Geol Survey

Hydrogeology of the Silurian Dolomite Aquifer in Parts of Northwestern Illinois

Timothy H. Larson • Anne M. Graese • Phillip G. Orozco

1993
ENVIRONMENTAL GEOLOGY 145

Department of Energy and Natural Resources
ILLINOIS STATE GEOLOGICAL SURVEY

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Natural Resources Building
615 East Peabody Drive
Champaign, IL 61820-6964

Cover photo Reef in the Silurian Racine Formation at Morrison, Whiteside County, Illinois. Photo by Anne M. Graese.

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FIGURES

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ABSTRACT

The Silurian dolomite aquifer within the Upper Bedrock Aquigroup in northwestern Illinois underlies more than 1,200 square miles in parts of six counties. The aquifer is divided into two units. The Blanding aquifer in the north is less than 100 feet thick and less productive than the Racine aquifer, which is up to 300 feet thick in the south and central parts of the area. The Silurian dolomite aquifer is used primarily for domestic supply; reports of yields greater than 100 gallons per minute (gpm) are rare. The dolomite aquifers are moderately to highly susceptible to contamination because of abundant vertical fractures exposed at or near the surface. The southwestern part of the region is an exception; there the overlying fine grained material is greater than 50 feet thick, resulting in lower susceptibility to contamination.

INTRODUCTION

The Silurian dolomite aquifer is a primary aquifer of the Upper Bedrock Aquigroup in northwestern Illinois (Visocky et al. 1985). Principally used for domestic water supply in northern Whiteside County, it could possibly sustain greater use throughout its region of occurrence (Csallany and Walton 1963). This shallow aquifer system can be highly susceptible to contamination where it occurs close to the ground surface or is overlain by coarse grained material because it is composed of fractured and relatively soluble carbonate rocks. The character of the shallow bedrock aquifers in the northwestern part of Illinois has not been studied in detail, despite its similarity to the character of the aquifer in northeastern Illinois, which has been studied in considerable detail (Suter et al. 1959, Zeizel et al. 1962, Hughes et al. 1966).

We have investigated the geology and hydrogeology of the Silurian dolomite aquifer of the Upper Bedrock Aquigroup in northwestern Illinois by studying the geologic framework and applying it to the hydrogeology of the region. The study area included all or part of six counties (Carroll, Whiteside, Lee, Rock Island, Henry, and Bureau) in northwestern Illinois where rocks of Silurian age occur at the bedrock surface (fig. 1). Although data available at the Illinois State Geological Survey (ISGS) are relatively sparse for this region, meaningful generalizations are possible about the geology and hydrogeology of this region.

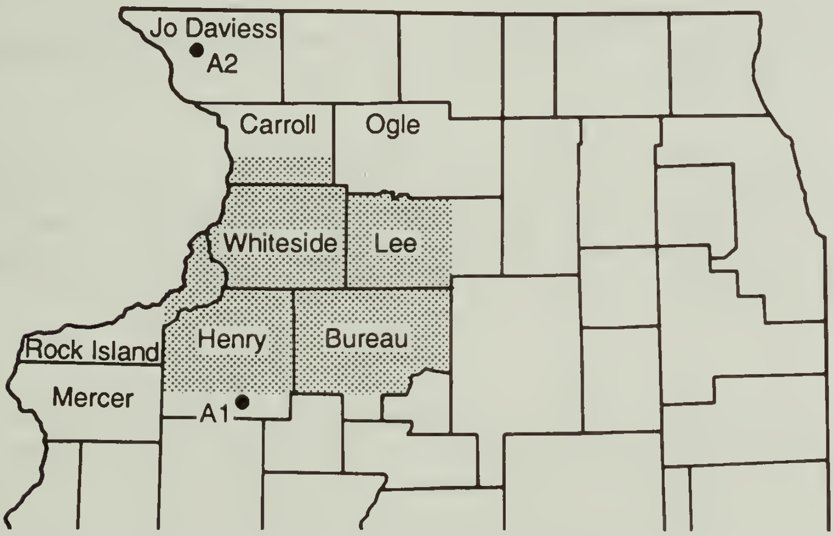


Figure 1 Study area in northwestern Illinois and locations of cores A1 and A2.

METHODS

Data from ISGS files were supplemented by field investigations of quarries and outcrops in the study area. Two cores (appendix A) and 114 sample sets (appendix B) were examined, and another 238 well descriptions were used for the geologic framework analysis. The hand specimens and thin sections of the cores were described using both standard illumination and cathodoluminescence. The mineralogy of the cores also was analyzed by x-ray diffraction. Small plugs were cut from the cores to determine permeability and porosity. We also compiled a database of more than 2,400 values representing water well drilling records for use in determining bedrock surface elevation (D. Larson et al. in press).

We selected six samples from each of the two available cores for detailed analysis. Although the samples are considered to be representative of the various lithologies present, they do not constitute a valid statistical population. The samples are identified by county (JD for Jo Daviess and HEN for Henry) and depth in feet. From each sample we prepared one polished thin section and one thin section stained with potassium ferricyanide and Alizarin Red S staining solution. The stained thin sections were examined by petrographic microscopy to identify minerals and to estimate amount and type of porosity. The polished thin sections were examined with cathodoluminescence to identify generations of carbonate minerals. A portion of each sample was crushed and analyzed using x-ray diffraction to identify minerals, especially carbonate types and clay minerals. Porosity and permeability were measured on 1-inch diameter plugs that were cut from the cores at the same locations as the thin sections.

The entire Silurian sections of the cores were examined visually for lithologic characteristics, and throughgoing vugs and fractures were noted in the Henry County core. This provided an independent analysis of the porosity at a slightly larger material scale than that obtained from the small diameter plugs. The 114 sample sets available at the ISGS were examined visually for lithologic character and color changes that indicate weathering.

GEOLOGIC FRAMEWORK

Carbonate rocks of the Hunton Supergroup (Willman et al. 1975) cover about 1,600 square miles of the bedrock surface in parts of nine counties of northwestern Illinois. Although the Hunton includes rocks of both Silurian and Devonian age (fig. 2), this report is limited to Silurian rocks. These same rocks extend to the southwest beneath younger strata and underlie another 3,600 square miles in the study area. The geologic framework for the Silurian rocks has not been as well developed as the underlying Maquoketa, Galena, and Platteville Groups. For this report, the geologic analysis of the Silurian is based on our examination of two cores, 114 sample sets, and 238 well descriptions.

Previous Studies

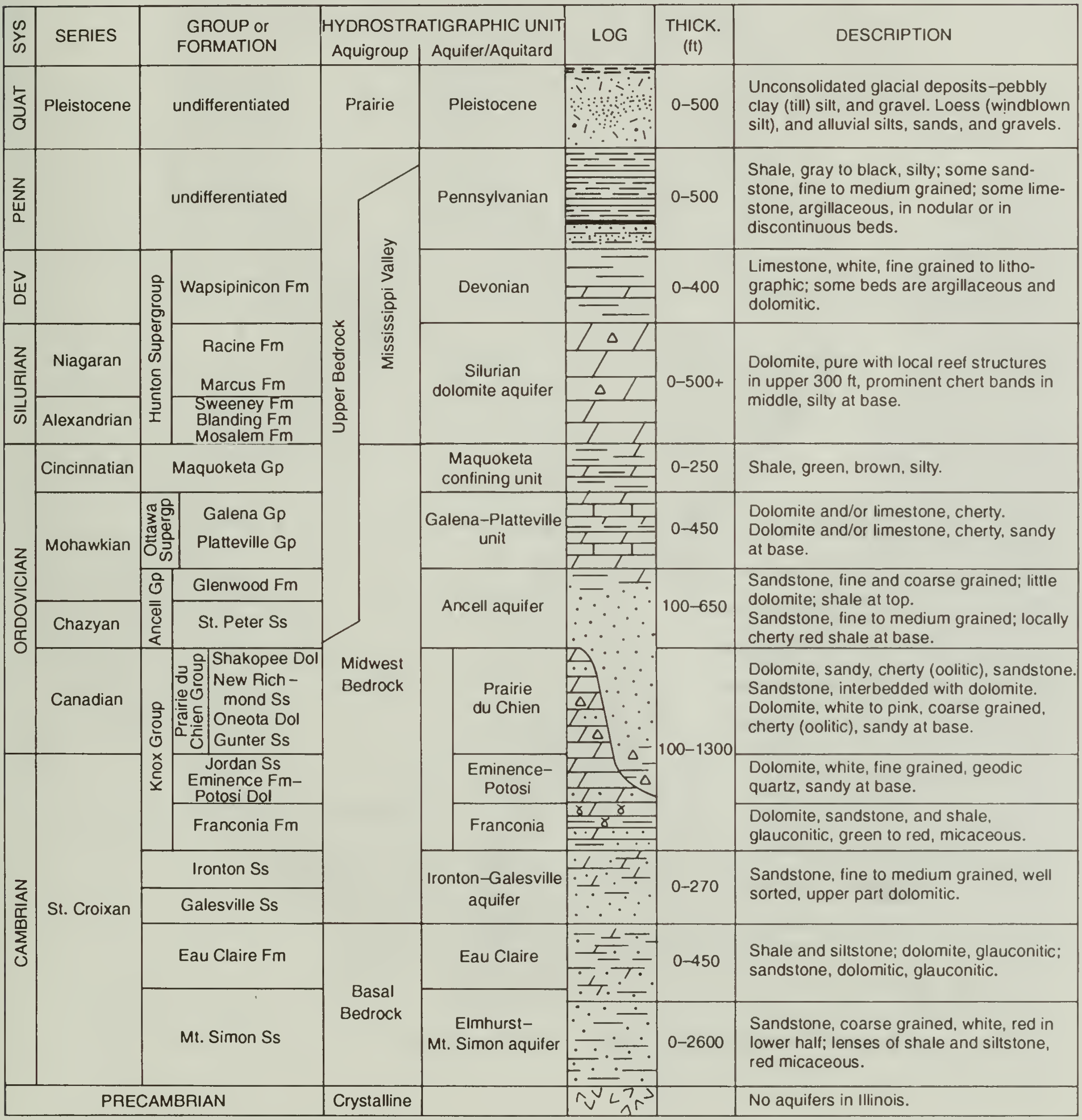
Although the general geologic setting of the region has been known for many years, detailed stratigraphic relationships have only more recently been described. The geology and groundwater characteristics of the Ancell Group rocks were summarized in Visocky et al. (1985). The Galena and Platteville Groups were described by Willman and Kolata (1978). The Maquoketa Group rocks, which occur at the bedrock surface in north-central Illinois, were described by Kolata and Graese (1983). Willman (1973) defined the stratigraphy for the Silurian-aged rocks in northeastern and northwestern Illinois.

Detailed information is available from two recent investigations east of the study area: the Silurian and uppermost Ordovician rocks encountered by the Tunnel and Reservoir Plan (TARP) project beneath Chicago (Harza Engineering 1984), and lower Silurian and Ordovician rocks in the study of the proposed site for the Superconducting Super Collider (SSC) (Graese et al. 1988). Also available is detailed information on the geology of the Plum River Fault Zone (Kolata and Buschbach 1976, Bunker et al. 1985).

Stratigraphy

The Silurian System in the study area includes from the base to the top: the Mosalem, Tete des Morts, Blanding, Sweeney, Marcus, and Racine Formations. The units were described by Willman (1973) and Willman et al. (1975). The Silurian is completely eroded in the northern part of the study area in Carroll, Whiteside, and northern Lee Counties. The thickness is greater than 500 feet at the southern margin of the area. The carbonates are more shaley at the base of the Silurian (Mosalem, Tete des Morts, Sweeney, and Blanding Formations), which is exposed at the bedrock surface in the northern and eastern part of the study area (figs. 3a and 3b), and less shaley towards the top of the Silurian (Marcus and Racine Formations), which is exposed in the central and southern part of the study area. The Silurian System is overlain in the south by the Pennsylvanian System in Bureau and Henry counties, and overlain by the Devonian System in southern Rock Island County. Devonian and Pennsylvanian units were described by Willman et al. (1975).

Mosalem Formation The Mosalem Formation is named for Mosalem Township in Dubuque County, Iowa (Brown and Whitlow 1960), and is the basal formation in the Alexandrian Series in northwestern Illinois. The Mosalem is well exposed in many places in northwestern Illinois, north of the Plum River Fault Zone, and fills channels as much as 100 feet thick. The unit thickens from a featheredge to more than 80 feet. Typically, records indicate that thickness values are from 10 to 30 feet or not present. It consists of gray, cherty, even to wavy, medium bedded dolomite; the lower part grades to very argillaceous dolomite, which then grades to dolomitic shale at the base. Algal laminae can be observed in the Mosalem at the Emerson quarry (primarily in NW, 36, T21N, R6E). The contact with the Maquoketa occurs at the top of the first soft greenish gray shale in contrast to the gray shale of the Mosalem. The top of the Mosalem is characterized by a dark gray, pitted surface.



SYS	SERIES	GROUP or FORMATION		HYDROSTRATIGRAPHIC UNIT Aquigroup	Aquifer/Aquitard	THICK. (ft)	DESCRIPTION
QUAT	Pleistocene	undifferentiated		Prairie	Pleistocene	0–500	Unconsolidated glacial deposits–pebbly clay (till) silt, and gravel. Loess (windblown silt), and alluvial silts, sands, and gravels.
PENN		undifferentiated		Upper Bedrock Mississippi Valley	Pennsylvanian	0–500	Shale, gray to black, silty; some sandstone, fine to medium grained; some limestone, argillaceous, in nodular or in discontinuous beds.
DEV		Hunton Supergroup	Wapsipinicon Fm		Devonian	0–400	Limestone, white, fine grained to lithographic; some beds are argillaceous and dolomitic.
SILURIAN	Niagaran		Racine Fm Marcus Fm		Silurian dolomite aquifer	0–500+	Dolomite, pure with local reef structures in upper 300 ft, prominent chert bands in middle, silty at base.
	Alexandrian		Sweeney Fm Blanding Fm Mosalem Fm				
ORDOVICIAN	Cincinnatian	Maquoketa Gp		Midwest Bedrock	Maquoketa confining unit	0–250	Shale, green, brown, silty.
	Mohawkian	Ottawa Supergp	Galena Gp Platteville Gp		Galena–Platteville unit	0–450	Dolomite and/or limestone, cherty. Dolomite and/or limestone, cherty, sandy at base.
		Ancell Gp	Glenwood Fm		Ancell aquifer	100–650	Sandstone, fine and coarse grained; little dolomite; shale at top. Sandstone, fine to medium grained; locally cherty red shale at base.
	Chazyan		St. Peter Ss				
	Canadian	Knox Group Prairie du Chien Group	Shakopee Dol New Richmond Ss Oneota Dol Gunter Ss		Prairie du Chien	100–1300	Dolomite, sandy, cherty (oolitic), sandstone. Sandstone, interbedded with dolomite. Dolomite, white to pink, coarse grained, cherty (oolitic), sandy at base.
CAMBRIAN	St. Croixan		Jordan Ss Eminence Fm–Potosi Dol		Eminence–Potosi		Dolomite, white, fine grained, geodic quartz, sandy at base.
			Franconia Fm		Franconia		Dolomite, sandstone, and shale, glauconitic, green to red, micaceous.
		Ironton Ss			Ironton–Galesville aquifer	0–270	Sandstone, fine to medium grained, well sorted, upper part dolomitic.
		Galesville Ss					
		Eau Claire Fm		Basal Bedrock	Eau Claire	0–450	Shale and siltstone; dolomite, glauconitic; sandstone, dolomitic, glauconitic.
		Mt. Simon Ss			Elmhurst–Mt. Simon aquifer	0–2600	Sandstone, coarse grained, white, red in lower half; lenses of shale and siltstone, red micaceous.
PRECAMBRIAN				Crystalline			No aquifers in Illinois.

Figure 2 Stratigraphy and hydrostratigraphy of the rocks in the study area (modified from Visocky et al. 1985).

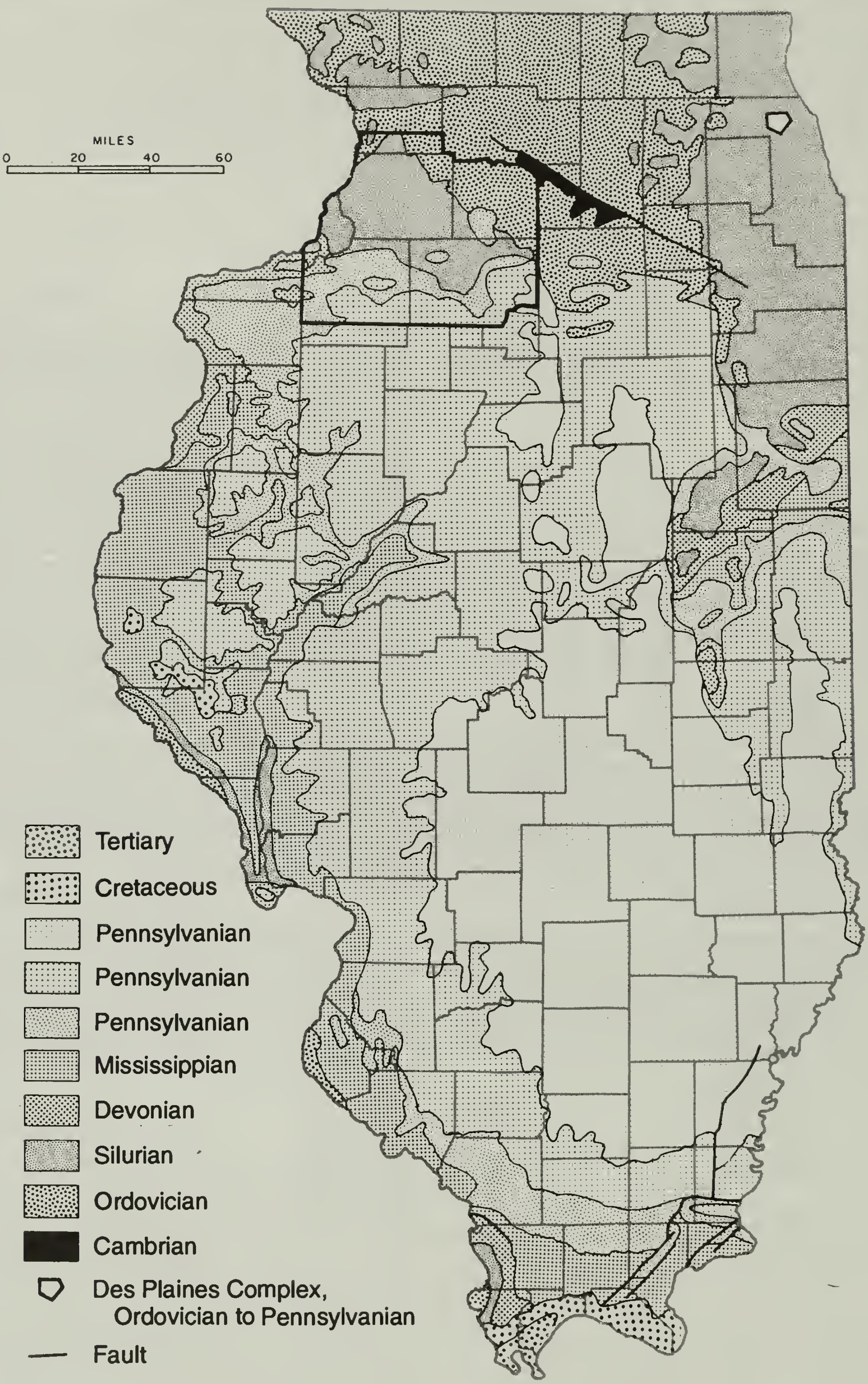


Figure 3a Geologic map of Illinois with study area indicated.

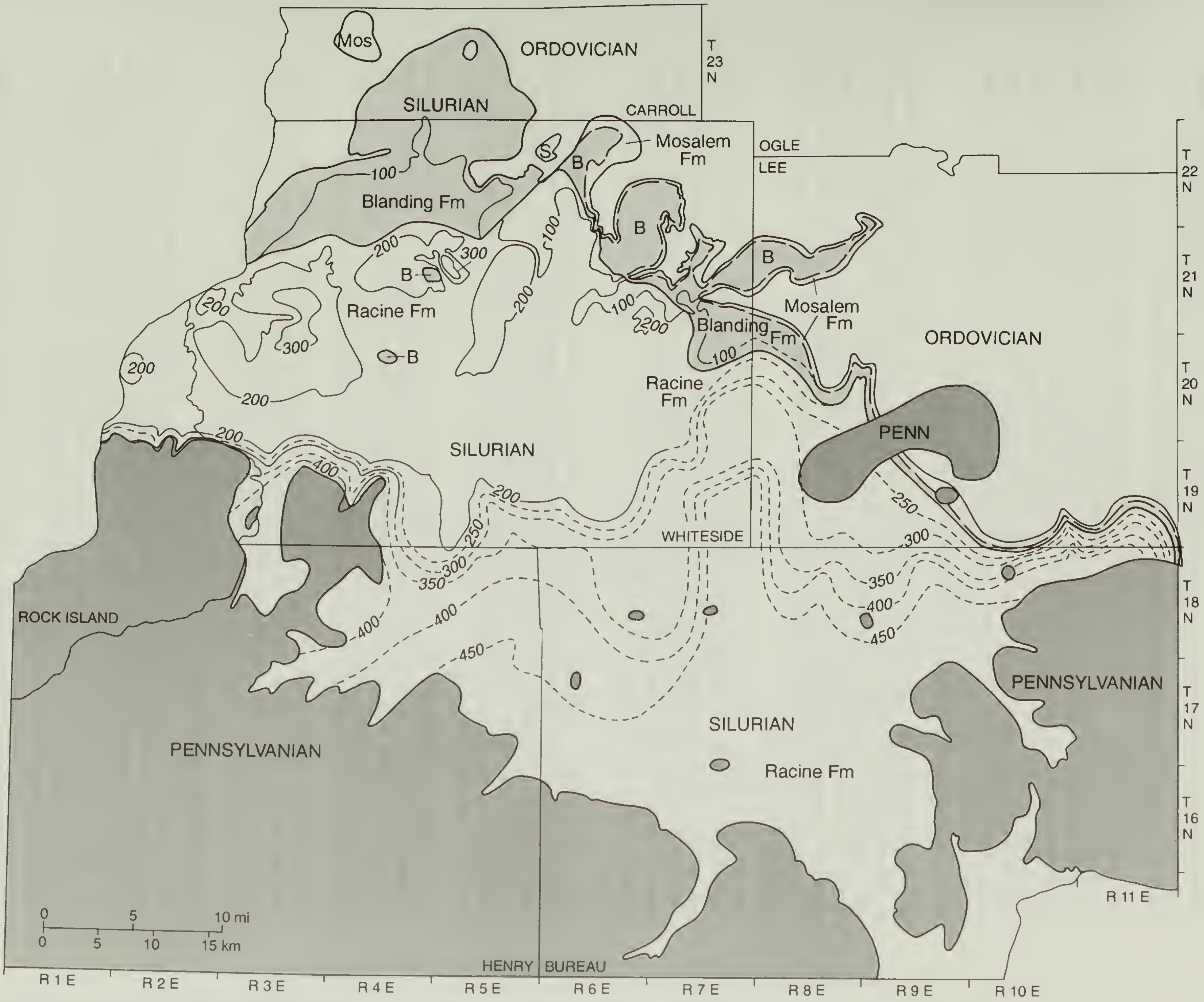


Figure 3b Geologic map of the Silurian System for the study area. Combined thickness of Silurian units in feet.

Tete des Morts Formation The Tete des Morts Formation, named for Tete des Morts Creek in Dubuque County, Iowa, overlies the Mosalem Formation in northwestern Illinois, typically north of an east-west line through Hanover in Jo Daviess County. The type section is located at the same exposure as the type section of the Mosalem Formation (Willman et al. 1975). At the type section, the Tete des Morts Formation is 24 feet thick. In the study area it is absent.

Blanding Formation The Blanding Formation (Willman 1973), which overlies the Tete des Morts Formation (or the Mosalem Formation where the Tete des Morts is absent) in northwestern Illinois, is named for the Village of Blanding, Jo Daviess County, 3 miles south of the type section in the upper part of the Mississippi River bluffs where the formation is 51.5 feet thick. The Blanding is commonly 35 to 50 feet thick in the study area. The unit consists of pale yellowish brown to light olive gray, fine grained, slightly argillaceous to pure dolomite in 2 to 6 inch beds. It contains layers of white chert, most of which are 1 to 3 inches thick and commonly separated by 4 to 6 inches of dolomite. In some localities, chert forms 50% of the upper part of the formation. The Blanding Formation is similar in lithology to the Elwood Formation in northeastern Illinois.

Sweeney Formation The Sweeney Formation (Willman 1973), named for the Sweeney Islands in the Mississippi River, a short distance west of the type section, is exposed in the bluffs in Mississippi Palisades State Park, north of Savanna, Carroll County, where the formation is 55 feet thick. The Sweeney is pinkish to greenish gray, vesicular, pure dolomite in beds 1 to 4 inches thick with thin greenish gray clay partings or laminae. The unit is equivalent to the upper part of the Hopkinton in Iowa and tentatively correlated with the Kankakee and the Sexton Creek Formations elsewhere in Illinois.

Marcus Formation The Marcus Formation (Willman 1973) is the basal Niagaran Series unit in northwestern Illinois. It is named for Marcus, Carroll County, 4 miles northwest of the type section, which is located in an abandoned quarry in the southern part of Mississippi Palisades State Park (SW SE SE, Sec. 33, T25N, R3E), where it is 40 feet thick. It consists of pure, vesicular, brown, massive dolomite. The base of the unit contains abundant molds and casts of pentamerid brachiopods, which also are common in the upper part of the formation along with other fossils, particularly corals.

Racine Formation The Racine Formation, named for exposures in quarries at Racine, Wisconsin, is the uppermost Niagaran Formation in northern and western Illinois. The quarries at Racine are in reefs. In northwestern Illinois, reef structures are not as common as they are in Wisconsin or northeastern and central Illinois, and most of the Racine consists of flat-lying, pure dolomite. The interreef rocks are commonly argillaceous, silty, and cherty (nodules), whereas the cores of the reefs are pure, vesicular, and vuggy.

Known reefs in northwestern Illinois where Silurian rocks are at the bedrock surface include one near Morrison and three along the outcrop belt north of Moline (Whitaker 1988). In the northeast quarter of Section 21, T20N, R3E, anticlines were noted by Leighton (1922). Although nothing is visible now, a nearby rock quarry in Section 11, T21N, R2E, shows mud mound/reef structures about 20 feet thick and draped by layers of fine grained material. The mounds are relatively nonporous.

The Racine Formation thickens (fig. 4) southward toward the Illinois Basin. At the margin of the Pennsylvanian, the Racine reaches a thickness of more than 300 feet. The Racine thins to an erosional edge in northern Whiteside, Carroll, and Lee Counties. There are some Pennsylvanian outliers throughout the area, including one extending over three townships in Lee County.

Weathering Character

Wells finished in these dolomites yield water primarily from cracks and solution openings near the bedrock surface (Foster 1956, Brueckmann and Bergstrom 1968). Assuming that weathering is evidence for preferential groundwater flow, we examined outcrops and sample sets in the study area for signs of weathering (appendix C). In outcrops and whole cores, we were able to determine the qualitative degree of chemical weathering, seen as dissolution of cracks and vugs. Analysis of sample sets, which consist of rock cuttings, is based on gradations of rock color. Thickness of the weathered zone is shown in figure 5.

The units show few signs of weathering, except in the northern and western parts of the study area where the drift is thinner, generally less than 50 feet. Extensively weathered areas are primarily within the Racine Formation on bedrock uplands. There are three areas, each several miles across,

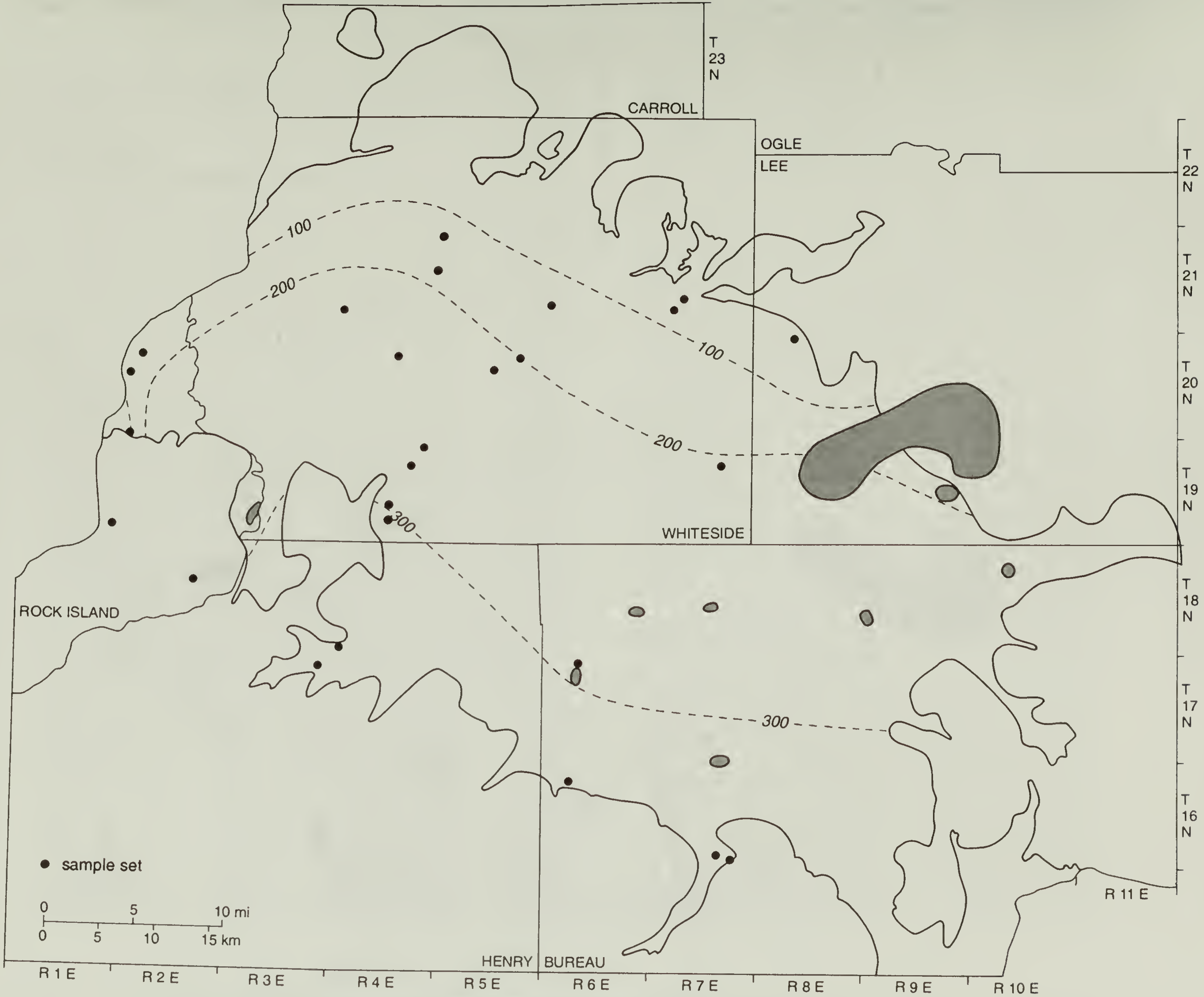


Figure 4 Combined thickness (ft) of the upper units — Racine and Marcus. Pennsylvanian strata are shaded only within the area of interest.

Figure 5 Thickness (ft) of weathering in the study area. Pennsylvanian strata are shaded only within the area of interest.

where the weathering thickness is up to 200 feet or more (fig. 5); they are located in T20N, R5E; T20N, R2E; and T19N, R4E. Eight small weathered areas, up to 1 mile in diameter, were also found. Samples from most of the remaining area had no observable weathering.

HYDROGEOLOGIC FRAMEWORK

Previous Studies

The most recent discussion of the regional hydrogeology of the Upper Bedrock Aquigroup was presented by Visocky et al. (1985); however, that report dealt primarily with the deeper Midwest Bedrock Aquigroup. Much of the information in that report dealing with the Galena–Platteville unit is also pertinent to the Upper Bedrock Aquigroup. Information from the TARP and SSC sites provides the most recent insights into the detailed hydrogeologic setting of the Upper Bedrock Aquigroup, particularly for the Silurian rocks in northeast Illinois and the upper Ordovician rocks in north-central Illinois. An investigation of the hydrogeology of the Silurian rocks in Iowa (Wahl and Bunker 1986) provides the most recent detailed study of the flow system expected in northwestern Illinois.

Previously, a series of reports prepared by the ISGS and the Illinois State Water Survey described the regional hydrogeology of portions of the aquigroup. The most comprehensive of the reports (Csallany and Walton 1963) incorporated a large amount of information primarily concerning the Silurian dolomite aquifer in Du Page County, but also including data from the rest of northern Illinois. Other relevant reports describe the groundwater resources and hydrogeology in Lee and Whiteside Counties (Hanson 1955, Foster 1956), Winnebago County, (Hackett 1960), Du Page County (Zeizel et al. 1962), west-central Illinois (Brueckmann and Bergstrom 1968), and the Chicago region (Suter et al. 1959, Hughes, et al. 1966). These detailed reports describe the groundwater geology of each different bedrock terrain in northern Illinois and serve as a basis for future study. Groundwater pumpage in northern Illinois, including Lee and Whiteside Counties, was surveyed in 1970 (Sasman et al. 1974). Another series of reports concerning the regional hydrogeology of portions of northern Illinois (Bergstrom 1956, Bergstrom et al. 1955, Bergstrom and Zeizel 1957, Hackett and Bergstrom 1956, Selkregg and Kempton 1958) provides only general information.

Hydrostratigraphy

Hydrostratigraphic units for Illinois (fig. 2) were defined by Visocky et al. (1985), from whom the following definitions were taken. Hydrogeologic units are divided into three major aquisystems, each of which is subdivided into aquigroups. Detailed study of the Silurian dolomite aquifer has shown that hydraulic properties vary substantially in different lithologic units.

Midwest Bedrock Aquigroup In northern Illinois, the Midwest Bedrock Aquigroup consists of rock from the base of the Galesville Sandstone through the top of the Maquoketa Group, except where these rocks occur at the surface or beneath nonindurated deposits of the Prairie Aquigroup. The Midwest Bedrock Aquigroup is characterized by intermediate and regional groundwater flow systems in indurated rock that are overlain by indurated rock confining units. The top of the aquigroup is defined as the top of the Maquoketa Group or other confining units where the Maquoketa is absent. The base of the aquigroup is at the top of the Eau Claire Formation or stratigraphically higher where the Ironton and Galesville Sandstones are absent. This aquigroup is basically the same as the Cambrian–Ordovician Aquifer previously defined in northeastern Illinois (Suter et al. 1959).

Upper Bedrock Aquigroup The Upper Bedrock Aquigroup is basically the same as the shallow dolomite aquifer previously defined in northern Illinois (Suter et al. 1959). This aquigroup consists of local and intermediate flow systems in indurated sediments with open connection to the Prairie Aquigroup, thus its water quality is similar to that of the Prairie Aquigroup.

The Galena–Platteville unit, the Maquoketa confining unit, and locally the Ancell aquifer become part of the Upper Bedrock Aquigroup in north-central Illinois, where they are exposed at the surface or overlain by glacial deposits. These aquifers are moderately productive. In this region, dissolution of the rock by groundwater has occurred, enlarging the joints and fractures in the rock and increasing its permeability. The degree of jointing, fracturing, and dissolution decreases with increasing depth of penetration in the rock. Most of the water is obtained from the uppermost 100 feet of rock (Bruekmann and Bergstrom 1968).

The most significant and productive aquifer of the aquigroup is the Silurian dolomite aquifer, which underlies the study area in northwestern Illinois and much of northeastern Illinois. In these areas, large yields are sometimes obtained, reducing the dependence on the Midwest Bedrock Aquigroup.

Other significant aquifers that make up the Upper Bedrock Aquigroup in northwestern Illinois are the Galena–Platteville unit in the northwestern part of the region and the Devonian and Mississippian carbonate rocks in the southwestern part of the region.

Prairie Aquigroup This aquigroup consists of local and intermediate flow systems in nonindurated geologic materials. The major component of recharge to the system is local precipitation. The aquigroup is confined locally by fine grained nonindurated sediments. In some regions, the Prairie Aquigroup is 400 to 500 feet thick; whereas in others, it is absent or up to 50 feet thick. Two major aquifers are present in the Prairie Aquigroup in this region. The upper aquifer is about 50 feet thick and separated from the lower aquifer by an interval of fine grained lake sediments. The lower aquifer fills a major buried bedrock valley system and exceeds 150 feet thick in some places. (D. Larson et al. in press).

Aquifers and Aquitards in the Upper Bedrock Aquigroup

Ancell Aquifer The St. Peter Sandstone and the overlying Glenwood Sandstone form the Ancell aquifer. It is widespread in the north-central United States and is present under the entire state of Illinois, except where it has been eroded. This aquifer is locally included in the Upper Bedrock Aquigroup, where it occurs at the bedrock surface. At some locations in northern Illinois, only a thin section of fractured dolomite of the Galena–Platteville unit overlies the Ancell aquifer. In these transitional regions, the Ancell aquifer is provisionally assigned to the Midwest Bedrock Aquigroup, but is hydraulically connected to the Upper Bedrock Aquigroup. At most locations in the state, the Ancell aquifer is separated from the overlying Galena–Platteville unit by either non-water-bearing carbonates or confining shale beds in the upper Glenwood Sandstone.

The thickness averages about 200 feet; however, the thickness ranges greatly from less than 100 feet to more than 600 feet. The thickening reflects the irregular base of the formation; the upper surface is regular. The lower Kress Member, which accounts for much of the increase in thickness, frequently adds little to the yield of wells, being a rubble-like deposit in a clay or shale matrix. Thus, increases in yield are not proportional with increases in thickness.

Galena–Platteville Unit The Galena–Platteville unit is found through most of Illinois and is usually considered to be in the Midwest Aquigroup. It overlies the Ancell aquifer and sometimes forms part of the confining unit for that aquifer, although it is locally productive. In northeastern Illinois and south of the Illinois River, the Galena–Platteville unit is overlain by the Maquoketa Group or younger shales. In northwestern Illinois the Galena–Platteville unit immediately underlies glacial deposits or is exposed at the surface. In this region, the Galena–Platteville dolomites become part of the Upper Bedrock Aquigroup where they are considered to be dependable, though not large, suppliers of water.

Maquoketa Confining Unit In northern and western Illinois, the Maquoketa Group, where present, forms the principal confining bed separating the Upper Bedrock Aquigroup from the lower Midwest Bedrock Aquigroup. Where the Maquoketa directly underlies the glacial deposits, it is included as part of the Upper Bedrock Aquigroup and limited amounts of water are obtained from joints and fractures.

Silurian Dolomite Aquifer The Silurian dolomite aquifer immediately underlies the glacial deposits throughout the northwestern Illinois study area and much of northeastern Illinois. In these regions, it is the principal aquifer of the Upper Bedrock Aquigroup. It attains thicknesses up to 1,000 feet in northeastern Illinois and 400 feet in northwestern Illinois. It has produced 2,000 gpm at one location in east-central Whiteside County (Csallany and Walton 1963), but typically produces between 25 and 50 gpm in northern Whiteside County. At present, it is used almost exclusively for domestic or small industrial purposes (Sasman et al. 1974). Because most water is produced from open fractures in the upper part of the rock, the aquifer is potentially susceptible to contamination.

Production from the aquifer is variable and difficult to predict from place to place; however, several factors are known to influence the formation of fractures and dissolution enlargement of existing fractures. In northeastern Illinois, production is influenced by the occurrence of shale zones that act as local semiconfining units (Hughes et al. 1966). The Brandon Bridge Member of the Joliet Formation (previously known as the Lower Niagaran shale unit) is an example of a discontinuous shale, which effectively reduces aquifer productivity. Another potentially important shale interval occurs at the contact between the Racine Formation and the underlying Joliet or Sugar Run Formations.

Productivity within the Silurian dolomite aquifer is controlled, in part, by changes in carbonate facies. Reef facies in the Racine Formation are more highly productive, yielding water from primary and secondary porosity (Harza Engineering 1984). Interreef facies are shaley and not very productive unless highly fractured.

We recognize two aquifer units within the Silurian dolomite aquifer in the study area (fig. 6). The Racine aquifer unit is the thicker and more productive shallow bedrock aquifer in the area; however, the thinner and less extensive Blanding aquifer unit is important in the north and north-central parts of the area.

The Racine aquifer unit, formerly known as the Niagaran dolomite aquifer (Foster 1956, Brueckmann and Bergstrom 1968), includes rocks of the Racine and Marcus Formations. Although the aquifer is up to 300 feet thick in the southern parts of the area, groundwater is generally obtained from fractures and open bedding planes within the upper 50 to 100 feet of the unit (Foster 1956). Water may also be obtained locally from the highly permeable reef or biohermal rocks. An example of this second type of occurrence was documented in Iowa where a distinct aquifer subunit within equivalent strata yielded up to 50 gpm (Wahl and Bunker 1986).

The Blanding aquifer unit, formerly known as the Alexandrian dolomite aquifer (Foster 1956, Brueckmann and Bergstrom 1968), consists of rocks of the Sweeney, Blanding, and Mosalem Formations. Chert beds in the Blanding are the most distinctive features in both outcrops and subsurface cores. The Blanding aquifer unit is thinner than the overlying Racine aquifer unit and generally has lower permeability due to the presence of chert, shale, and shaley dolomite. In the northern parts of the study area, however, the Blanding aquifer unit is highly fractured and produces water sufficient for domestic wells. Wells developed in the Blanding aquifer typically have capacities of 10 to 30 gpm and rarely deliver as much as 50 gpm. The Blanding aquifer unit often occurs at depths of less than 50 feet, and it is highly or moderately susceptible to contamination.

Hydrogeologic History of the Carbonate Aquifers

The regional flow system in the carbonate aquifers of northern Illinois was investigated several times in the past 30 years (Foster 1956, Brueckmann and Bergstrom 1968, Visocky et al. 1985). Flow is primarily controlled by systems of fissures and fractures that extend for 50 to 100 feet below the surface, a common feature in carbonate rocks (Brahana et al. 1988). In the study area, the carbonate rocks exposed at the ground surface or buried beneath Pleistocene glacial drift range in age from Ordovician to Devonian, that is, they were deposited 500 to 345 million years ago (m.a.). Local or regional flow systems may have formed in these rocks at several times since their deposition. Although the present flow system is most likely controlled by modern topography and stream levels, relict features of previous flow systems may be imprinted on the present one. This possibility was investigated by a petrographic analysis of two Silurian cores (appendix A).

Three major unconformities marking intervals of extensive erosion have affected the Silurian rocks in the area. The first occurred prior to the deposition of the Middle Devonian Wapsipinicon Formation, and the second prior to deposition of the Pennsylvanian clastics. Based on regional coalification studies (Damberger 1971) and fission track dating analyses (Zimmermann 1986), the Silurian carbonates were buried by 3,000 to 5,000 feet of late Pennsylvanian, Permian, and possibly, Mesozoic sediment. A third period of extensive erosion began sometime after deposition of this thick late Paleozoic to early Mesozoic sediment and continues to the present. Regional flow systems with variable degrees of fissure development must have been established during each of these periods of erosion.

One indirect method for tracing the history of flow systems in carbonate rocks is to investigate the process of dolomitization, in which the original calcite is diagenetically altered to dolomite. Our petrographic analysis (appendix A) revealed two episodes of dolomitization within the Hunton rocks of the area. We can only speculate as to the timing of the dolomitization. If the primary dolomitization occurred very early in the diagenesis of the rocks, as indicated by the mineral textures, then it is possible that the entire dolomitization process was complete prior to deposition of the Wapsipinicon limestone. This would explain the abrupt change in lithology from dolomite to limestone at the contact between the Racine and the Wapsipinicon, observed in the Henry County core.

Regionally, minor amounts of dolomite are present in Middle and Upper Devonian, as well as Mississippian strata, but not in Pennsylvanian strata (Willman et al. 1975). The regional association of dolomite rocks indicates that the second generation of dolomite could have been deposited any

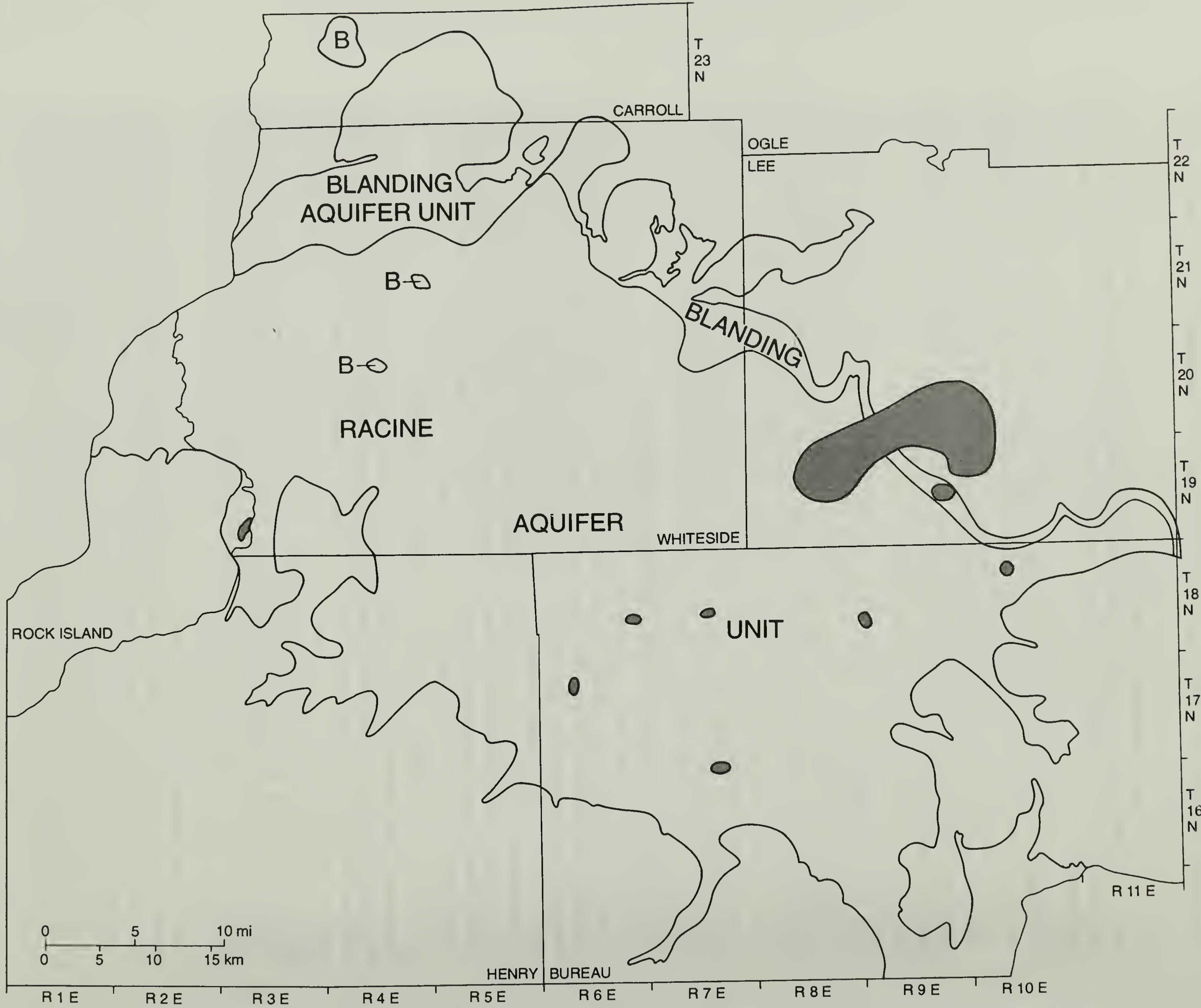


Figure 6 Blanding and Racine aquifer units in the Silurian dolomite aquifer. Pennsylvanian strata are shaded only within the area of interest.

time before the Pennsylvanian. It is less likely that dolomitization occurred after Pennsylvanian time without affecting Pennsylvanian strata.

Timing of dolomitization has hydrogeologic significance because dolomite is much less susceptible to chemical weathering than pure limestone. Multiple stages of dolomitization also imply cycles of dissolution and recrystallization. The recrystallization at least partly closes voids created by previous dissolution and negates the hydraulic effects of earlier erosion. If all the dolomitization occurred during the Paleozoic, then the period of erosion that began sometime after the Pennsylvanian and continues to the present has been characterized by carbonate dissolution. The carbonates have probably been exposed for several million years, including all of the Quaternary Period. Formation of thick residuum or geest on the top of the Silurian and Ordovician surfaces in the driftless areas of Illinois, Wisconsin, and Iowa (Willman et al. 1989) suggests that low energy, chemical weathering has been predominant for at least the past several million years.

Remnants of Paleozoic (pre-Pennsylvanian) fracture patterns may still exist; however, the present groundwater flow pattern has been primarily created by glacial and postglacial forces. This is indicated by present weathering patterns, which are controlled primarily by thickness of overburden and secondarily by lithology (Csallany and Walton 1963).

Aquifer Potential

The Silurian dolomite aquifer is primarily used for domestic supply (Sasman et al. 1974); typical well yields are 30 to 50 gpm. The occasional report of yields of 100 gpm or more indicate, however, that the aquifer is not fully utilized. We have combined several hydrogeologic variables to obtain a qualitative prediction of the potential yield of the aquifer throughout its area of occurrence, regardless of its current use. This generalized map of aquifer potential is shown in figure 7. Factors that were considered when constructing this map include aquifer units present, thickness of aquifer units, and thickness and character of overlying materials. The map of the Racine and Blanding aquifer units (fig. 6) was used as the base for figure 7. General conditions of the shallow materials were obtained from Willman and Frye (1970), Berg et al. (1984), and Berg and Kempton (1988). Maps showing thickness of the overlying Prairie Aquigroup aquifer were also consulted (D. Larson et al. in press). Weathering of the bedrock can also be a factor in aquifer potential, but weathered areas were either too small or too poorly documented to be considered in compiling this map.

Areas where the Blanding aquifer unit is at the bedrock surface are shown by map units A1, A2, and A3 (fig. 7). Units A1 and A2 differ in the amount of overlying material; A1 has less than 50 feet of overburden and A2 has greater than 50 feet. In some areas, the overlying material is residual soil or terra rosa chemically weathered from the carbonate rock. In other areas, overlying material is glacial drift (primarily outwash sand and gravel) or alluvium. In areas mapped as A3, the Blanding aquifer unit is covered by till of variable thickness, but generally greater than 50 feet thick.

The Blanding aquifer unit rarely yields as much as 50 gpm to any one well, and where it occurs near the ground surface (unit A1), it is highly susceptible to contamination. Areas mapped as A2 or A3 may have greater aquifer potential, particularly in A2 areas that have thick sand and gravel overlying the bedrock.

Areas where the Racine aquifer unit is less than 100 feet thick are shown as map units B1, B2, and B3. In map unit B1, the Racine aquifer unit lies at a depth of less than 50 feet, whereas in map unit B2, the Racine aquifer unit is overlain by more than 50 feet of material, mostly sand and gravel. Thick till overlies the Racine aquifer in areas mapped as B3. The Racine aquifer is generally more productive than the Blanding aquifer; however, areas mapped as B1 have a high potential for contamination. In most of the area mapped as B2 and B3, the Racine aquifer is overlain by at least 50 feet of either alluvium or the basal sand and gravel aquifer of the Prairie Aquigroup, which may be expected to enhance the productivity of the dolomite aquifer. This is probably the case for the largest reported yield (2,150 gpm, Sec. 33, T21N, R7E) where a well was finished in the Racine aquifer below thick alluvium of the Rock River.

The Racine aquifer unit is at least 100 feet thick in areas shown as map units C1, C2a, C2b, and C3. The relative potential for groundwater yield is greatest in these areas because of the greater thickness of the aquifer. Areas shown as C1 have less than 50 feet of overburden and a high potential for contamination. The Racine aquifer can be found at depths greater than 50 feet in areas C2a, C2b, and C3. The overlying basal sand and gravel aquifer of the Prairie Aquigroup is less than 50 feet thick in areas mapped as C2a and greater than 50 feet thick in areas mapped as C2b. In a

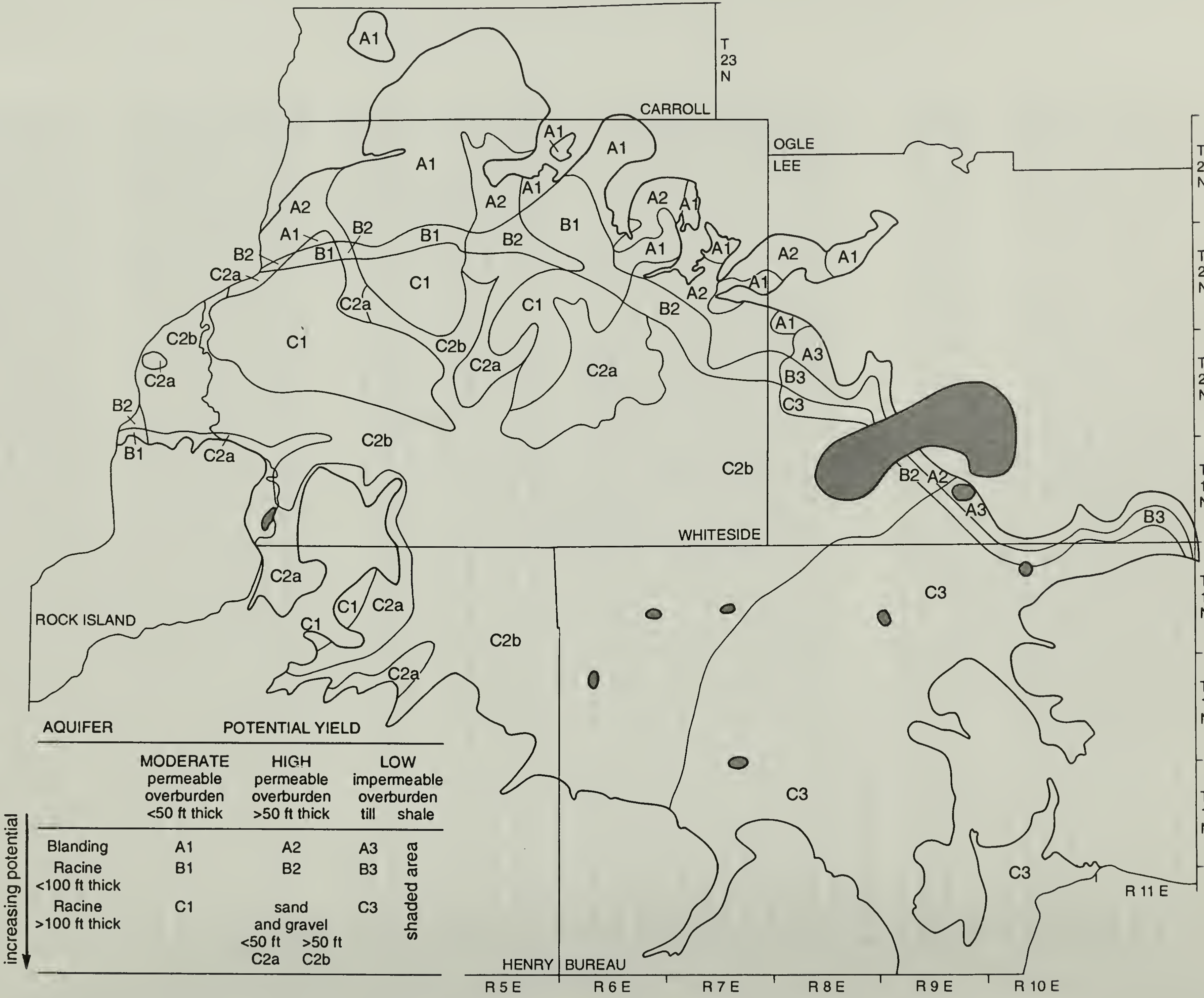


Figure 7 Generalized potential aquifer yields in the study area. Pennsylvanian strata are shaded only within the area of interest.

large part of the central region shown as C2b, the Racine aquifer is found at depths greater than 150 feet beneath thick sand and gravel aquifers of the Prairie Aquigroup. The relative importance of the Racine aquifer compared to the overlying Prairie Aquigroup aquifers is small even though the thick sand and gravel should enhance the yield of the underlying dolomite aquifer by increasing the recharge potential. In map unit area C2a, the sand and gravel aquifers are thinner, decreasing their relative importance as aquifers compared with the underlying Racine aquifer. A large, southeastern region, shown as C3, is covered by thick till. Although the till provides protection against contamination to the underlying aquifers, it also reduces groundwater recharge rates. A thick sand and gravel aquifer separates the till from the underlying Racine aquifer in areas mapped as C3. In several areas, Pennsylvanian-aged shale overlies the Racine aquifer and is designated by shaded areas on the map. Productivity and water quality can be expected to be diminished in these areas.

Through most of the area where the Racine and Blanding aquifers are at the bedrock surface, they are capable of providing a dependable, although small to moderate supply of water. These aquifers are generally overshadowed, however, by the overlying Prairie Aquigroup aquifers which are usually more productive and easier to develop. Not surprisingly, the Racine and Blanding aquifers are most completely utilized in northern Whiteside County where the Prairie Aquigroup aquifers are thinner (C2a, B1, and most of A1).

Contamination Potential

Groundwater in the dolomite aquifer flows primarily in open fractures within the upper 50 to 100 feet of the top of the unit (Foster 1956) making the aquifer susceptible to contamination. Little or no attenuation of either chemicals or bacteria occurs where groundwater moves through joints and fissures in rocks (Berg et al. 1984). Consequently, the contamination potential of the aquifer depends on the nature and thickness of the overlying materials and the nature and source of contamination. Thick, fine grained overburden generally provides the greatest protection from contamination. Also, large landfill operations are potentially more damaging than septic systems.

Concentrations of contaminants in groundwater are reduced by the physical processes of dilution, dispersion, and filtration. Dilution and dispersion are most effective when flow rates and volumes are maximized. In groundwater, this occurs in sand and gravel aquifers with high hydraulic conductivities and high gradients. Filtering is most effective in removing bacterial contamination in materials with small pores such as silt and clay. Chemical attenuation, through ion exchange, primarily in clays, can reduce the concentration of some objectionable substances in landfill leachate and septic effluent (Berg et al. 1984).

Figure 8 shows the potential for contamination of the Silurian dolomite aquifer from land burial of municipal wastes. This map is based on plate 1 from Berg et al. (1984). In figure 8, the Berg et al. map units were grouped into new units according to their capacity to transmit contaminants to the bedrock aquifer. Because the Berg et al. map showed the contamination potential of materials between ground surface and the uppermost aquifer, whether the aquifer was sand and gravel or bedrock, some units considered to have high contamination potential were downgraded. For instance, although their map units B1, B2, and C2 may have sand and gravel aquifers within 50 feet of the surface, these near-surface sand and gravel units are all underlain by thick layers of impermeable till or bedrock. Because this thick impermeable layer affords protection to the Silurian dolomite aquifer, these units are included in our unit C, which indicates low contamination potential.

For this study, five map units were defined, based on the original Berg et al. list of 18 units. Units A1, A2, and Ax are identical with the original designations. Units B and C each incorporate several of the original units. Areas mapped as A1, A2, and Ax generally have a high potential for contamination of the Silurian dolomite aquifer. Areas where the Silurian dolomite is within 20 feet of the land surface are mapped as A1. These are the most sensitive areas for contamination in the study region. Areas where the extensive, thick, sand and gravel aquifer that blankets most of the region lies within 20 feet of the surface are mapped as unit A2. Although some filtering of the groundwater can be expected because the surficial materials are as much as several hundred feet thick in this region, sand and gravel is a poor attenuator of most contaminants. Dissolved chemicals may be transmitted directly to the bedrock aquifer, even through thick sections of material. Areas mapped as Ax are alluvium of variable composition and thickness. In most of the study region, alluvium can be expected to act as a conduit for contaminants to reach the underlying bedrock aquifer.

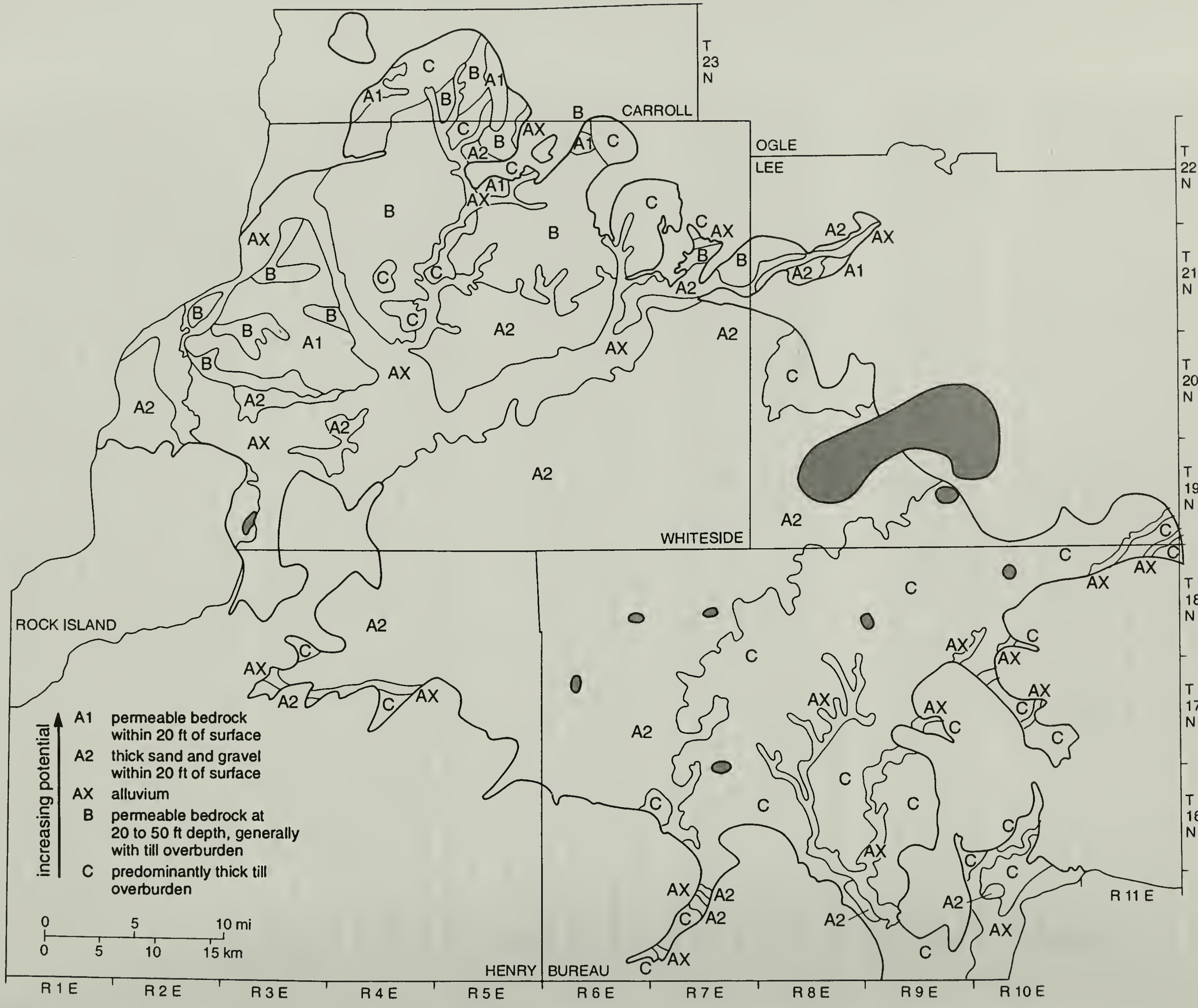


Figure 8 Potential for contamination of Silurian dolomite in the study area (after Berg et al. 1984). Pennsylvanian strata are shaded only within the area of interest.

An intermediate level of contamination potential is represented by our new map unit B, which generally consists of fine grained material at the surface, overlying permeable bedrock at depths of 20 to 50 feet. This unit includes the Berg et al. units A5, C1, and C3. The fine grained surface material protects the underlying bedrock aquifer to some extent; however, land burial of wastes in surface trenches increases the probability of contaminants entering the bedrock aquifer. Surface application of wastes and shallow septic systems pose less of a threat in these areas.

Areas mapped as unit C have the least potential for the Silurian bedrock aquifer to become contaminated. New map unit C consists predominantly of thick, impermeable till or impermeable bedrock and includes the Berg et al. units B1, B2, C2, C5, D, E, F, and G. An extensive area in the southeast part of the study region mapped as unit C has a thick sand and gravel aquifer between a surficial layer of till and the bedrock aquifer. The till in this area is generally greater than 50 feet thick and provides substantial protection from contamination. Any contamination entering the sand and gravel aquifer can be expected to be transmitted, in turn, to the underlying bedrock aquifer without further attenuation.

SUMMARY

Two distinct aquifer units are recognizable within the Silurian dolomite aquifer. The thick Racine aquifer unit is almost pure dolomite and is more productive than the thinner Blanding aquifer unit, which is cherty and shaley. Actual productivity from either unit can be expected to be higher in zones of dense joints and fractures, especially in the upper parts of the units. Except for the southeast part of the region which is blanketed by glacial till, the Silurian dolomite aquifer is highly to moderately susceptible to contamination.

ACKNOWLEDGMENTS

This project was partially funded by Illinois Department of Energy and Natural Resources Aquifer Assessment Program; Karen Miller, project manager. Wan Bing Li of the Department of Geology at the University of Illinois performed the petrographic analyzes. At the ISGS, D. Scott Beaty made the thin sections and Dennis J. Haggerty furnished the porosity and permeability measurements.

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APPENDIX A: CORE ANALYSIS

Visual Examination

Two cores from the vicinity of the study area were available for study at the ISGS Samples Library, one from Henry County south of the study area and the other from Jo Daviess County north of the study area. The New Jersey Zinc Company Core (fig. A1) drilled on the W. O. Cailberg Farm in 1968, is located at the northwest corner of Section 13, T14N, R3E, Henry County, and penetrates a portion of the Pennsylvanian and Devonian section above the Silurian. It provides detailed information on lithology such as bedding, fractures, weathering, vugs, and larger openings. This detailed information supplements the more numerous well cuttings and drill logs, which only give general characteristics such as lithology and grain size.

The overlying Devonian Wapsipinicon Formation in the Henry County core is a medium light gray (N6) limestone, fine grained to lithographic with dark gray (N3) to black partings (N1), often stylolitic. Some of the partings are slightly stained grayish orange (10/YR 7/4). At the contact, the Silurian Racine Formation is very pale orange (10/YR 8/2), mottled with medium gray (N5) to medium dark gray (N4), fine grained dolomite with a few small oil stains. Below the contact is a pale yellowish brown (10YR 6/2), slightly mottled dark gray (N3), fine grained dolomite with numerous calcite-filled vugs. The Racine Formation consists of 211 feet of dolomite, pale yellowish brown (10/YR 6/2), light brownish gray (5/YR 4/1), and medium gray (N5), with wavy beds every 1 to 6 inches. It is medium grained, vesicular, and vuggy with numerous joints and open bedding planes. Some of the vugs are filled with calcite and some joints are healed.

Below the Racine Formation, the Sweeney is 68 feet thick and consists of a yellowish gray (5/Y 8/1) dolomite. There is some moderate light gray (N7) mottling, some greenish gray (5/G 6/1) to medium dark gray (N4) laminae, a few small chert nodules, a few stylolitic hard grounds, some flattened vugs, and traces of glauconite and sulfate mineralization. There is some caliche on vug surfaces, some of which have a chalky, weathered appearance.

Below the Sweeney is the Blanding Formation, which consists of 20 feet of yellowish gray (5/Y 8/1) to light olive gray (5/Y 6/1) dolomite. It occurs in fine grained beds separated by greenish gray (5/G 6/1) laminae with abundant chert and a trace of glauconite.

Rocks identifiable as the Mosalem Formation were not present in the core. Maquoketa Group rock, which occurs below the Blanding Formation, is dark greenish gray (5/G 4/1), dolomitic, highly burrowed siltstone.

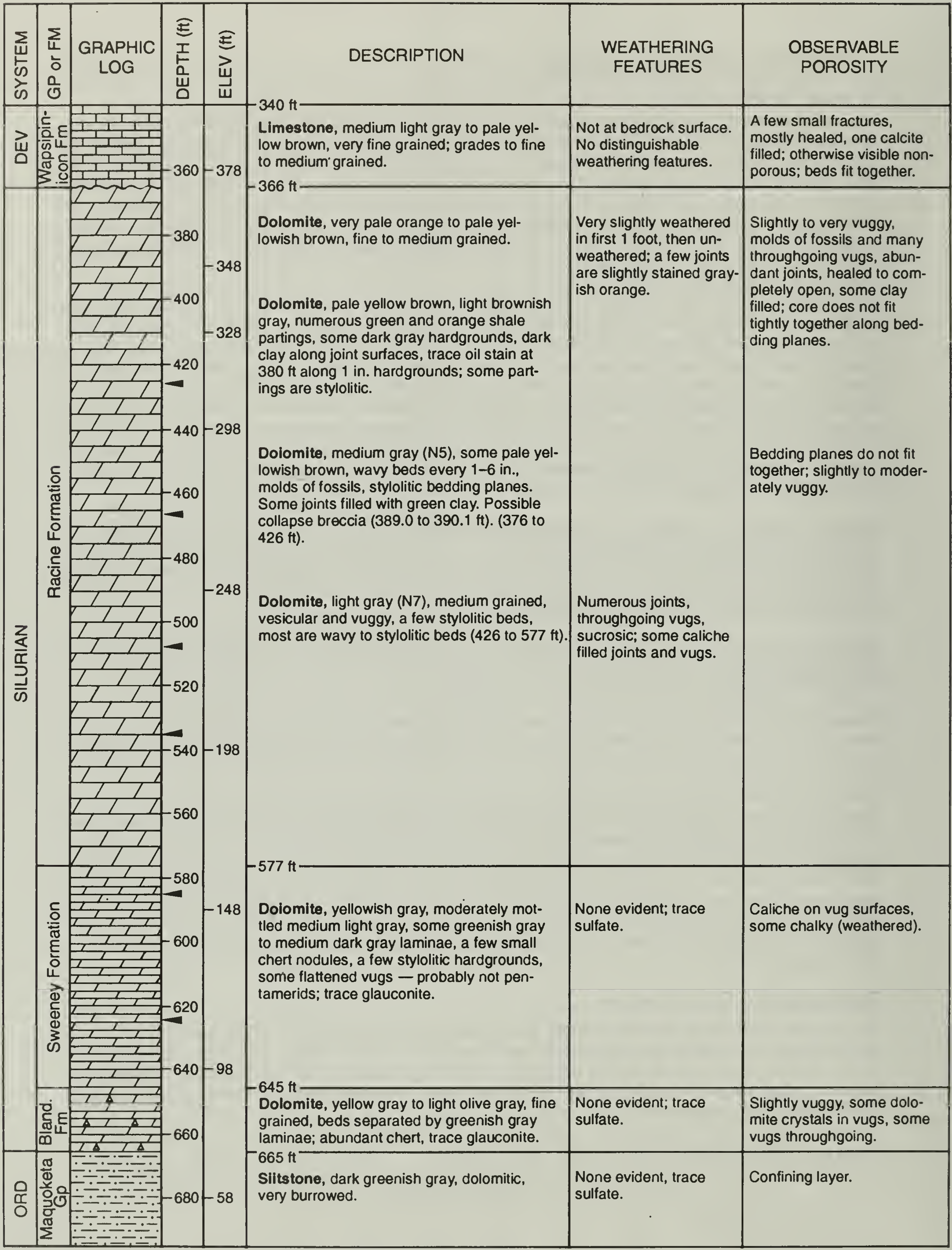
The Jo Daviess County core from Section 6, T27N, R2E (fig. A2), is typical of an eroded and weathered Silurian section; it consists of 27 feet of Blanding Formation, 39 feet of Tete Des Morts Formation, and 73 feet of Mosalem Formation. The Blanding Formation consists of grayish orange (10/YR 7/4), fine grained dolomite with wavy bedding and abundant white chert nodules. The Tete des Morts consists of light olive gray (5/Y 6/1), medium grained, wavy bedded, slightly vuggy dolomite and white chert nodules. The Mosalem Formation is light gray (N7), very fine grained, burrowed dolomite with white chert nodules. Near the base it grades to medium gray (N5), laminated shale. The base of the Mosalem is in contact with the greenish gray (5/G 6/1) shales and siltstones of the Maquoketa.

Petrographic Examination

Six samples from the Jo Daviess County core (C6702) and six samples from the Henry County core (C7858) were selected for petrographic analysis (table A1). The core from Jo Daviess County is from a very shallow depth and shows the effects of weathering. The core from Henry County comes from an area slightly beyond the limits of the study area, but it is representative of the entire thickness of the Silurian rocks in the region.

Table A1 Depth of samples used in petrographic analysis.

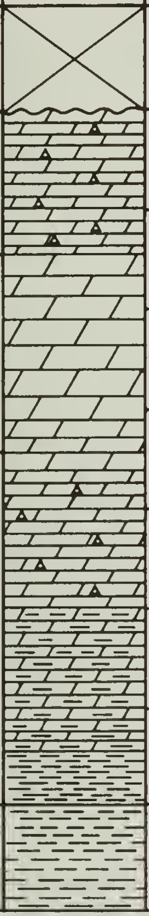
Core	Sample depth (ft)					
Jo Daviess Co. (C6702)	21	44	49	66	68	99
Henry Co. (C7858)	425	467	509	535	584	624



SYSTEM	GP or FM	DESCRIPTION	WEATHERING FEATURES	OBSERVABLE POROSITY
DEV	Wapsipinicon Fm	340 ft **Limestone**, medium light gray to pale yellow brown, very fine grained; grades to fine to medium grained. 366 ft	Not at bedrock surface. No distinguishable weathering features.	A few small fractures, mostly healed, one calcite filled; otherwise visible nonporous; beds fit together.
SILURIAN	Racine Formation	**Dolomite**, very pale orange to pale yellowish brown, fine to medium grained. **Dolomite**, pale yellow brown, light brownish gray, numerous green and orange shale partings, some dark gray hardgrounds, dark clay along joint surfaces, trace oil stain at 380 ft along 1 in. hardgrounds; some partings are stylolitic. **Dolomite**, medium gray (N5), some pale yellowish brown, wavy beds every 1–6 in., molds of fossils, stylolitic bedding planes. Some joints filled with green clay. Possible collapse breccia (389.0 to 390.1 ft). (376 to 426 ft). **Dolomite**, light gray (N7), medium grained, vesicular and vuggy, a few stylolitic beds, most are wavy to stylolitic beds (426 to 577 ft). 577 ft	Very slightly weathered in first 1 foot, then unweathered; a few joints are slightly stained grayish orange. Numerous joints, throughgoing vugs, sucrosic; some caliche filled joints and vugs.	Slightly to very vuggy, molds of fossils and many throughgoing vugs, abundant joints, healed to completely open, some clay filled; core does not fit tightly together along bedding planes. Bedding planes do not fit together; slightly to moderately vuggy.
	Sweeney Formation	**Dolomite**, yellowish gray, moderately mottled medium light gray, some greenish gray to medium dark gray laminae, a few small chert nodules, a few stylolitic hardgrounds, some flattened vugs — probably not pentamerids; trace glauconite. 645 ft	None evident; trace sulfate.	Caliche on vug surfaces, some chalky (weathered).
	Bland. Fm	**Dolomite**, yellow gray to light olive gray, fine grained, beds separated by greenish gray laminae; abundant chert, trace glauconite. 665 ft	None evident; trace sulfate.	Slightly vuggy, some dolomite crystals in vugs, some vugs throughgoing.
ORD	Maquoketa Gp	**Siltstone**, dark greenish gray, dolomitic, very burrowed.	None evident, trace sulfate.	Confining layer.

◄ Samples removed for thin section, x-ray, and cathodoluminescence analyses

Figure A1 Stratigraphic description and weathering characteristics of New Jersey Zinc core C7858, Section 13, T14N, R3E, Henry County.

SYSTEM	GP or FM	GRAPHIC LOG	DEPTH (ft)	ELEV (ft)	DESCRIPTION	WEATHERING FEATURES	OBSERVABLE POROSITY
Quat Fm	not re-covered		20	1025	Soil and clay	Not recorded.	Not recorded.
SILURIAN	Bland. Fm		40	1000	21 ft **Dolomite**, grayish orange, fine grained, wavy bedding; contains abundant white chert nodules.	Grayish orange weathered chert; open bedding planes; bedding surfaces more orange.	Some vugs, some calcite-filled; bedding plane porosity; no open fractures noticeable. Tiny intercrystalline porosity, some bedding planes and other areas are sucrosic and corroded.
	Tete des Morts Fm ?		60 80	975 950	48 ft **Dolomite,** light olive gray to medium grained, wavy bedding, sucrosic to slightly vuggy; contains some white chert nodules.	Bedding planes stained orange to dark yellowish orange.	Pinpoint pores, sucrosic zones, some small vugs.
	Mosalem Fm		100 120 140	925 900	87 ft **Dolomite,** light gray, very fine grained, burrowed and churned; bedding not visible; white chert nodules. **Shale**, moderate gray, dolomitic, laminated (158.3 to 160.1 ft).	Yellow orange stained zone at 143.3 to 143.6 ft.	No observable porosity. No observable porosity.
ORD	Maq Gp		160	875	160 ft Greenish gray shale.	No observable weathering features.	Confining layer.

◄ Samples removed for thin section, x-ray, and cathodoluminescence analyses

Figure A2 Stratigraphic description and weathering characteristics of New Jersey Zinc core C6702, Section 6, T27N, R2E, Jo Daviess county.

Dolomite is the predominant mineral in all the samples, except C6702-21 from Jo Daviess County, which is dominated by quartz. Small amounts of clay minerals were found in several samples from Jo Daviess County. Most of the samples from Henry County (C7858), particularly those from the upper part of the core, were almost pure dolomite. The dolomite was formed in two generations. The first generation is characterized by planar-subhedral crystals accumulated to form fine grained, dense dolostone with low porosity. The second generation dolomite is characterized by planar-euhedral crystals accumulated near empty channels. The dolostone is very porous. Porosity includes both channels and well connected intercrystalline pores.

The amount of porosity is probably controlled by stages of dolomitization. The majority of dolomite crystals are from the first generation of dolomite. Commonly, the second generation dolomite occurs as overgrowth on the cores of the first generation dolomite. Thus, zonation can be observed with polarized microscopy and cathodoluminescence.

The contrasting characteristics of the two generations of dolomite suggest that they were formed in different hydrochemical environments. The main episode of dolomitization might have occurred at a very early stage of diagenesis, considerably increasing the porosity of the rocks. The reaction fluids were probably of marine origin. The second, minor, episode of dolomitization occurred late in diagenesis, perhaps during a time of erosion. The fluid probably was meteoric water. The thin, second generation overgrowths of dolomite were deposited in zones of higher porosity caused by dissolution. Although these overgrowths slightly reduce the local porosity, they can be used to mark zones of higher porosity and permeability within the rock.

Porosity and Permeability Testing

Porosity and permeability of carbonate rocks can vary over an extremely wide range of values . For instance, porosity is known to vary from 40% to less than 1%. A similarly large range of values can be expected for permeability, from as large as 10,000 millidarcies (md) to as small as 0.01 md (Freeze and Cherry 1979). Knowing this possible wide range of values in hydraulic properties, we decided to measure the permeability and porosity of a sampling of carbonate rocks in our study area to determine the actual range of values present.

Results of the porosity and permeability tests are shown in figure A3. In this graph, porosity is plotted on the x-axis with a linear scale, whereas the permeability of the same sample is plotted on the y-axis with a logarithmic scale. The points are labeled with the county and depth of each sample. All measurements are within the expected ranges for carbonate rocks. The data set roughly follows a linear trend, as expected in this type of presentation. The porosity evenly spans the range from 34% to 2%. Permeability ranges from a high of 1,998 md to a low of 0.033 md. Permeability values are clustered in two groups. The low permeability group of seven samples ranges from 0.033 to 0.181 md; their porosities are 15% or less. The high permeability group of five samples ranges from 52.90 md up to 1,998 md; their porosities are all greater than 15%. There is a wide gap in permeability from 0.2 to 50 md, with no representative samples. This distribution pattern may be a consequence of the small sample set, but it may also represent a fundamental distinction in the rocks.

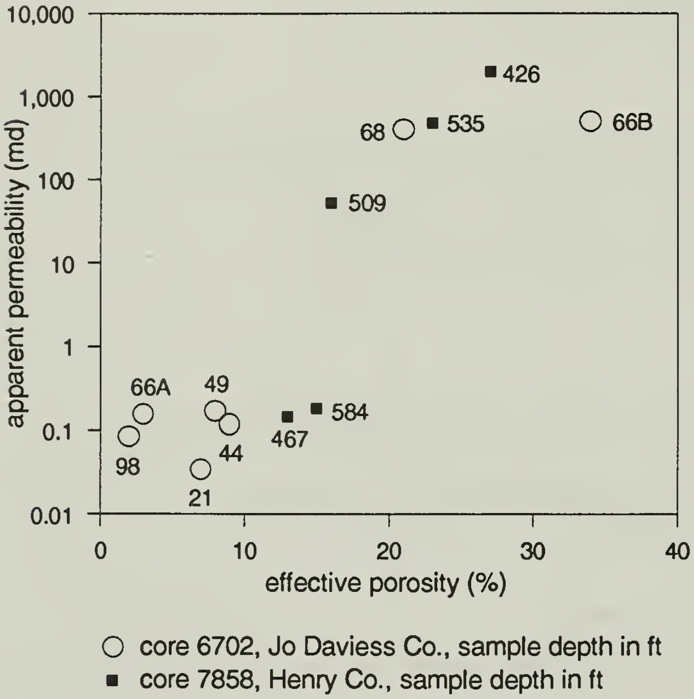


Figure A3 Results of hydraulic property measurements of upper bedrock aquifer system comparing the effective porosity to the apparent permeability.

The Henry County core was visually inspected for throughgoing vugs, joints, and vugginess. These three properties provide a qualitative measure of secondary porosity. The number of throughgoing vugs and joints was determined for each 10-foot section of the core and plotted in figure A4. The minimum number of vugs and joints was two per section, with 25 the maximum number, and 7.38 the average. The greatest number of joints and vugs was found in a 30-foot section in the middle of the Racine Formation. This section was also characterized by abundant crinoid debris and may be part of a reef. The Racine Formation also included a relatively thick section (525 to 555 ft) of rock with very few vugs and joints.

A qualitative assessment of vugginess (very slightly vuggy, slightly vuggy, moderately vuggy, and very vuggy) was assigned to each 10-foot section of core. These assessments were translated into values of relative porosity ranging from 1 (very slightly vuggy) to 4 (very vuggy) and plotted as a function of depth within the core (fig. A5). When a range of porosity was reported for any one segment, the maximum value was chosen as representative, assuming that the local flow regime was controlled by zones of greater porosity, regardless of the relative volume of the zones.

Most laboratory samples with high measured porosity are from the Henry County core, which consists predominantly of pure dolomite. Thin sections reveal that this material has many large pores. The core from Jo Daviess County consists of shaley and cherty fine grained dolomite. These rocks could be expected to have lower porosity; however, macrofeatures such as fossil traces are common in all of these rocks. Larger fossil traces, particularly fossil crinoid stems, tend to show a more open structure and result in microzones of increased permeability. This is true even in the Jo Daviess County core, which normally has low permeability. An example of the local variability caused by the presence of macrostructures is shown in samples JD-66A and B. Both plugs were cut from

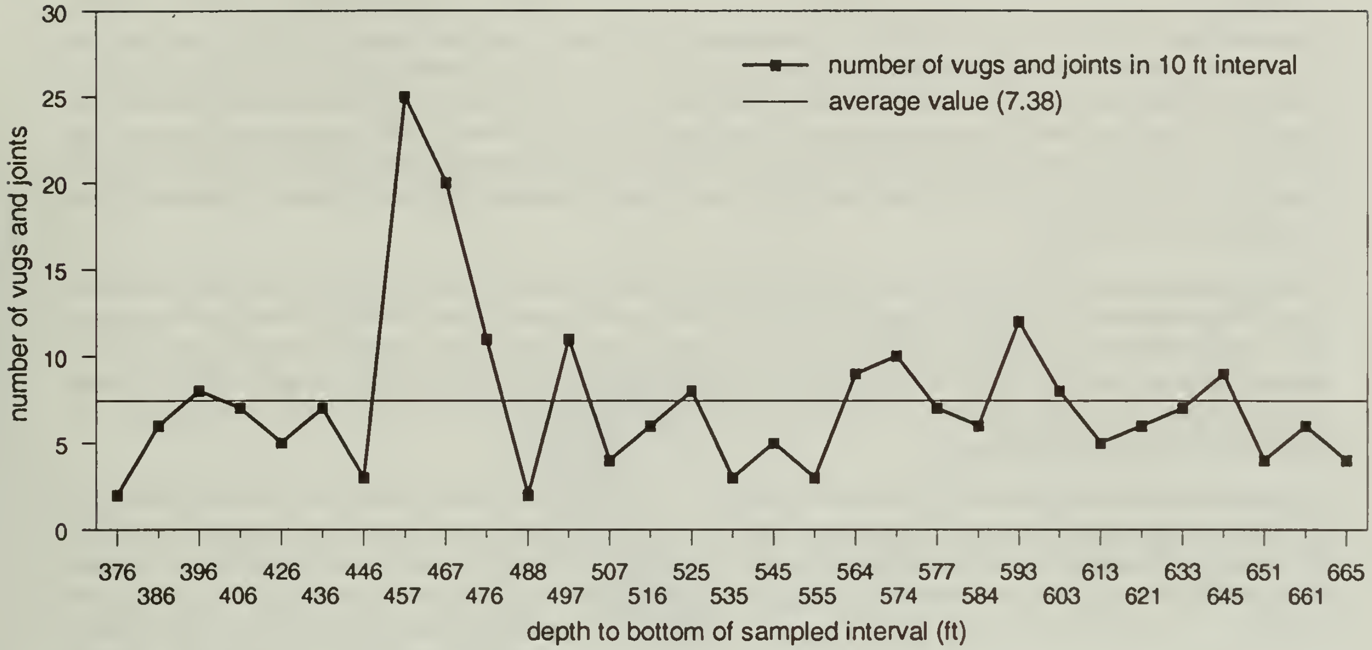


Figure A4 Throughgoing vugs and joints relative to depth for Silurian dolomites in the Henry County core.

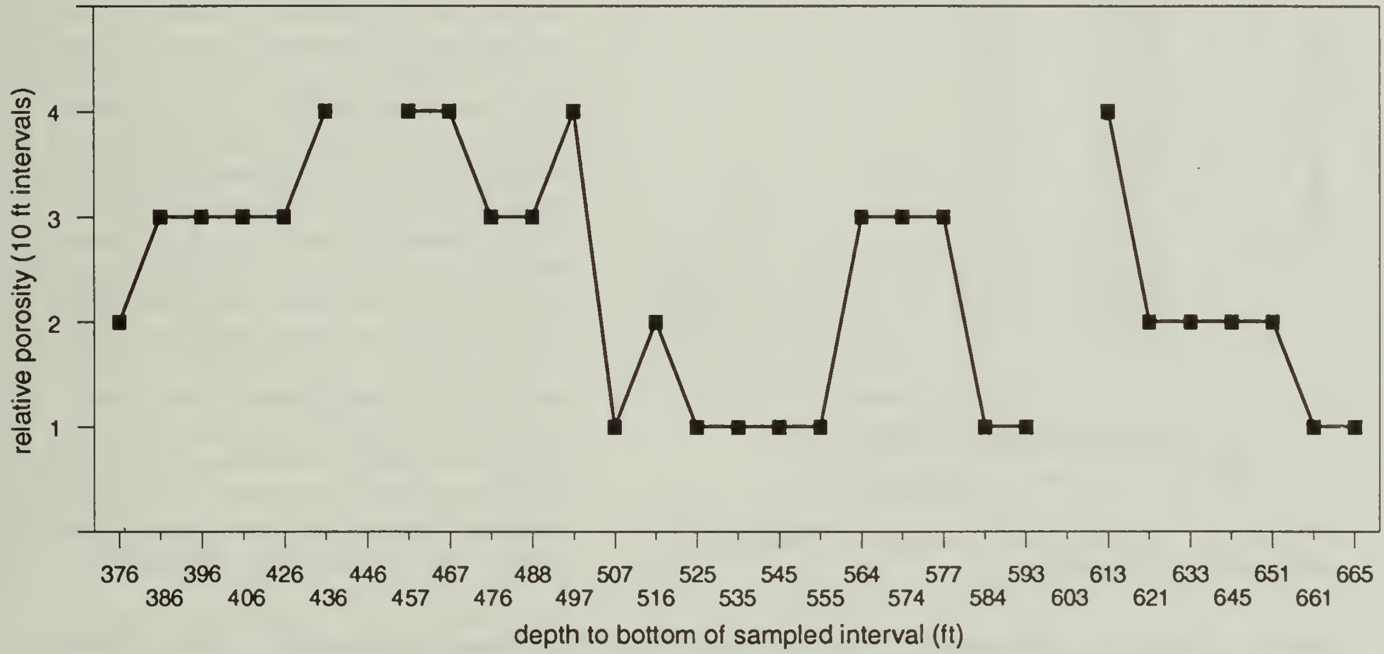


Figure A5 Core porosity relative to depth for Silurian dolomites in the Henry County core.

the same core sample, but JD-66A contained a visible fossil trace. This sample was determined to have the largest porosity (34%) and one of the largest permeability values (491.0 md). The other plug, JD-66B, did not contain visible fossils and had very low porosity (3%) and very low permeability (0.154 md). This suggests that the variations in permeability depend on the internal fabric of the rocks. Those portions of the rocks with pores enlarged by fossil molds and casts have high permeability. Portions of the rocks devoid of fossils have low porosity and permeability.

Another possible source of high permeability is microfractures or bedding planes within the rocks. Fracture permeability would be indicated by samples having high permeability but low porosity. That is, the fractures have negligible volume, yet allow fluid to pass. We did not detect the presence of such structures in these samples. All samples with high permeability also had high porosity, indicating that the structures allowing fluid flow have substantial volume and are not microfractures.

Laboratory measurements were conducted on very small samples (1-inch nominal diameter). These measurements provide an indication of the range of porosity and permeability in the core, but are not representative of larger volumetric segments of the core. Interestingly, measured porosity of sample plugs does not correlate with qualitative assessments of core segments. A sample from the interval containing the highest number of vugs and joints (HEN–467) had a relatively low porosity (23%). The sample from an interval that had much less visible porosity (HEN–536), however, had a porosity of 13%. This is not contradictory data, but merely illustrates the two different scales at which the data were analyzed.

When taken as a whole core and smoothed over 10-foot intervals, the porosity is relatively constant over long reaches of the Silurian section. High porosity sections are restricted to a few narrow zones. We expect that the few high porosity zones would control the overall permeability of the rocks if subjected to an aquifer test. The measured permeability from such an analysis, which is at an even greater scale, would depend on the interconnectedness of vugs and joints such as those found in the core within the rock mass.

In areas where the Racine aquifer unit is present, it tends to be more productive than the Blanding aquifer unit (Brueckmann and Bergstrom 1968). Zones of high permeability are known to occur in the Marcus Formation (immediately below the Racine Formation) or in the reef facies of the Racine Formation. An aquifer in which permeability is controlled by massive fossil remains, has been documented in lower Racine equivalent strata in Iowa (Wahl and Bunker 1986). This distinction would seem reasonable from our qualitative analysis of the Henry County core. We have plotted the relative porosity versus percent of the core segments having that porosity in or below the Racine aquifer unit (fig. A6). The Racine aquifer unit is 65% moderately to very vuggy, whereas 88% of the Blanding aquifer unit is only slightly or very slightly vuggy. Only one segment of the Blanding aquifer unit (11%) was rated as very porous. This distinction is probably less important in areas where the Racine has been partly or completely eroded. In those areas, jointing and solution enlargement in the Blanding aquifer unit produces many zones of high permeability. For instance, the high permeability measurements from the Jo Daviess County core were determined entirely from the Blanding aquifer unit.

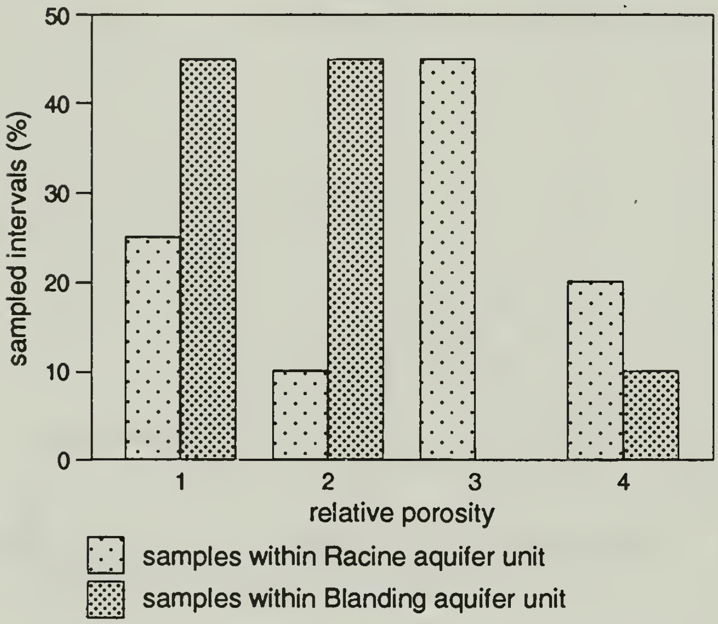


Figure A6 Porosity in various sections of Silurian dolomite in the Henry County core.

Commonly, the throughgoing macropores observed in the present study do not exhibit sufficient interconnectedness to result in high permeability at larger scales. The fossils tend to be isolated within the rock mass; they exhibit high porosity but limited permeability. At larger scales, rock fractures or bedding planes tend to control the permeability. Wells that intersect fractures have high permeabilities, and those that do not intersect fractures have very low permeabilities. Even at the larger scale of the well test, however, it is likely that the measurements would exhibit bimodal clustering with values similar to those measured in our test. Except in very unusual circumstances (such as thick biohermal zones or reef rocks) large scale aquifer testing would probably find that high permeabilities are caused by open fractures and open bedding planes.

APPENDIX B: SUMMARY OF LITHOLOGIC DATABASE

Table B1 summarizes data from 114 sample sets that we examined as the primary data set for lithologic mapping for this study. Another 238 well records were used as a secondary data set (fig. B1). The left half of the table gives the ISGS county identification number (County no.) and location information that includes township, range, section, and location in the section either as footage from the indicated boundary or as a division in the section.

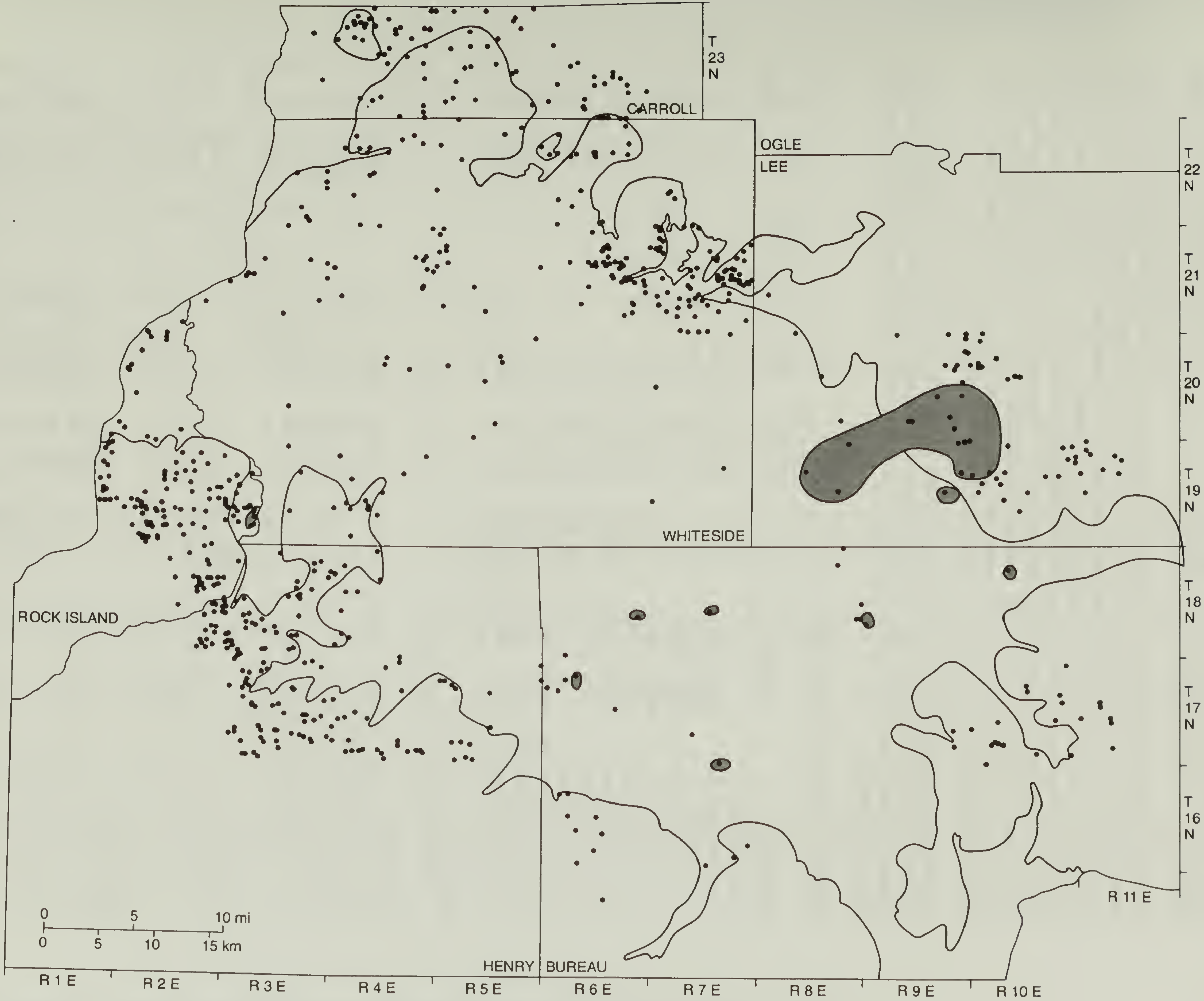


Figure B1 Locations of wells in study area. Pennsylvanian strata are shaded only within the area of interest.

Data obtained from our study are given in the right half of the table. Surface elevations estimated from topographic maps (TM elev) and bedrock elevations (BR elev) were used to calculate drift thicknesses. For some of the sample sets, one or both of these pieces of information was either unavailable or indeterminable and is signified by NA in the table.

We estimated the thickness of the entire Silurian section of rock (Sil thick) in each sample set and noted whether the underlying Maquoketa Group rocks were included in the set, thus providing a complete (C) or not complete (NC) section. We were able to differentiate the Silurian rocks into three units in most of the sample sets by using the cherty Sweeney Formation as a basis for dividing into an upper Racine–Marcus (Rac) unit, a middle Sweeney–Blanding (Swe) unit, and a lower Mosalem (Mos) unit. The Mosalem unit is differentiated from the Sweeney–Blanding by shale content. We used a dash (–) symbol for units that could not be differentiated by shale content. We used a plus symbol (+) for units that were not fully penetrated. All of these samples can be retrieved from the ISGS Samples Library by using the sample set number (SS no.) listed in the table.

We examined each sample for signs of weathering (Weath.) and listed the thickness of the weathered zone in feet. Most of the samples we were able to examine completely (C) for weathering; however, for samples that did not completely penetrate the entire Silurian section (NC) the reported value is a minimum.

Table B1 Data from 114 sample sets.

County no.	Location						TM elev	BR elev	Sil thick	Unit thickness Rac	Swe	Mos	SS no.	Weath.
Bureau County														
166	16N	6E	Sec. 8	1250S	500W		640	533	125 NC	–	–	–	25407	0 C
439	16N	6E	Sec. 8	1190S	580W		640	529	175 NC	45	130	0	50011	0 C
42	16N	7E	Sec. 34	1500S	1800W		765	460	455 C	365	90	0	672	0 NC
347	16N	7E	Sec. 35	1450N	690E	NE	750	475	508 C	358	130	20	54194	0 C
819	17N	6E	Sec. 5	28N	150E	NW	627	NA	432 C	230	100	22	57825	0 C
822	17N	6E	Sec. 6	537S	64W	NW SW	613	NA	420 C	–	–	–	57827	0 C
817	17N	6E	Sec. 7	115S	107W	NW	621	NA	460 C	–	–	–	57826	30 C
243	17N	6E	Sec. 8			SE SE NW	620	402	416 C	–	–	–	1619	0 C
346	17N	6E	Sec. 23	200N	100W	NE NW	650	NA	440 C	–	–	10	54193	0 C
336	17N	7E	Sec. 28	318S	86W	NE	663	NA	480 C	–	–	–	53284	0 C
270	18N	8E	Sec. 2	112N	188E	SE SW SE	800	450	365 C	–	–	–	4449	5 C
275	18N	8E	Sec. 24	150N	450E	NW NE NE	850	434	51 NC	–	–	–	4862	3 C
Carroll County														
87	23N	4E	Sec. 36	1400N	2450W		777	753	63 C	–	–	–	5127	31 C
Henry County														
587	17N	3E	Sec. 1	200S	200E	SW	612	490	403 C	198	205	0	4505	0 C
90506	18N	2E	Sec. 28				NA	NA	45 NC	45+	+	+	50275	0 C
621	18N	2E	Sec. 31	340N	850W	SW	570	535	40 NC	40+	+	+	3773	0 C
21095	18N	2E	Sec. 31			NE NW SW	570	534	115 NC	–	–	–	60527	0 C
607	18N	2E	Sec. 31	75S	835W	NW	570	535	40 NC	0	40+	+	3772	0 C
364	18N	4E	Sec. 31	765N	1117W	SW	610	529	419 C	319	100	0	42798	0 C
Lee County														
21720	19N	9E	Sec. 1			C/ S/2 NE	722	477	115 C	65	20	25	1079	0 C
2	19N	9E	Sec. 14	330S	330E	SE SE SE	958	610	60 C	0	60	0	24762	0 C
21272	19N	10E	Sec. 6	100N	50W		890	660	105 C	105	0	0	65974	105 C
95	20N	8E	Sec. 4	100N	125W	NE	670	630	48 C	33	10	5	54523	3 C
Rock Island County														
90504	18N	1E	Sec. 1	330N	2310E		700	NA	158 NC	158+	+	+	50272	0 C
90503	18N	1E	Sec. 8	125S	1774E	NE	585	NA	235 NC	235+	+	+	59006	25 C
298	18N	1E	Sec. 8			SE	590	560	130 NC	130+	+	+	17529	0 C
849	18N	1E	Sec. 9			W/2 W/2	NA	NA	98 NC	98+	+	+	17745	0 C
437	18N	1E	Sec. 11	182N	60E	SW SE	680	610	225 NC	225+	+	+	55113	0 C
133	18N	1E	Sec. 18			NW	570	560	50 NC	50+	+	+	36765	0 C
305	18N	1E	Sec. 19	2000S	1150E		650	560	342 C	262	80	+	17817	0 C
432	18N	1E	Sec. 24	40N	560W	NE	580	410	273 C	120	150	3	55065	0 C

Table B1 *continued*

						TM	BR	Sil	Unit	thickness		SS	
County no.	Location					elev	elev	thick	Rac	Swe	Mos	no.	Weath.
309	18N	1E Sec. 29	710S	770W		600	492	292 C	210	80	0	5484	2 C
90505	18N	1E Sec. 30	90S	142E	NW SE SE	590	NA	330 C	150	170	10	54606	0 C
72	18N	1E Sec. 31	40N	2040W	SE	615	545	330 C	235	95	0	30733	0 C
314	18N	1E Sec. 31	60S	2050E	SE	610	540	340 C	295	30	15	22747	0 C
313	18N	1E Sec. 31			SE NE NE	NA	NA	244 C	215	29	+	6047	0 C
315	18N	1E Sec. 32			NW SE NW	590	558	302 C	302	–	–	19041	0 C
328	18N	1E Sec. 32	3000S	1000E		560	484	86 NC	86+	+	+	4621	86 NC
860	18N	2E Sec. 8			NE SW SE	660	630	150 C	60	+	+	53994	0 C
861	18N	2E Sec. 13	350S	800W	NE	580	562	50 NC	–	–	–	52472	0 C
656	18N	2E Sec. 14	2685N	1206E		580	556	415 C	315	90	10	56954	5 C
664	18N	2E Sec. 14	2746N	1040E		580	565	407 C	278	120	9+	57195	38 C
663	18N	2E Sec. 14	1765N	1020E		575	557	425 NC	270	125	30+	57197	0 C
648	18N	2E Sec. 14	1675N	6E		580	552	405 NC	250	150	5+	56913	5 C
140	19N	1E Sec. 13	1980N	3300E		580	503	46 C	46+	+	+	36768	10 C
343	19N	1E Sec. 25			SE SW	600	593	301 C	287	14	0	22652	38 C
341	19N	1E Sec. 25	374S	3070E	N2	580	560	315 C	–	–	–	8649	0 NC
342	19N	1E Sec. 25	1900N	1500E	NE	720	596	330 C	–	38	28	22651	252 C
344	19N	1E Sec. 36			NW NW SE	600	564	99 NC	+	+	+	24408	10 C
689	19N	2E Sec. 4	160S	520W	NW NE	600	542	67 NC	+	+	+	53193	52 C
805	19N	2E Sec. 20	1420N	770E		730	675	30 NC	+	+	+	62714	0 C
435	19N	2E Sec. 21	133S	330E	NE NE SE	710	620	260 NC	+	+	+	55066	70 C
871	19N	2E Sec. 22	38N	330E	NE NW NW	710	632	45 NC	45+	+	+	52471	45 NC
872	19N	2E Sec. 26	100S	200E	SE SW SE	680	639	66 NC	66+	+	+	52709	0 C
21728	19N	2E Sec. 29				710	635	58 NC	58+	+	+	65096	0 C
876	19N	3E Sec. 20	83S	48W	SW SE SE	580	568	55 NC	55+	+	+	53277	55 C
875	19N	3E Sec. 20			SE SE	580	576	70 NC	70+	+	+	55072	70 NC
119	19N	3E Sec. 29			NW NE	580	557	50 NC	50+	+	+	35207	50 C
878	19N	3E Sec. 29			SE NW NW	580	574	54 NC	54+	+	+	53254	54 NC
879	19N	3E Sec. 30	1150S	114E	SW	600	582	32 NC	32+	+	+	52475	32 NC
880	19N	3E Sec. 30			SW NE	590	582	35 NC	35+	+	+	52474	0 C
881	20N	1E Sec. 36	556S	250E		590	588	88 NC	88+	+	+	52473	88 C
383	20N	2E Sec. 8	50S	350W		610	552	192 NC	192	+	+	53796	172 C
475	20N	2E Sec. 18	1360N	300E		610	543	208 C	–	35	10	55607	160 C
384	20N	2E Sec. 18	840N	780E	NE	606	557	220 NC	170	50+	+	53601	180 C
643	20N	2E Sec. 31	1600S	350E	NW	600	430	162 C	62	85	15	56914	102 C
Whiteside County													
140	19N	4E Sec. 1	50S	50W	SE SE	625	440	185 C	60	110	15	45287	0 C
101	19N	4E Sec. 11	35S	75E	SW	607	444	227 C	133	89	5	45313	137 C
377	19N	4E Sec. 17			NW SW NE	587	547	80 NC	80	0	0	57935	80 NC
23	19N	4E Sec. 22	330N	328E	NE NW	607	607	389 C	285	104	0	22342	295 C
24	19N	4E Sec. 27	330N	330W	SW NW	607	522	416 C	315	100	0	21523	5 C
30	19N	7E Sec. 11	757N	2535E	SE	651	459	351 C	222	114	15	5952	1 C
90502	19N	7E Sec. 19	2600S	2600E		NA	NA	20 C	0	20	0	67105	20 C
1	20N	4E Sec. 10				633	603	50 NC	+	50+	+	25361	30 C
31	20N	4E Sec. 10			SE SW	642	622	75 NC	75+	+	+	7051	75 NC
495	20N	5E Sec. 11	140S	250W	SW NW SW	618	548	150 NC	150+	+	+	58929	150 C
21260	20N	5E Sec. 15	1100S	250W	SW	630	NA	160 NC	5	105	50	64618	35 C
123	20N	5E Sec. 15	1100S	250W		612	527	159 NC	159+	+	+	41426	159 NC
36	20N	5E Sec. 33	200S	2300W		615	422	15 NC	15+	+	+	17594	15 NC
37	20N	7E Sec. 2			NE NE	645	568	10 NC	10+	+	+	24429	10 NC
129	21N	3E Sec. 25	950S	330W	NE	728	678	310 C	235	75	0	34665	40 C
20648	21N	4E Sec. 12	900S	500W	SW	700	630	70 C	0	70	0	60070	60 C
20575	21N	5E Sec. 6	1100N	1700E	NE	722	647	90 NC	90+	0	0	59470	90 NC
149	21N	5E Sec. 18	50N	478E	NE	708	644	304 C	186	105	13	55124	186 C
47	21N	5E Sec. 18	1850N	1350W		656	556	230 C	–	–	–	16357	190 C
46	21N	5E Sec. 18	1830S	320W	SW	630	615	168 NC	–	–	–	57	168 NC
48	21N	5E Sec. 18	850N	475W	NW SW	640	551	165 C	–	30	10	20368	85 C

Table B1 *continued*

County no.	Location						TM elev	BR elev	Sil thick	Unit thickness			SS no.	Weath.	
										Rac	Swe	Mos			
21412	21N	6E Sec. 13	100S	40E			640	630	60 NC	–	–	–	66408	50	C
90501	21N	6E Sec. 25	2800S	1800W			640	NA	157 C	0	–	0	44401	45	C
141	21N	6E Sec. 25	3300S	1600W			640	570	125 C	90	25	10	53125	25	C
55	21N	6E Sec. 35	126N	238E	NW NE NE		625	532	170 C	–	–	35	7016	50	
240	21N	7E Sec. 10			SE SE SE		700	660	25 C	0	25	0	56828	0	C
144	21N	7E Sec. 10	75S	200E	SE SE SE		700	688	50 C	0	50	0	54810	18	C
241	21N	7E Sec. 12			SW SW SE		738	698	20 C	0	15	5	56829	5	C
61	21N	7E Sec. 14			NE NE SW		690	660	49 C	0	49	0	22097	7	C
63	21N	7E Sec. 16			SE NE		670	601	21 C	0	0	21	6015	0	C
76	21N	7E Sec. 20			SW		670	617	29 NC	0	29+	+	7627	29	NC
81	21N	7E Sec. 21	750S	200E			668	633	35 NC	–	–	–	8665	35	C
3	21N	7E Sec. 21					655	625	95 C	80	15	+	30670	35	C
80	21N	7E Sec. 21			SE NW		675	655	94 NC	–	–	–	5159	25	C
84	21N	7E Sec. 23	1574N	653E	NW		688	671	17 NC	0	17+	+	20130	10	C
17	21N	7E Sec. 27	1000N	1000W	NW		640	625	100 C	0	100	0	35189	10	C
86	21N	7E Sec. 27					640	615	55 C	0	55	0	7049	30	C
94	21N	7E Sec. 28	950N	2250W			630	618	130 C	0	130	0	3798	35	C
97	21N	7E Sec. 28					640	618	103 C	–	103	10	5191	43	C
93	21N	7E Sec. 28					640	607	47 NC	0	47+	–	7047	12	C
21534	21N	7E Sec. 29	460S	510W			635	635	140 C	–	35	0	62917	75	C
100	21N	7E Sec. 29	635N	248E			628	608	135 C	25	105	5	22611	25	C
5	22N	5E Sec. 5	330N	440E	NW		748	668	10 C	–	–	–	31803	10	C
18	22N	5E Sec. 5	526N	330E	NW		695	NA	40 NC	–	–	–	34761	35	C
134	22N	6E Sec. 11	2300N	50E			784	744	15 C	+	+	15	42918	0	C
112	22N	6E Sec. 16	300N	75E			820	810	115 C	0	35	80	5140	35	C
113	22N	6E Sec. 16	123N	226E			815	770	10 C	0	0	10	6683	0	C
163	22N	6E Sec. 7			NE NE NE		790	745	85 C	0	75	10	55376	40	C

APPENDIX C: WEATHERING ANALYSIS

Various stages of subsurface weathering are described in sample studies as gradations in color from grayish orange indicating weak weathering, through moderate reddish brown indicating intense weathering. Very pale orange, yellowish gray, and greenish gray coloring indicate no weathering. Thin occurrences (less than 5 ft) of terra rosa were noted in seven samples from Whiteside County.

Surface weathering was visible in outcrop and quarry exposures along the partly connected bedding planes, joints, and open cavities several feet across. Near the surface, tree roots have enlarged the joints. Some of the joints are stained orange, others are unweathered. Templeton (1937) described some cavities filled completely with white to pale gray massive friable, silty clay in the Kankakee (Blanding Formation) at the abandoned quarry in Sinnissippi State Park in Sterling, Illinois. Templeton considered the cave-filling material to be Pennsylvanian in age.

In the quarry at Emerson (Section 36, T2N, R6E), we found 35 feet of weathered cherty dolomite with bedding plane openings less than 1 inch thick. The upper 15 feet was moderate yellowish brown dolomite; the lower 20 feet was grayish orange. Below that, the unit was predominantly unweathered yellowish gray dolomite. At Morrison, the upper weathered zone was about 5 feet thick.

We visually examined the cores from Henry and Jo Daviess Counties for weathering characteristics. The Silurian rocks in the Henry County core showed a very pale orange zone (10/YR 8/2) at the Devonian unconformity. There were no pronounced fractures at the Racine Formation contact, but there were a few small oil shows that were not connected with vugs. There were some calcite-filled vugs, and some of the fossil molds and open fractures were filled with clay. Many joints were healed. In some places the core (593.25 to 603 ft) did not fit together well, indicating bedding plane porosity. There was a small solution collapse feature at 618 feet.

The core from Jo Daviess County started in the Blanding and continued through the Tete des Morts and Mosalem to the top of the Maquoketa Group. Weathered, grayish orange (10/YR 7/4) rock occurred continuously from 21 to 40 feet. The rock below was predominantly unweathered. Vugs and open bedding planes were stained orange, but no open fractures were noticeable. Some of the vugs were calcite-filled. Some of the chert in the Blanding was weathered. The Blanding and Tete Des Morts rocks showed observable porosity, whereas the Mosalem showed no observable weathering features except for a yellow, orange stained zone at 143.3 to 143.6 feet. Below the Mosalem, the Maquoketa Group showed no observable weathering features.

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Address Correction Requested