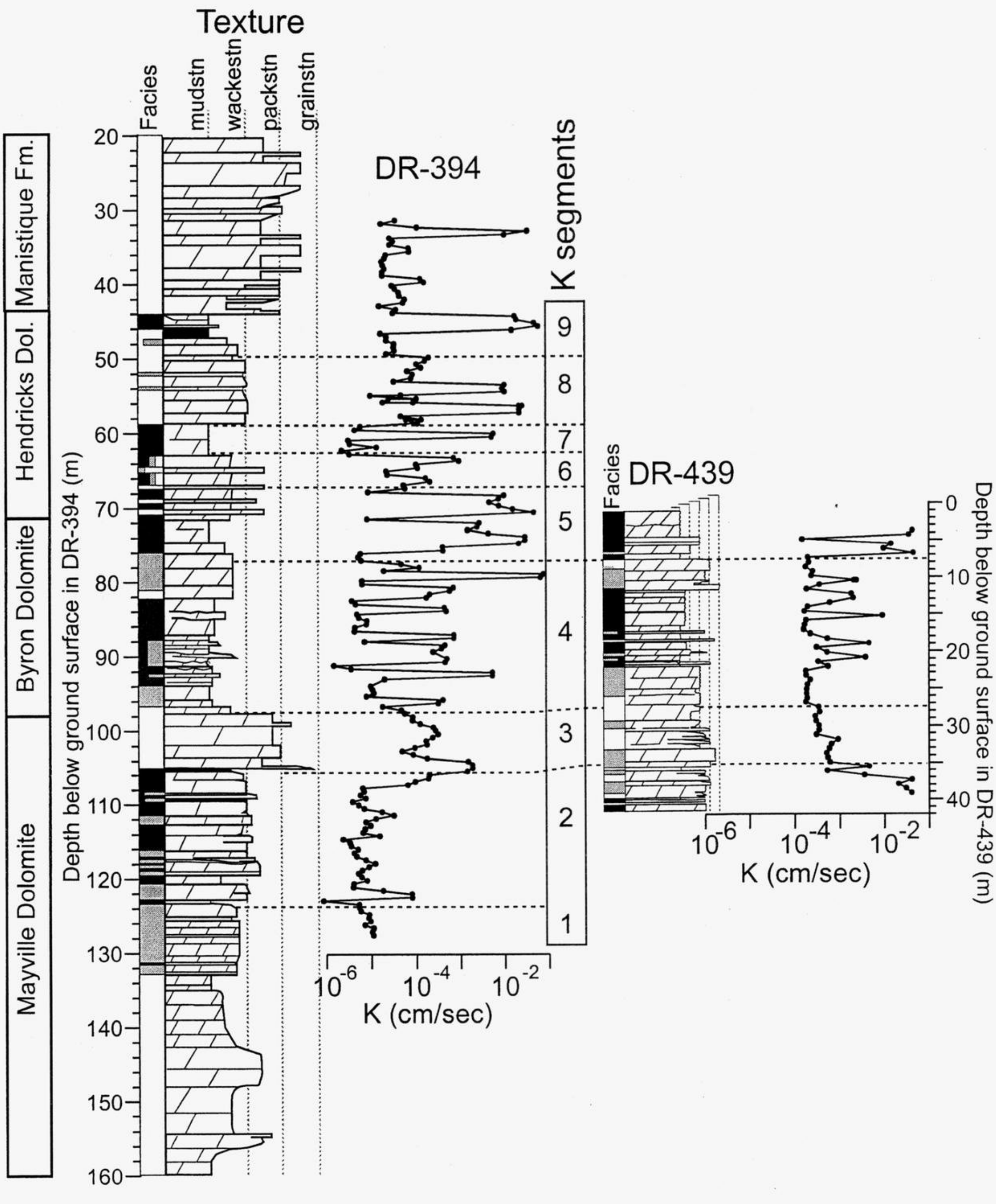


Figure 15. Hydraulic conductivity profiles and stratigraphic columns for coreholes DR-394 and DR-439; legend for the facies associations is in Figure 8. The profiles have been divided into nine segments based on variations in hydraulic conductivity and lithology. The profiles were correlated using natural gamma logs.

In hole DR-394, segment 2 exhibits a slightly lower matrix hydraulic conductivity and more variability than segment 1 (Figure 16). Examination of the cores suggests that higher values of hydraulic conductivity in segment 2 of DR-394 are associated with discontinuities between contrasting lithologies (121.9 - 123.1 m), zones with moldic porosity (111.6), and a combination of vertical fractures and discontinuities developed at contrasting lithologies (105.5 - 107.3 m). Moldic porosity develops by the dissolution of fossils. Hole DR-439 just penetrates the top of segment 2 where a zone of moldic porosity (37.2 - 39 m) and an open fracture (35.4 m) led to generally high hydraulic conductivity values.

Segment 3 is developed in the Middle Shelf Facies Association. The profiles (Figure 15) suggest that this zone has higher average matrix permeability than the underlying and overlying

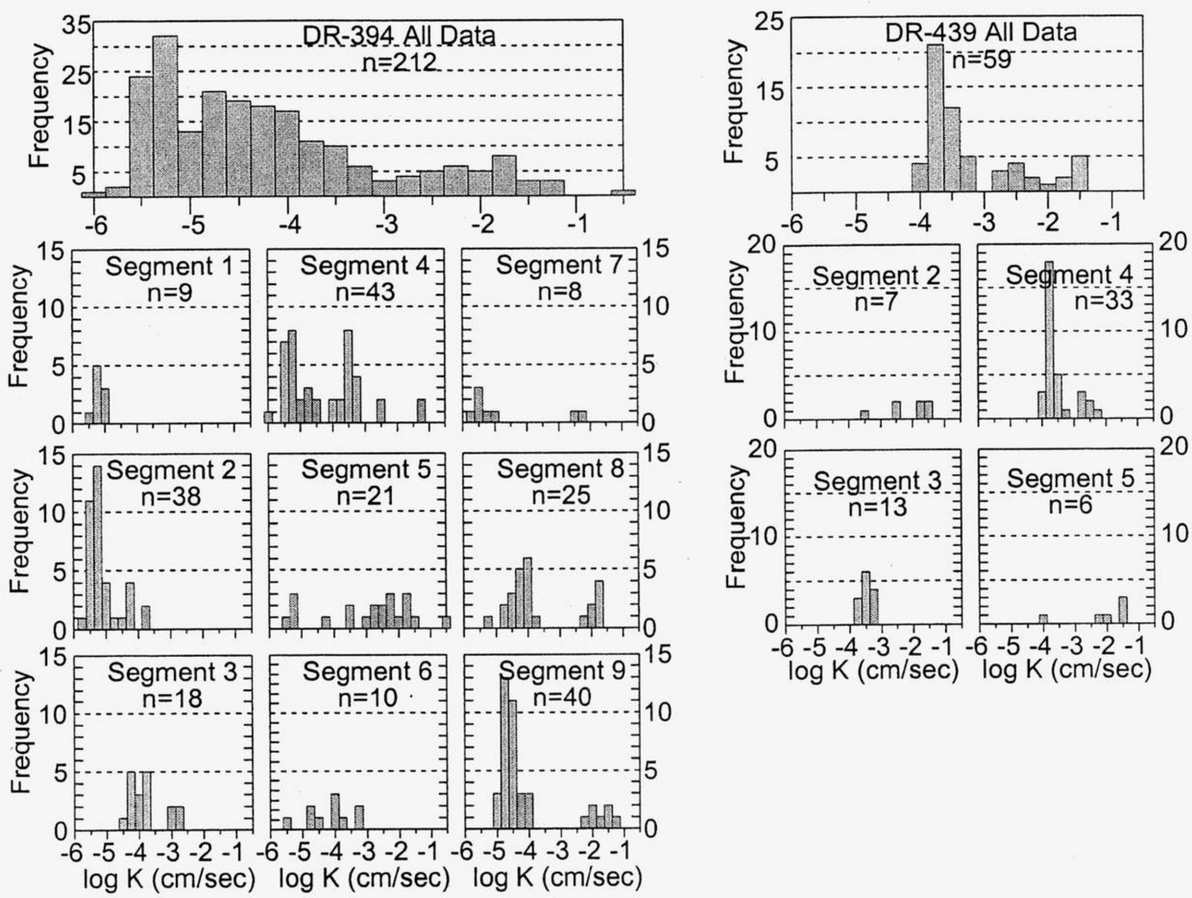


Figure 16. Histograms of hydraulic conductivity values measured with short-interval packer tests in holes DR-394 and DR-439.

dolomite, reflecting the generally coarser texture of these facies. Comparison with the cores suggests that variations of hydraulic conductivity in this segment are controlled by development of moldic porosity; higher values are associated with fossiliferous zones.

Segment 4, developed within the Inner and Inner-Middle Shelf Facies Associations of the Byron Dolomite (restricted marine), has a strongly bimodal distribution of hydraulic conductivity in both holes (Figures 15 and 16). Most measurements in this segment alternate between low values, which represent the matrix permeability of these finer-grained sediments, and higher values (approximately two orders-of magnitude greater) which may be due to bedding-plane partings located at cycle boundaries. The highest measured hydraulic conductivities in DR-394 occur in a zone of transitional lithologies near the top of the segment where the open-marine and restricted-marine facies alternate at the mm- to cm-scale.

Segment 5 is characterized by generally high hydraulic conductivity values that are associated with two very different lithologies. Argillaceous laminites (71.9 - 75 m), easily correlated by their high natural gamma signatures, are present at the base of segment 5 in both cores. This unit exhibits numerous cycle boundaries and appears quite well-cemented and brittle. The combination of abundant bedding-plane partings at cycle boundaries and numerous vertical fractures account for the high permeability of the argillaceous unit.

The upper portion of segment 5 and segments 6 and 7 (71.6 - 58.8 m, Figure 15) represent a gradual transition in lithology from the dominantly fine-grained mudstones of the Inner and Inner-Middle Shelf Facies Associations (restricted marine) to the coarser, more fossiliferous Middle Shelf Facies Association (open marine). These segments are composed of cyclic alternations of those lithologies. At 67.1 m there is a transition in predominant lithology that is marked by subtle changes in the hydraulic conductivity distribution. In the upper portion of segment 5, open-marine facies with abundant large fossil molds are common while in section 6 restricted-marine facies are more common and the open-marine facies are less fossiliferous. The high hydraulic conductivities in the upper portion of segment 5 correlate with abundant large fossil molds in the open-marine facies, while segment 6 has a variable distribution of moderate hydraulic conductivity values. The argillaceous mudstones (section 7, 62.4-58.8 m in Figure 15), marked by a natural gamma high (Figure 8), have a bimodal distribution of hydraulic conductivity (Figure 16) with very low matrix values, approximately $10^{-5.5}$ cm/sec, and higher values (10^{-2} cm/sec) that correspond to large, open fractures developed at cycle boundaries. This unit is not as brittle as the deeper argillaceous unit (71.9 - 75 m) and vertical fractures are not as common.

Segments 8 and 9 are developed primarily in the Middle Shelf Facies Association; the frequency of restricted marine-facies decreases upward (Figure 15). Both segments have bimodal distributions of hydraulic conductivity (Figure 16). There is, however, a shift in matrix conductivity (approximately 1/2 an order of magnitude) at 49.7 m. This shift appears to correlate with a decrease in chert content. The high-permeability features in these segments also appear to be controlled by different factors. Segment 8 contains abundant zones of white chert nodules (replacing fossils); extensive dissolution around the chert nodules leads to zones of high permeability (53.6-54.2, and 56.1-57.3). In segment 8, large open fractures, also enhanced by dissolution, preferentially develop at lithologic contrasts (near 45.7 m).

Regional Distribution of High-permeability Zones

Fluid temperature/resistivity logs, flowmeter logs, and short-interval packer tests from 13 existing domestic and municipal wells and three coreholes were used to identify flow features within the individual wells. These data were then used to define 14 regionally-important high-permeability zones. Most wells are open to only a small portion of the Silurian aquifer; flow features could only be detected in the uncased, saturated portion of a given well. It is possible that a flow feature is present in a given hole, but that it was not detected with the available data. This is particularly likely for holes where only fluid temperature/resistivity data, but not flowmeter data, are available. Changes in fluid temperature/resistivity are most pronounced in the spring when cold water from snowmelt is recharging the aquifer; the majority of the fluid logs were collected during the summer; thus some flow features may not have been detected. In addition, the accuracy of locating a flow feature with heat-pulse flowmeter measurements is determined by the spacing of the measurements. For holes with widely-spaced measurements, some flow features may not have been detected. Figure 17 illustrates flow features interpreted from the fluid temperature/resistivity and heat-pulse flowmeter logs for well DR-6. The flow features at 32.9, 64.0, 76, 80.8, and 89 m are suggested both by inflections in the temperature or resistivity log and by changes in measured vertical flow rate. The flow features at 37.8 and 51.2 m are inferred from changes in vertical flow rate and the locations of prominent fractures identified in the caliper log.

A compilation of flow features from 16 wells is presented in Figure 18. After the data had been compiled for each well, natural gamma logs were used to identify the stratigraphic position of flow features in each well and to project the features onto the core lithology and gamma signature from hole DR-394 (Figure 8). This was necessary since the thickness of lithologic units varies slightly across the study area. By projecting data onto hole DR-394, this variable thickness could be taken into account and flow features could be directly compared with lithologic data.

Fourteen, regionally-important, high-permeability zones (A to N in Figure 18) have been defined based on the distribution of flow features in the wells. Eleven of the 14 high-permeability zones appear to correlate with a specific stratigraphic horizon. A specific stratigraphic horizon was designated a high-permeability zone if flow features were observed in 40% or more of the wells open and saturated at that stratigraphic horizon. Three of the high-permeability zones (K, I, and E) represent broader intervals of similar lithologies where numerous flow features were observed in wells open to that interval.

The high-permeability zones correlate well with both the noted variations in the hydraulic conductivity profiles (Figure 15) and with stratigraphic features such as bedding planes developed at sharp contrasts in texture or lithology, zones of moldic porosity, and lithologies with numerous discontinuities developed at cycle boundaries. Zones A, B, C, F, M, and N occur in the Middle Shelf Facies Association (Figure 18). In these facies, high-permeability features occur primarily at bedding-plane discontinuities that appear to develop where contrasting

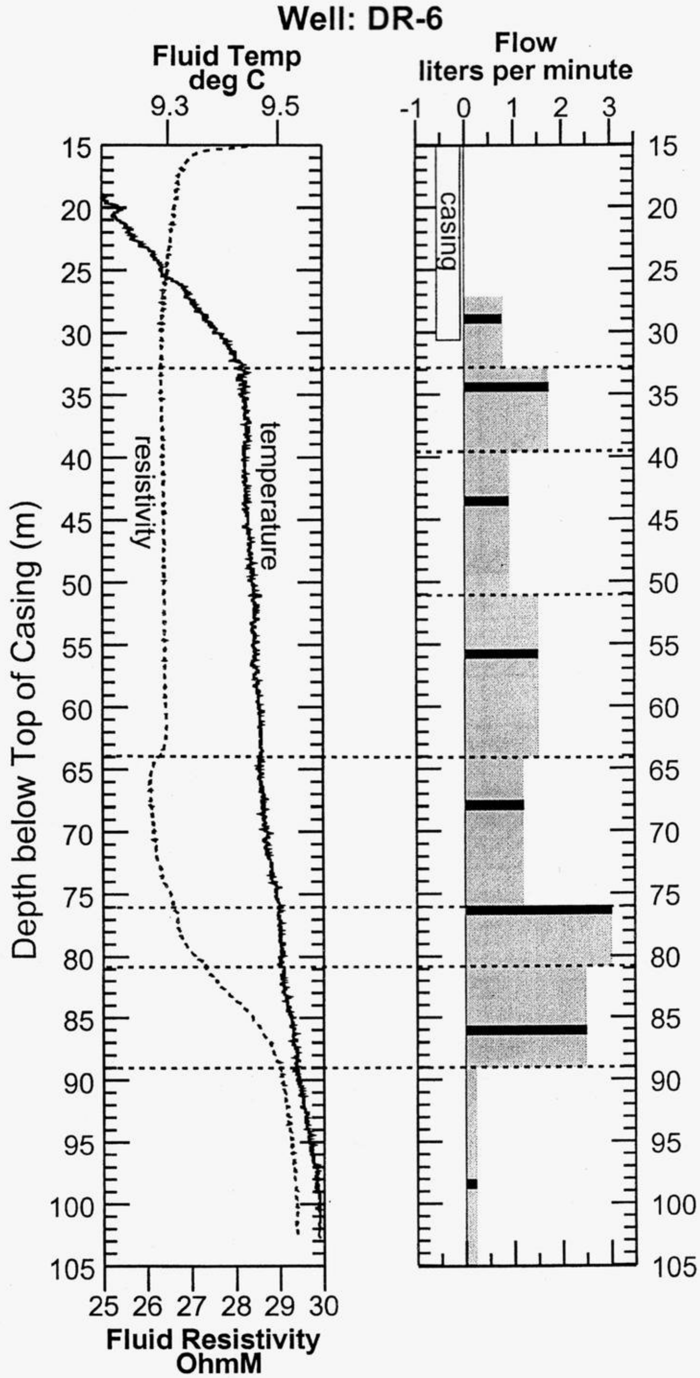


Figure 17. Fluid temperature/resistivity (left) and heat-pulse flowmeter (right) logs for hole DR-6; the static water level was 2.9 m. Dashed horizontal lines indicate flow features interpreted for this well. The temperature/resistivity log was collected under static conditions. The heat-pulse log was collected while pumping from the top of the water column, measured flow rates are shown at the top of the heat-pulse log (positive values indicate upward flow and negative values indicate downward flow). The black bars indicate the measured vertical flow rates at specific points in the hole. The gray-shaded boxes illustrate the changes in measured flowrates which were used, in combination with caliper log data, to interpret the position of flow features.

textures (i.e., wackestone and packstone) are juxtaposed. Zone F, developed in the middle of a massive bed, occurs in a fossiliferous zone where extensive moldic porosity has developed.

Zones E, G, H, I, and K are developed primarily in the Inner and Inner-Middle Shelf Facies Associations (Figure 18). Zone E, which corresponds to the upper portion of segment 2 in the hydraulic conductivity profiles (Figure 15), is characterized by numerous high-permeability features developed at discontinuities between contrasting lithologies (contact of open-marine and restricted-marine facies) and at cycle boundaries. Zone I corresponds to the top of segment 4 in the hydraulic conductivity profile, a zone of transitional lithologies where open marine and restricted marine facies alternate at the mm to cm scale. Zone K, which corresponds to segment 7 in the hydraulic conductivity profiles (Figure 15), correlates with a unit of argillaceous and organic-rich laminites. High-permeability features are common both within and at the boundaries of this unit. Zones G and H both develop at cycle boundaries with the Inner Shelf Facies Association; zone G also corresponds to the boundary of segments 3 and 4 in the hydraulic conductivity profile (Figure 15).

Several flow zones (D, J, and L) correlate with bedding-plane discontinuities developed where open-marine and restricted-marine facies are juxtaposed. Zone D also correlates with the contact of segments 1 and 2 in the hydraulic conductivity profile (Figure 15).

Sinnipee

Vertical Distribution of Hydraulic Conductivity

Figures 19 and 20 show the vertical profiles of the hydraulic conductivity distributions for the DG-1061 (Swan Road, southern) and BN-371 (Brown County, northern) coreholes. There was significant vertical and lateral variability in the hydraulic conductivity (K) measurements. The K distribution for DG-1061 is highly variable with K values ranging over six orders of magnitude from 10^{-6} to 10^{-1} cm/s. The K distribution for BN-371 is more uniform, with K values of 10^{-4} cm/s comprising 90% of the measured values. Based on correlations of hydraulic conductivity (K) values with the lithologic descriptions, the lowest K values for each corehole (10^{-6} to 10^{-5}

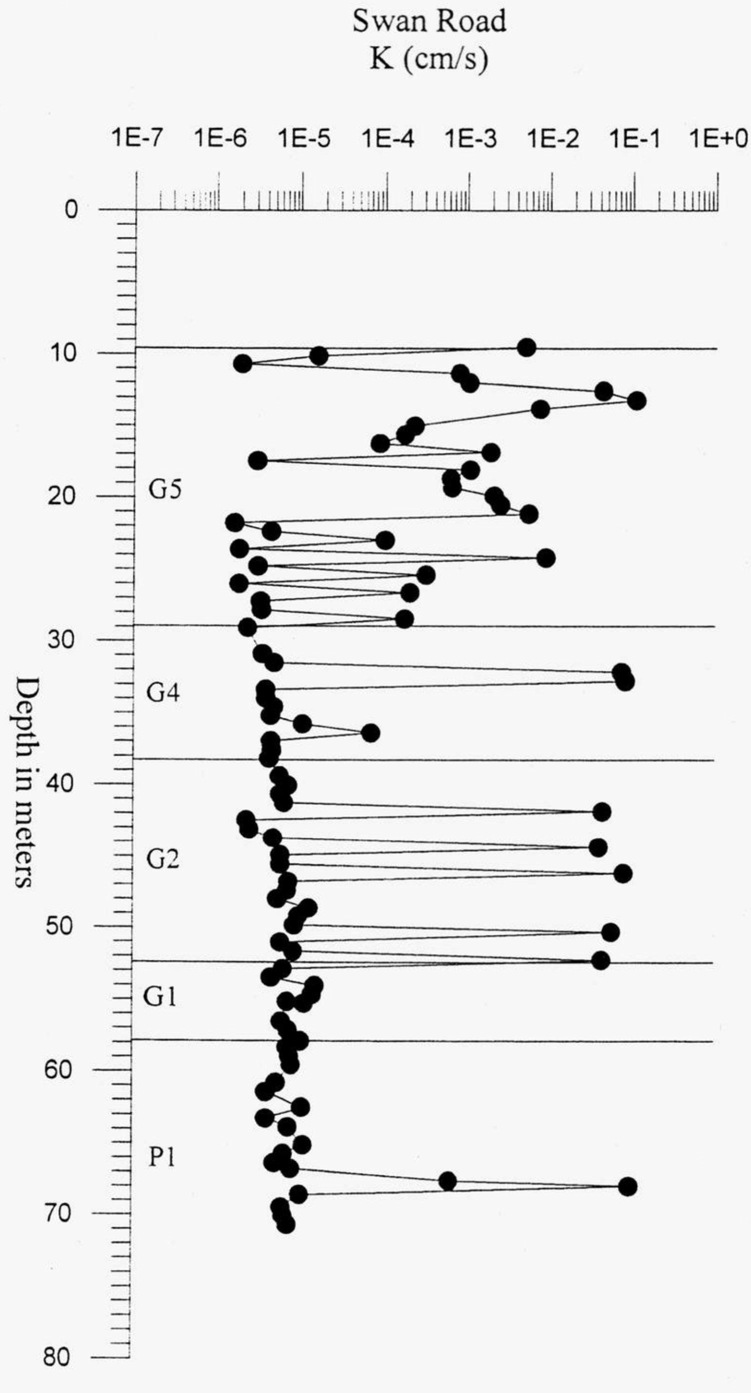
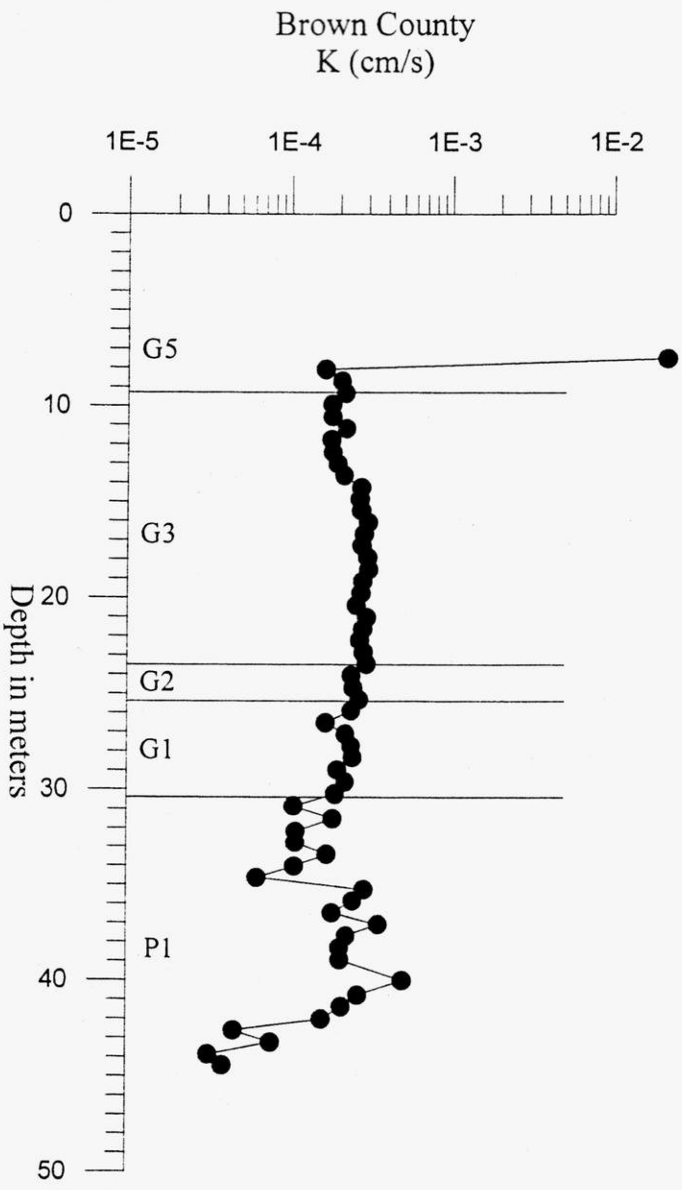


Figure 19. Vertical profile of hydraulic conductivity for the Ordovician corehole DG-1061



Brown County
K (cm/s)
1E-5
1E-4
1E-3
1E-2
0
10
20
30
40
50
Depth in meters
G5
G3
G2
G1
P1

cm/s in the southern corehole and 10^{-5} to 10^{-4} cm/s in the northern corehole) correspond to the intervals of fairly homogenous mudstone to wackestone lithologies common to the Platteville Formation. Moderate values, 10^{-4} to 10^{-3} cm/s, correspond to a variety of factors including increased dolomite granularity, increased bioturbation, and moderate occurrences of clay seams, vugs, and secondary porosity. These lithologies were common in the upper portions of the Galena Formation in both study areas. High K values, 10^{-2} to 10^{-1} cm/s, correspond to fracture and dissolution zones. Fractures preferentially occurred in intervals with abundant clay seams and at contacts between contrasting lithologies in both study areas. Fractures were the primary high-permeability features inferred from the flow transitions noted in the heatpulse, fluid temperature, and fluid resistivity logs.

Regional Correlation of Hydrostratigraphic Units

Six hydrostratigraphic units were defined for the OSG. The lithostratigraphic units were grouped into hydrostratigraphic units based on measured hydraulic conductivity values, fracture locations noted in the caliper logs and borehole videos, and high-permeability features as inferred by transitions in heatpulse flowmeter, fluid temperature, and fluid resistivity logs. Table 4 summarizes the hydrostratigraphic units, listing the lithostratigraphic units to which they correspond and their relative transmissivities based on lithologic descriptions, hydrogeologic data, and degree of fracturing.

The vertical hydraulic conductivity profiles for the two coreholes have been divided into the hydrostratigraphic units (Figures 19 and 20) and assigned relative transmissivities. Previous OSG hydraulic conductivity values, available from standard hydrogeologic field techniques such as open-hole pumping tests or slug-tests over longer intervals (see Stocks, 1998a for a Table of values), provided bulk measurements of K. While these values may be appropriate for large-scale regional models, they tend to underestimate both the values of and the variability in OSG hydraulic conductivity. This research shows that 1) there is significant south to north, lateral variability in hydraulic conductivity that corresponds to facies changes and 2) that fractures, which preferentially occur at contacts between contrasting lithologies and in lithofacies with high

Table 4. Summary of Ordovician Hydrostratigraphic Units

Hydrostratigraphic Units	P1	G1	G2	G3	G4	G5
Lithostratigraphic Units	B1-B6	C1	C2	C3	C4	C5-C6
Relative Transmissivity	Low in the south Low to moderate in the north	Low to Moderate	High	Moderate to High	Low to Moderate	High
Hydraulic Conductivity (cm/s)	South: 10^{-6} to 10^{-5} North: 10^{-5} to 10^{-4}	South: 10^{-6} to 10^{-5} North: 10^{-4}	Bimodal, 10^{-6} to 10^{-5} values alternating with 10^{-1} values	10^{-4} to 10^{-3}	10^{-6} to 10^{-5}	10^{-4} to 10^{-1} common 10^{-6} to 10^{-5} present
Degree of Fracturing and Dissolution	Fractures occur at lithologic contacts and are important transmissive features where they are present	Transmissive fractures are noted at the base and top of unit	Fractures common and transmissive, controlled by clay seems	Fractures occur at lithologic contacts and are important transmissive features where they are present	Fractures occur at lithologic contacts and are important transmissive features where they are present	Fractures and vugs are common and transmissive

percentages of clay seams, are important high-permeability pathways in several of the hydrostratigraphic units.

A regional hydrostratigraphic cross section was constructed and it illustrates the locations of the hydrostratigraphic units in regional wells based on geophysical correlations of the lithostratigraphic units (Plate 4a & b). Plate 4 has been divided into a northern and southern section; the Michels Jorgensen Quarry appears on both and can be used to tie the plate together. Hydrostratigraphic units were correlated based on their characteristic geophysical signatures and on quarry and core descriptions of previous research (Choi, 1998; Simo et. al, 1996). The hydrostratigraphic units provide regional estimates of the hydraulic properties of the OSG. The datum for the hydrostratigraphic cross section is the contact between the Platteville and Galena Formations which is easily recognizable in natural gamma logs. The cross section and the structure-contour maps of this surface (Figures 13 and 14) can be used to predict the locations and relative transmissivities of the various hydrostratigraphic units throughout the two study areas.

CONCLUSIONS

Hydraulic properties are quite variable and thus difficult to characterize in fractured-carbonate aquifers. From this work, it is apparent that both the occurrence of fracture-controlled high-permeability zones and the variation in matrix hydraulic conductivity in the Silurian and Ordovician dolomite aquifers are controlled by the stratigraphy. In the Silurian aquifer, we have been able to correlate 14 high-permeability zones by combining stratigraphic, geophysical, and hydrogeologic data (Figure 18). These zones parallel bedding, are regional in extent, and can be correlated in wells more than 16 kilometers apart. Several of these zones develop where open-marine and restricted-marine facies are juxtaposed. In the open-marine facies, these zones develop at bedding-plane discontinuities formed between units of contrasting texture. Within the restricted-marine facies, high-permeability features preferentially develop at contacts between contrasting lithologies (cycle boundaries). We were not able to correlate specific high-permeability features within either study area in the Ordovician Sinnipee Group. This may be due to greater lithologic variation or it may be that the smaller number of wells tested precluded collection of the detailed data that is necessary to identify and correlation these discrete features over regional distance. While we not able to correlate specific high-permeability features, the density of bedding-plane parallel fractures was clearly correlated to lithologic variation.

Flow in fractured aquifers depends, to a large degree, on the interconnectedness of the fracture network. In flat-lying fractured-sedimentary sequences, with relatively dense distributions of vertical fractures, the important control on the lateral movement of groundwater is the lateral continuity of the bedding-plane fractures. Recently, Michalski and Britton (1997) have suggested that a limited number of bedding plane fractures, that are laterally continuous over long distances (>500 m), dominate groundwater flow in fractured-sedimentary sequences. Several workers have recognized the importance of bedding-plane fractures in controlling flow within the Silurian aquifer (e.g., Sherrill 1978, Novakowski and Lapcevic 1988, and Yager 1997). Sherrill (1978) even suggested that these features were regional in scale. The spareness of his data and his use of long-interval hydraulic tests, however, limited the predictive capability of his interpretation. To date, however, no one has documented the lateral continuity of high-permeability features at regional scales. In the Silurian study area, the correlation of flow features in individual wells to specific stratigraphic interfaces makes a convincing argument that these features are laterally continuous over distances of 16 km. The hydraulic continuity of these regional high-permeability features can only be truly verified with hydraulic tests such as pumping or tracer tests. At distances of 16 km, the logistic and regulatory limitations make this infeasible.

The short-interval packer tests used in this study allow the correlation of matrix hydraulic conductivity with lithostratigraphic variation at a scale less than 1 m. This methodology proved useful for the development of regional hydrostratigraphic frameworks for both the Ordovician Sinnipee Group and the Silurian Dolomite. This study suggests that matrix conductivity is controlled by textural variations. In the Silurian, the coarser open-marine facies (Middle Shelf Facies Association) generally have higher matrix hydraulic conductivity than the finer-grained laminites of the Inner and Inner-Middle Shelf Facies Associations. Both the open-marine and restricted marine facies contain fractures and bedding-plane discontinuities that have been enhanced by dissolution. The frequency of high-permeability fractures, however, is greater in the restricted-marine facies.

In the Ordovician, there was significant vertical and lateral variability in the hydraulic conductivity measurements. The K distribution for the southern corehole (DG-1061) was highly variable compared to the northern corehole (BN-371). Based on correlations of hydraulic conductivity values with the lithologic descriptions, the lowest hydraulic conductivity values for each corehole correspond to the intervals of fairly homogenous mudstone to wackestone lithologies common to the Platteville Formation. Moderate hydraulic conductivity values correspond to a variety of factors including increased dolomite granularity, increased bioturbation, and moderate occurrences of clay seams, vugs, and secondary porosity. These lithologies were common in the upper portions of the Galena Formation in both study areas. High hydraulic conductivity values correspond to fracture and dissolution zones. Fractures preferentially occurred in intervals with abundant clay seams and at contacts between contrasting lithologies in both study areas. Fractures were the primary high-permeability features inferred from the flow transitions noted in the heatpulse, fluid temperature, and fluid resistivity logs. This research shows that 1) there is significant south to north, lateral variability in hydraulic conductivity that corresponds to facies changes and 2) that fractures, which preferentially occur at contacts between contrasting lithologies and in lithofacies with high percentages of clay seams, are important high-permeability pathways in several of the hydrostratigraphic units.

The vertical profiles of hydraulic conductivity collected in coreholes were used to define six hydrostratigraphic units for the OSG (Figures 19 and 20) and nine distinct hydrostratigraphic units with in the Silurian (Figure 15). These results, while regional in scale, can serve as a starting point for smaller-scale, site-specific groundwater investigations. Knowledge of the variation in matrix hydraulic conductivity and the frequency and occurrence of high-permeability fractures is important for the design of monitoring systems, the investigation and remediation of existing contaminant sources, and the development of groundwater protection plans.

The methodology used in this study should have wide applicability and be a useful tool for predicting both the vertical variability of hydraulic conductivity and the frequency and regional occurrence of high-permeability zones in other fractured-carbonate aquifers.

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Plate 1. Correlation of natural gamma logs and lithofacies patterns from selected wells and quarries in the Sturgeon Bay area

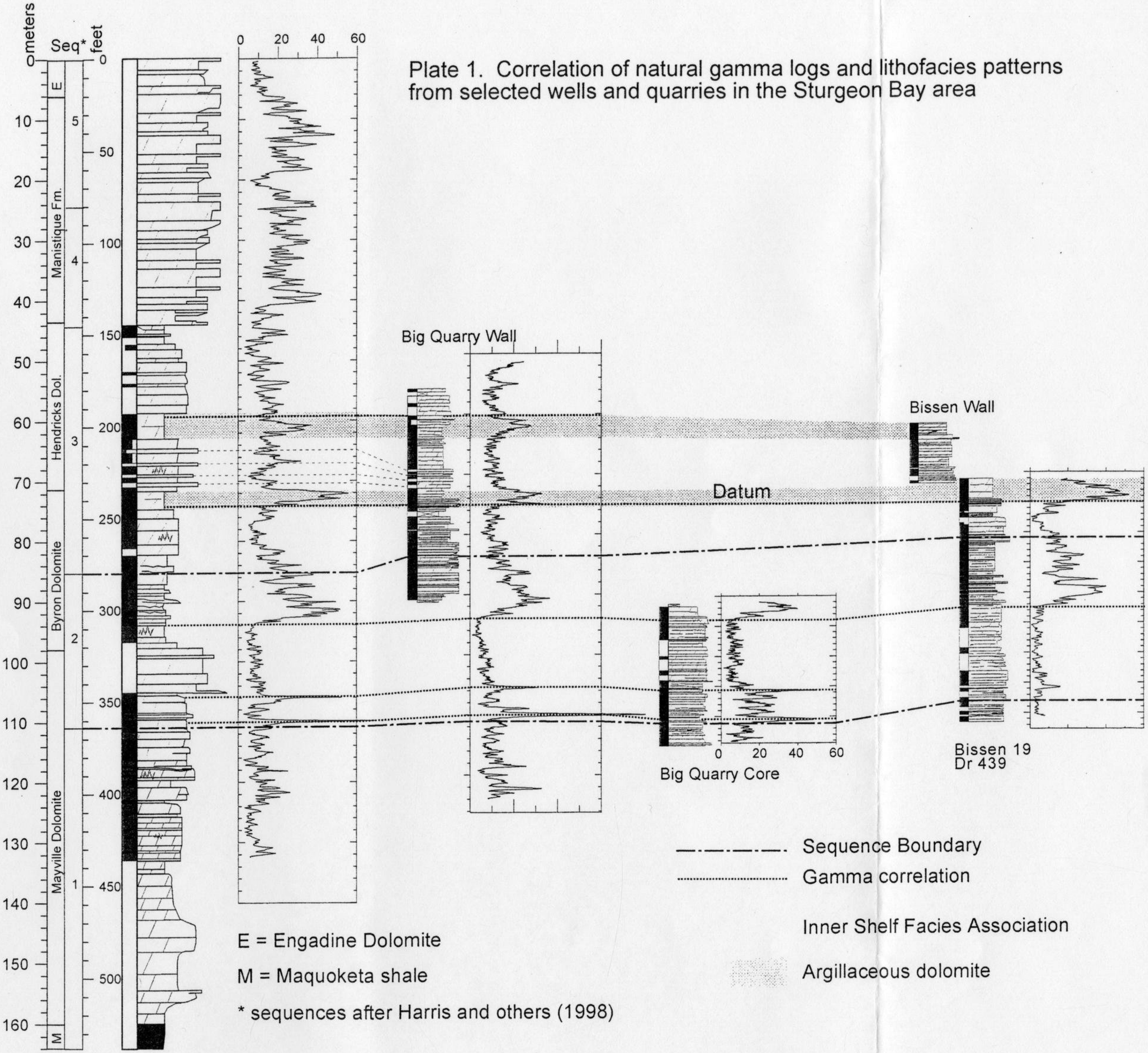


Plate 2. Gamma logs for southern study area showing correlated lithostratigraphic units. Datum is the Galena/Platteville contact. Logs are aligned on the line A-A' denoted in Figure 4.

Scales: Vertical axes show depth in meters below top of casing. Horizontal axes show natural gamma radiation in counts per second. Distance between wells is not to scale

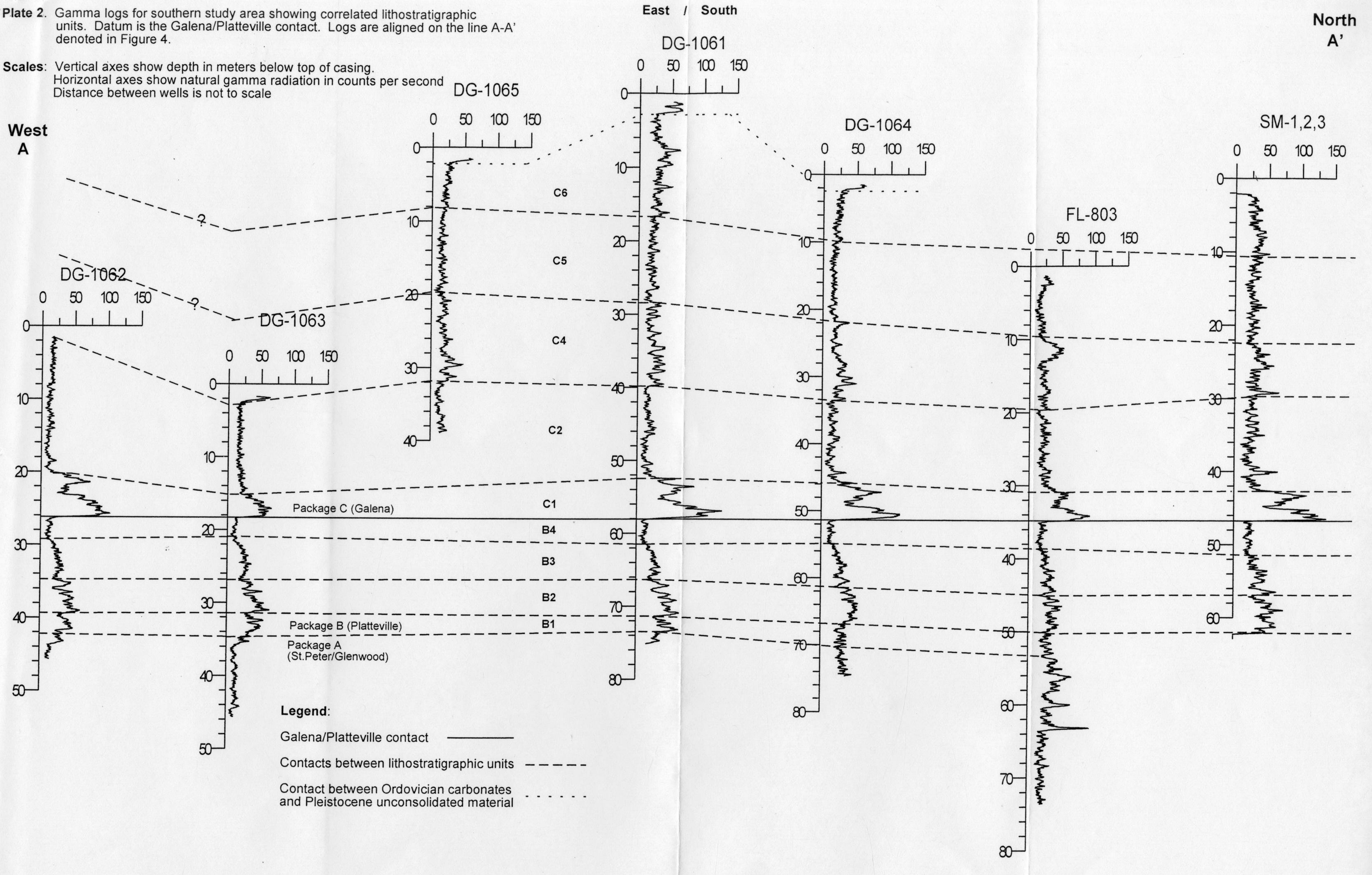
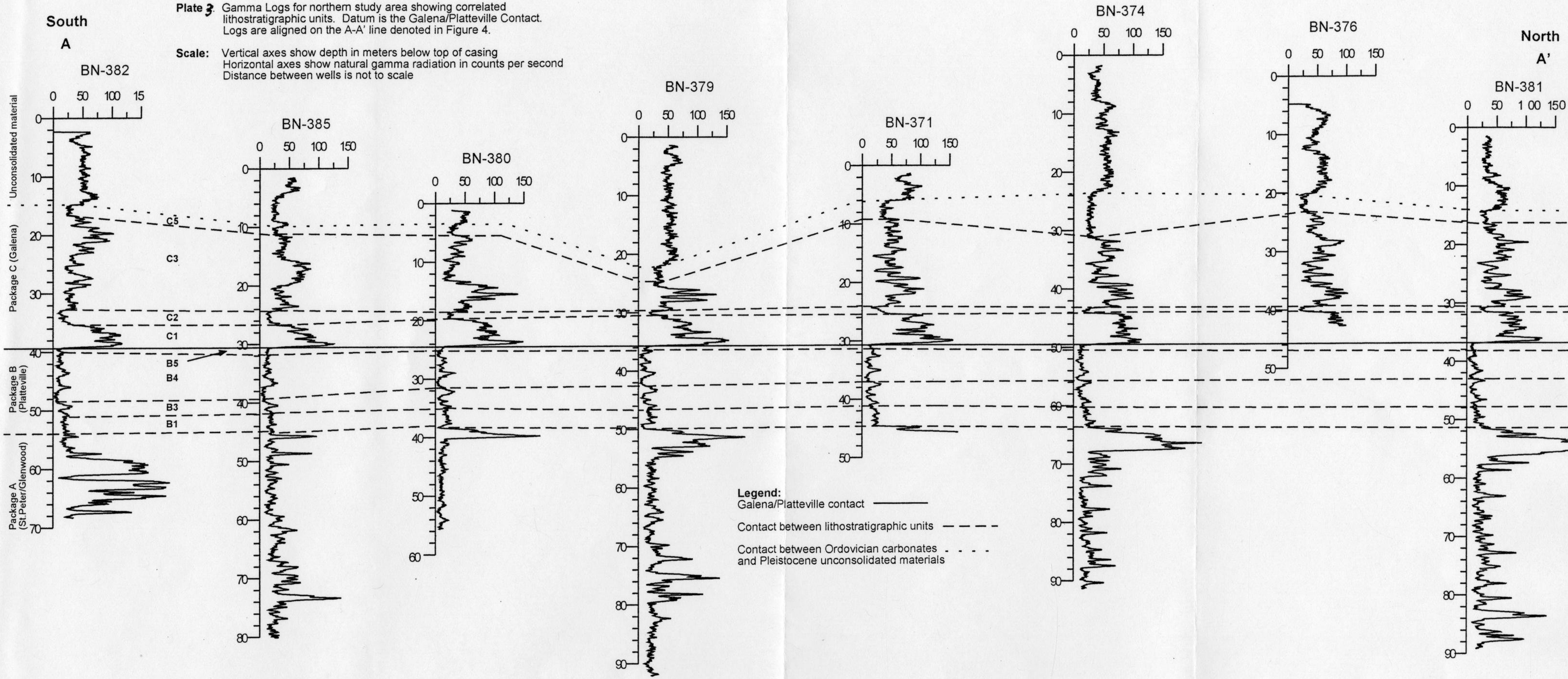


Plate 3. Gamma Logs for northern study area showing correlated lithostratigraphic units. Datum is the Galena/Platteville Contact. Logs are aligned on the A-A' line denoted in Figure 4.

Scale: Vertical axes show depth in meters below top of casing
Horizontal axes show natural gamma radiation in counts per second
Distance between wells is not to scale



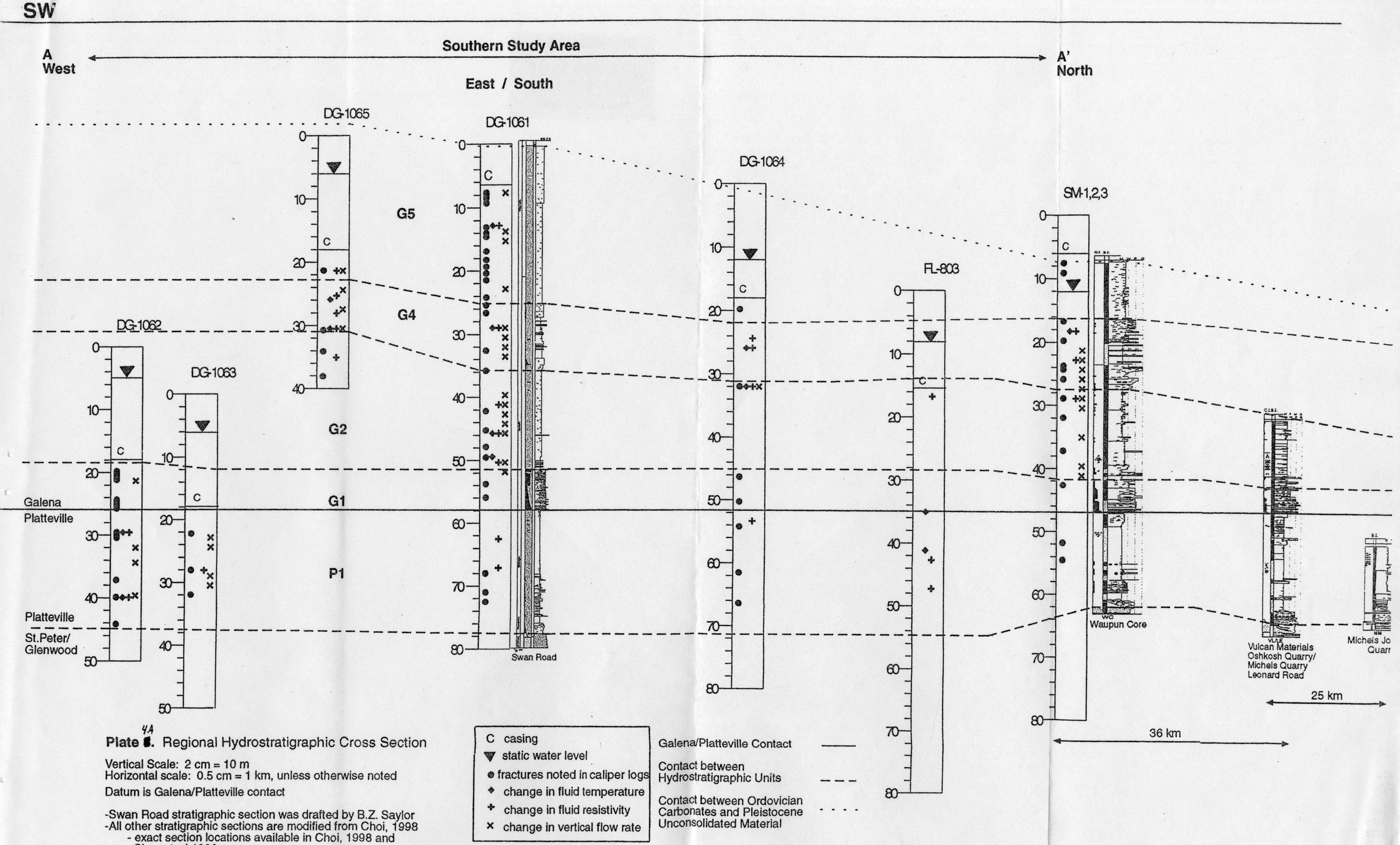
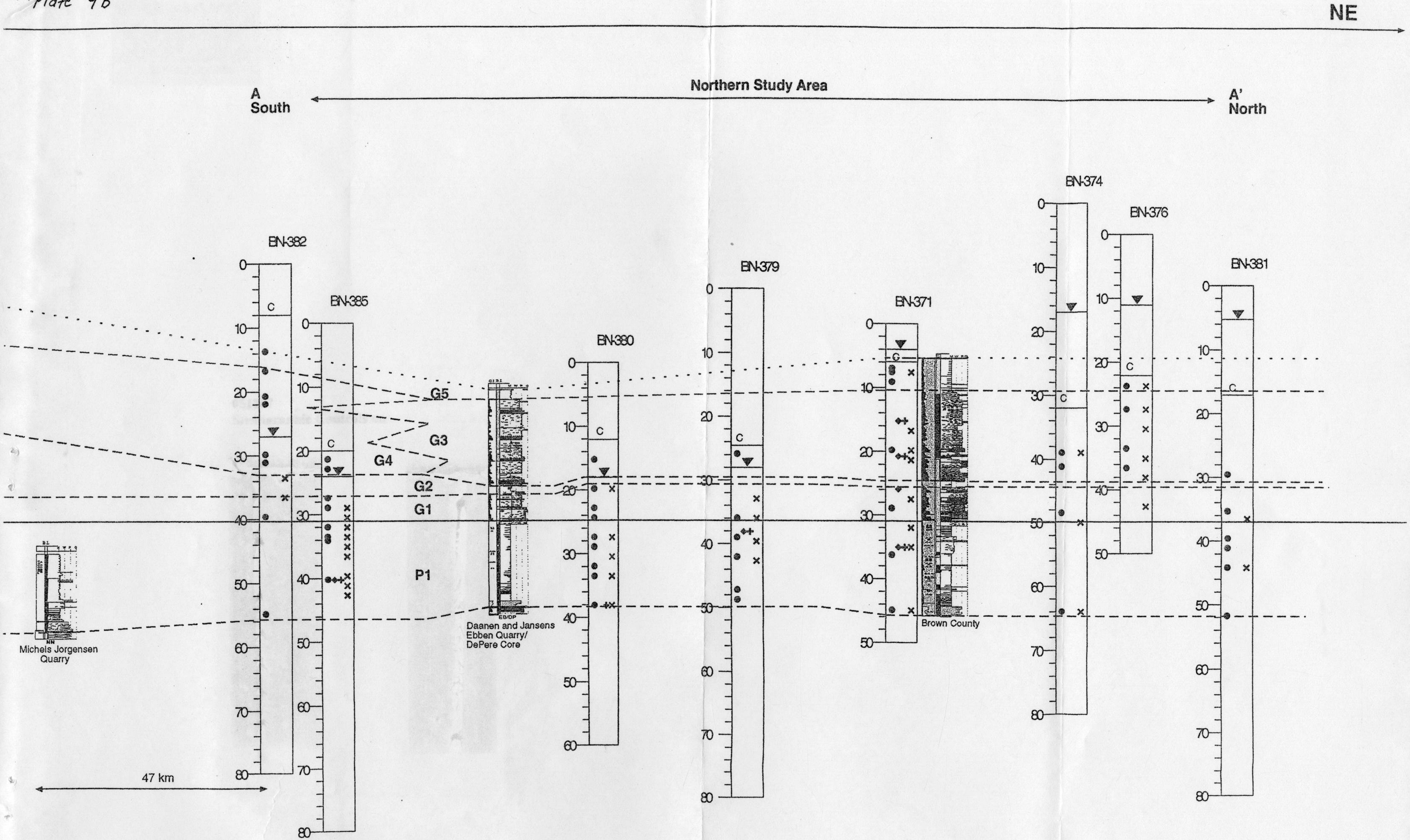


Plate 4A. Regional Hydrostratigraphic Cross Section

Vertical Scale: 2 cm = 10 m
Horizontal scale: 0.5 cm = 1 km, unless otherwise noted
Datum is Galena/Platteville contact

-Swan Road stratigraphic section was drafted by B.Z. Saylor
-All other stratigraphic sections are modified from Choi, 1998
   - exact section locations available in Choi, 1998 and Simo et. al 1996
-Legend for stratigraphic sections is in Appendix A

Plate 4b


NE
Northern Study Area
A
South
A'
North
BN-382
BN-385
BN-380
BN-379
BN-371
BN-374
BN-376
BN-381
G5
G3
G4
G2
G1
P1
Michels Jorgensen Quarry
Daanen and Jansens Ebben Quarry/ DePere Core
Brown County
47 km