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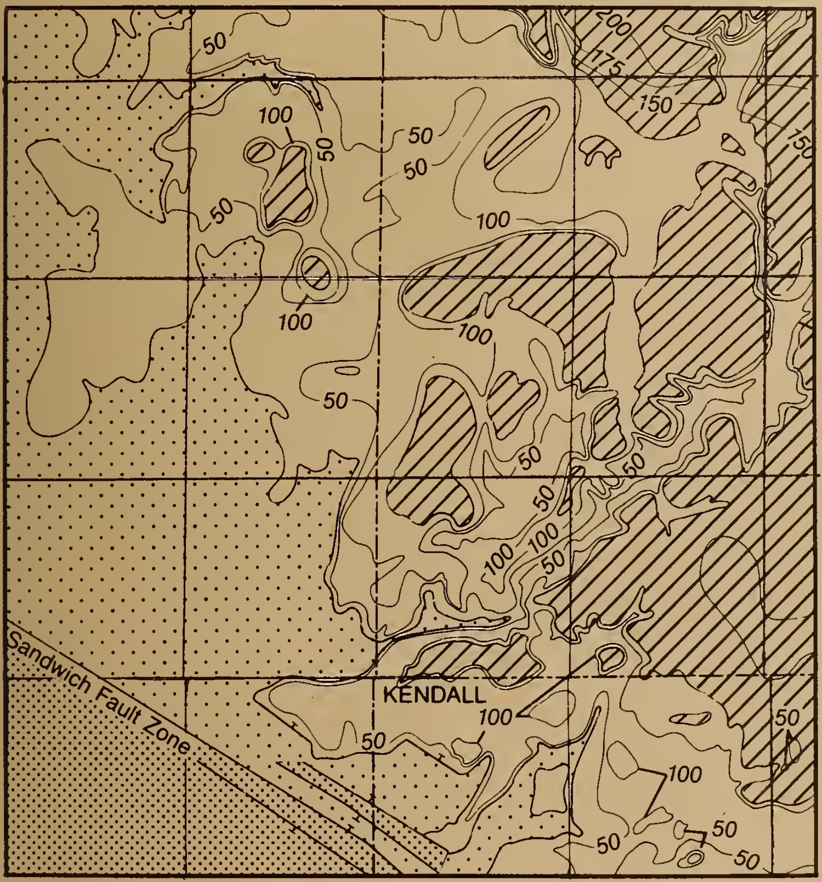
EGN 123

GEOLOGICAL-GEOTECHNICAL STUDIES FOR SITING THE SUPERCONDUCTING SUPER COLLIDER IN ILLINOIS:

REGIONAL SUMMARY



A. M. Graese
R. A. Bauer
B. B. Curry
R. C. Vaiden
W. G. Dixon, Jr.
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1988

ENVIRONMENTAL GEOLOGY NOTES 123

Department of Energy and Natural Resources
ILLINOIS STATE GEOLOGICAL SURVEY

Graphics: Jacquelyn Hannah

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GEOLOGICAL-GEOTECHNICAL STUDIES FOR SITING THE SUPERCONDUCTING SUPER COLLIDER IN ILLINOIS:

REGIONAL SUMMARY

ILLINOIS STATE GEOLOGICAL SURVEY
Morris W. Leighton, Chief

Natural Resources Building
615 East Peabody Drive
Champaign, Illinois 61820

A. M. Graese
R. A. Bauer
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R. C. Vaiden
W. G. Dixon, Jr.
J. P. Kempton

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Other ISGS staff members who assisted us were Jennifer Hines, Lucille Curran, and Carol Hindman of the Environmental Screening Task Force, and Jacquelyn Hannah, a member of the Geological Task Force staff, who drafted the maps and figures. Dennis Kolata, Paul DuMontelle, Dwain Berggren, and Jonathan Goodwin, of the ISGS and Adrian Visocky and Marcia Schulmeister of the Illinois State Water Survey reviewed drafts of the manuscript and offered helpful comments and suggestions. Kathy Cooley and Joanne Klitzing did the word-processing from draft stage through final camera-ready copy.

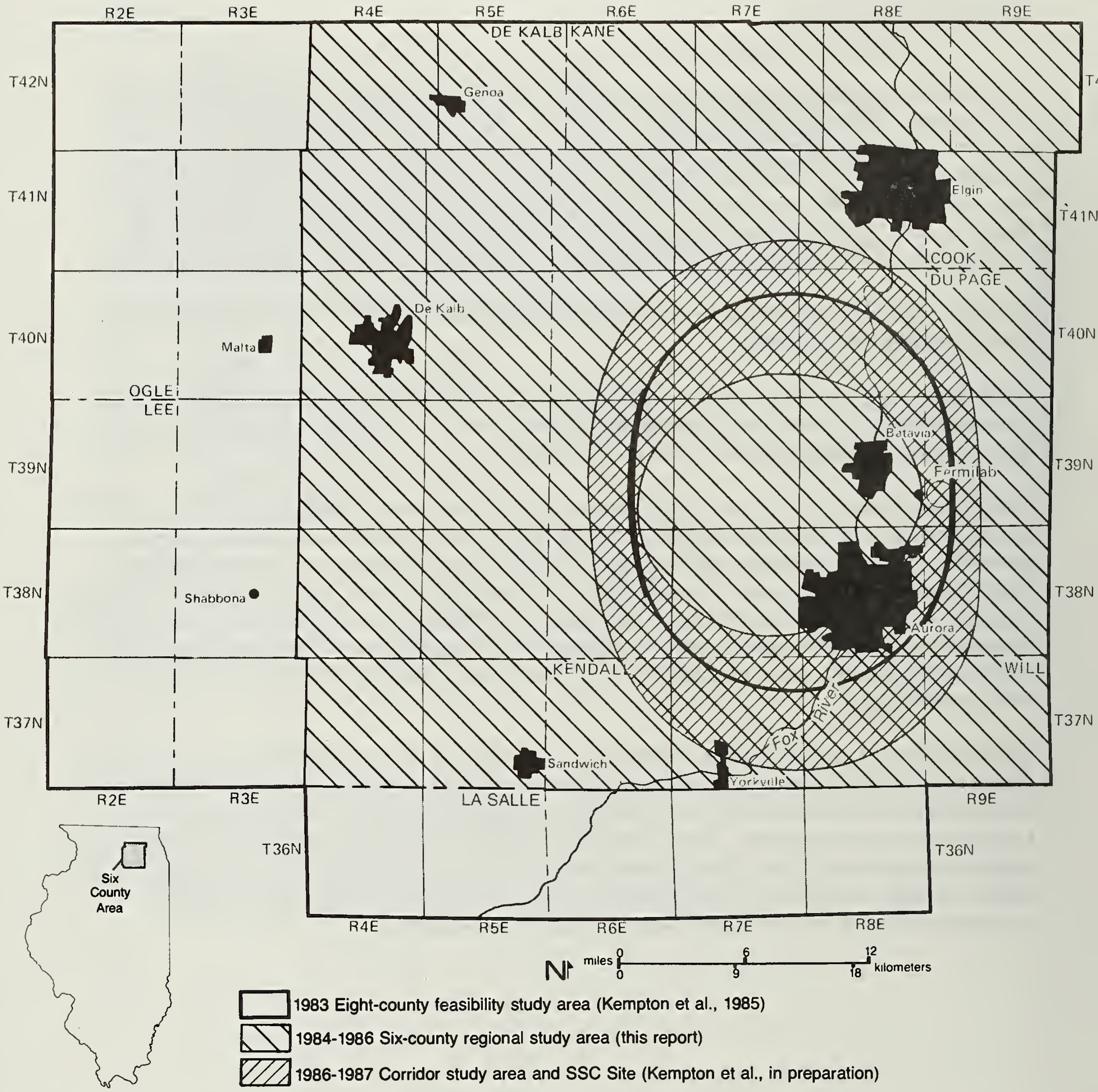


Figure 1 Study area in northeastern Illinois, showing one possible ring configuration for the SSC tunnel and the sequence of areas studied since 1983.

EXECUTIVE SUMMARY

From 1984 through 1986, geologists at the Illinois State Geological Survey (ISGS) conducted a thorough surface and subsurface field investigation of a six-county region west of Chicago to determine its geologic suitability as a potential site for the U.S. Department of Energy's proposed Superconducting Super Collider—a 20-TeV (trillion electron volt) particle accelerator to be used for high-energy research. The proposed site is adjacent to the Fermi National Accelerator Laboratory near Batavia; the Fermilab Tevatron could thus be used as an injector to the SSC.

The principal objective of the geological investigations was to verify that the characteristics and geotechnical properties of the bedrock underlying the region were suitable for construction of a 10-foot-diameter tunnel circling 53 miles approximately 280 to 610 feet below land surface. This tunnel would contain the accelerator and six to eight chambers to hold laboratory and utility facilities; up to 36 shafts (ranging in depths from 330 to 610 feet) would provide access to the tunnel and chambers. Figure 1 shows the geographic location of the ring proposed by the State of Illinois to the U.S. Department of Energy (USDOE) in September 1987 (State of Illinois, 1987). Figure 2 is a diagram showing how the SSC facility would be related to land surface and subsurface geology at the proposed Illinois site. As the diagram indicates, the only visible sign of the SSC at land surface would be structures over the access shafts and support buildings at the shafts and campus areas along the accelerator ring.

This regional summary covers field and laboratory work completed from June 1984 through April 1986 when the USDOE had not yet determined the final SSC design; additional test-hole data obtained later in 1986 were used to update geological maps, cross sections, and tables included in this report. Results of the two-phase regional drilling program in 1984 and 1985 confirmed and/or modified data from the Survey's initial SSC feasibility study of all data available prior to drilling and earlier studies conducted in northeastern Illinois. In the 1984-1985 drilling program, 17 test holes were drilled in the 36-township study area to establish a regional geologic framework for subsequent site-specific studies; in 1986, thirteen additional test holes were drilled to refine regional data within the SSC corridor area. A final ring location was selected within this corridor on the basis of the USDOE (1987) design of the ring, the attachment to Fermilab, and other environmental and land-use considerations. Figure 1 shows the progression of the geological studies from the broadest (eight-county) area investigated in the initial feasibility study to the most site-specific area (a corridor within three-counties and the proposed SSC site within this corridor) (Kempton et al., in preparation). This regional summary, focusing on a 36-township (six-county) area, represents an intermediate stage in the investigation.

The evaluation of the geology, hydrogeology, and geotechnical characteristics of the study area indicates that the region would be an excellent choice for the SSC site.

General Findings

- Construction of the tunnel in bedrock rather than in a shallow surface tunnel will minimize impact on homes, farms, and businesses and on groundwater, surface water, natural areas, and other surface features. Access and support facilities will be the only visible sign of the SSC at the land surface.
- The uniform, predictable geologic conditions throughout the study area provide flexibility in determining the final, precise site location for the SSC within the study area. Although a

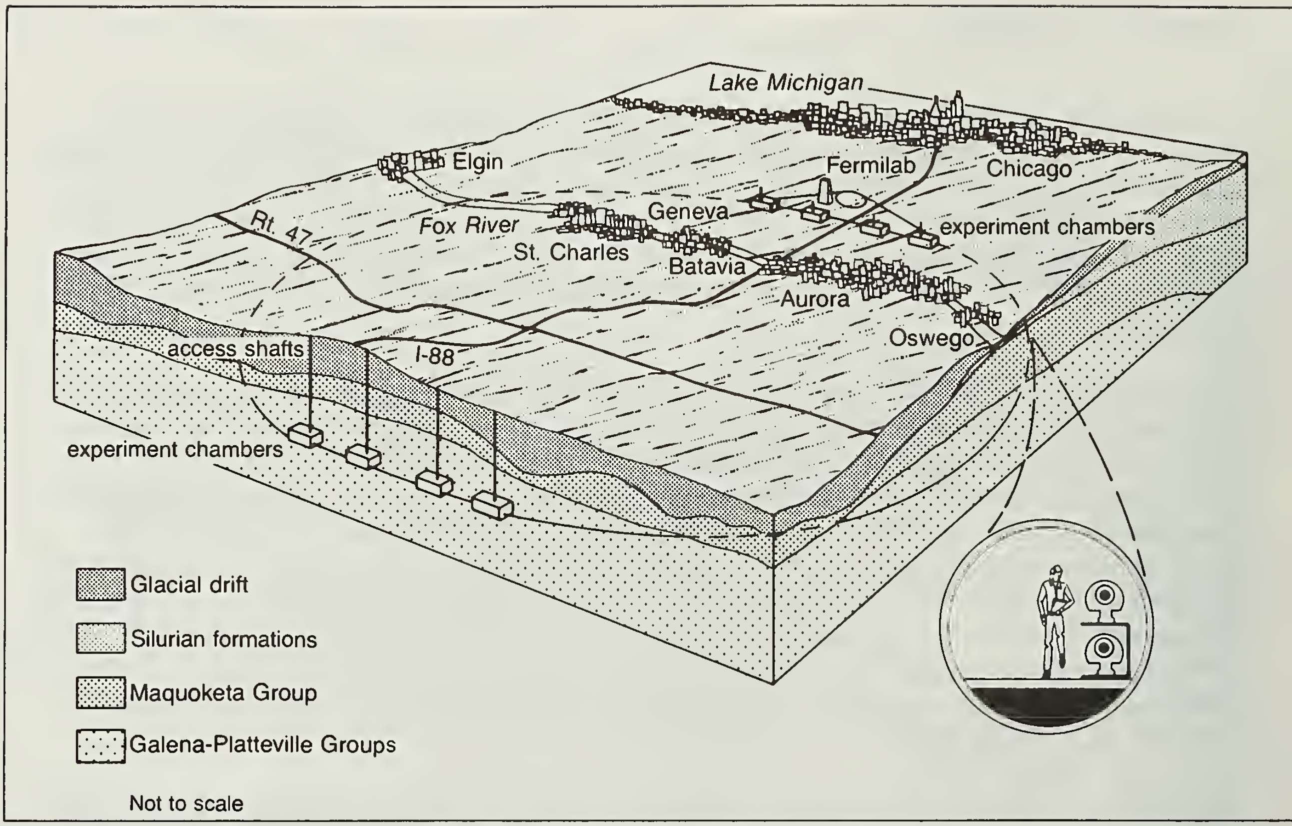


Figure 2 Cut-away of the area proposed for the SSC location. The insert at the lower right indicates the size of the ring in relationship to a man standing inside the 10-foot tunnel.

north-south orientation of the accelerator ring and associated chambers is preferred because of the orientations of fractures and joints in the bedrock, the ring could be pivoted slightly around the Fermilab Tevatron to minimize impact on surface features (Hines, 1986). The only geologic constraint in the area is depth: the tunnel is proposed to be located well below the bedrock valleys eroded into the bedrock surface. Tunneling through parts of these valleys—which may contain permeable materials—would be likely to cause increased water inflow that could result in construction and maintenance problems and affect groundwater resources. Construction costs would also be higher because several different types of tunneling equipment and techniques would have to be used through these materials.

- The region considered for the SSC is one of the most intensely studied areas in Illinois. The geology, geotechnical, and hydrogeological properties are well known and predictable. Data from more than 7,700 drilling records and from a total of 33 test holes drilled specifically for this project should minimize the likelihood of encountering major unknown geologic conditions during construction of the SSC facility.

Geology

- Geologic conditions are suitable for tunneling and chamber construction throughout the study area for siting the SSC. Glacial deposits overlie nearly horizontal Paleozoic carbonates and shales. The Galena and Platteville Groups together form a thick (300 to 380 feet), uniform, predictable, low-water-yielding carbonate unit; its excellent rock mass characteristics make

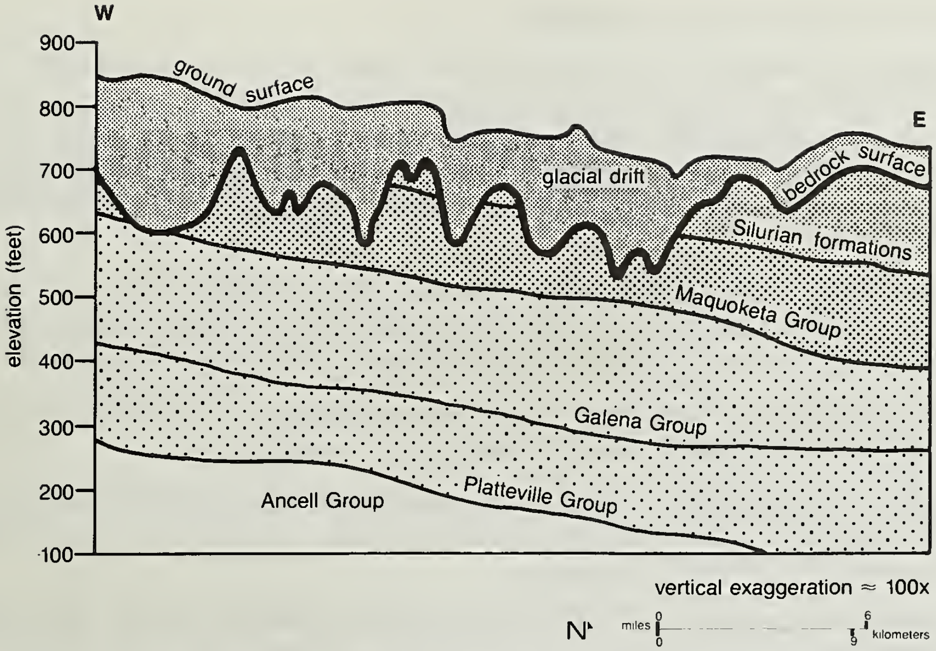


Figure 3 East-west-trending cross section (located approximately along Interstate 88 shown in fig. 2) showing generalized geology at the SSC site.

it suitable for construction by tunnel-boring machine – a safe, economical, fast method of tunnel excavation. Figure 3 is a cross section showing the geology at the site.

- The area is seismically stable. No earthquakes with epicenters along the Sandwich Fault Zone have been recorded.
- Detailed structure mapping on the top of the Galena Group (based on data from 850 deep wells) reveals that the bedrock units are nearly horizontal and relatively undeformed; there are no significant changes in elevation characteristic of major faults.

Hydrogeology

- Hydraulic conductivities of the bedrock at the proposed tunnel depth are low, mostly in the range of one foot per year. These low hydraulic conductivity values and low water levels in the region resulting from pumpage of the deeper sandstone aquifers in the Chicago and Fox River areas indicate that groundwater inflow and seepage should not be a major problem during construction and operation of the SSC tunnel and associated chambers.
- The low permeability of the Galena-Platteville and the fact that groundwater is generally not obtained from these units suggests that construction and operation of the SSC should have no significant impact on groundwater resources. Wells in the area obtain water from the upper bedrock aquifer above the zone proposed for the tunnel and from deeper midwest sandstone aquifers below the zone proposed for tunnel placement. Some wells are finished within the Galena-Platteville unit; these wells may provide some storage capacity but generally provide only minimal additional yield.
- Adequate water resources will be available from the drift, upper bedrock, and midwest sandstone aquifers for cooling and domestic purposes at the SSC facility.

Evaluation of Construction Conditions

- Investigations of the geotechnical properties of the bedrock and drift that would be excavated indicate that tunneling and construction conditions are very good; the bedrock is suitable for excavation by tunnel-boring machine. High boring-machine advance rates and low cutter costs are expected. The experimental chambers can be oriented north-south in the rock so as to bisect the angles of the two primary joint sets in the area, thereby maximizing chamber sidewall stability.
- Extensive in situ and laboratory tests of rock properties indicate that no major instability problems during construction are anticipated. Little or no systematic support—only spot bolting—will be required if the tunnel is constructed in the Galena-Platteville.
- The low seismicity of the area suggests that no unusual design or construction requirements are necessary with respect to earthquake ground motion.
- Material excavated during tunnel construction can be stored or disposed of in several dolomite quarries or gravel pits. ISGS studies indicate that no adverse effects on groundwater or surface water in the area are expected.
- Low water inflow rates into the tunnel (50 gallons per minute per mile, with grouting) are anticipated because of the low water-yielding nature of the rock.
- The excellent, homogeneous, predictable conditions of the rock mass and the successful experiences of contractors who bored 72 miles of tunnels through similar materials in the area during the Chicago Tunnel and Reservoir Plan (TARP), should minimize costs and construction risks. The TARP tunnels were on the average completed ahead of schedule and below cost estimates, which suggests that the proposed area is well suited for construction of the SSC tunnel. The LEP accelerator at CERN near Geneva, Switzerland has also been constructed in bedrock at similar depths to those proposed for the Illinois SSC.

INTRODUCTION

Since 1983 the Illinois State Geological Survey (ISGS) has had the lead role in assessing the geologic and geotechnical suitability of an area in northeastern Illinois for siting the proposed Superconducting Super Collider (SSC). The Illinois site for the SSC--a 20-trillion electron volt (TeV) particle accelerator to be used for high-energy physics research--would include, and extend west of, the Fermi National Accelerator Laboratory near Batavia so that Fermilab's Tevatron accelerator could be used as an injector for the SSC. The SSC and its laboratories and computers would be housed in chambers and a racetrack-shaped tunnel 53 miles in circumference and 10 feet in diameter, constructed in bedrock from 280 to 610 feet below ground level (average shaft depth about 432 feet). Figure 4 shows the location of the ring configuration of the SSC tunnel proposed by the State of Illinois to the U.S. Department of Energy (USDOE) in September, 1987.

The ISGS siting studies were planned to consist of four phases:

- preliminary feasibility study (Kempton et al., 1985; Hines, 1986), including collection and organization of existing geological data for screening and selecting possible sites for the SSC

- investigation of a selected region adjacent to Fermilab to locate the most suitable corridor for the SSC

- test-drilling program to verify predicted surface and subsurface conditions within the corridor and the surrounding area (Kempton et al., 1987a, 1987b; Curry et al., 1988; and Vaiden et al., 1988), and preparation of geological feasibility reports presenting study results (this study and Kempton et al., in preparation)

- consultation services during site selection and construction

Because Fermilab's Tevatron was built in the glacial drift, attention during the early stages of the feasibility study was focused on the materials constituting the drift. An initial look at detailed maps, cross sections, and land surface elevation for a hypothetical accelerator ring convinced the researchers that bedrock would be a much better tunneling medium than would drift, and they began a detailed study of the bedrock--particularly the Galena and Platteville Groups.

On the basis of results of the feasibility study, a 36-township area encompassing all of Kane County and parts of De Kalb, Cook, Du Page, Will, and Kendall counties was then selected for further investigation (fig. 4). A drilling program in which cores from 17 test holes were thoroughly examined and analyzed was carried out in 1984 and 1985 to verify the bedrock information available from water-well records and samples.

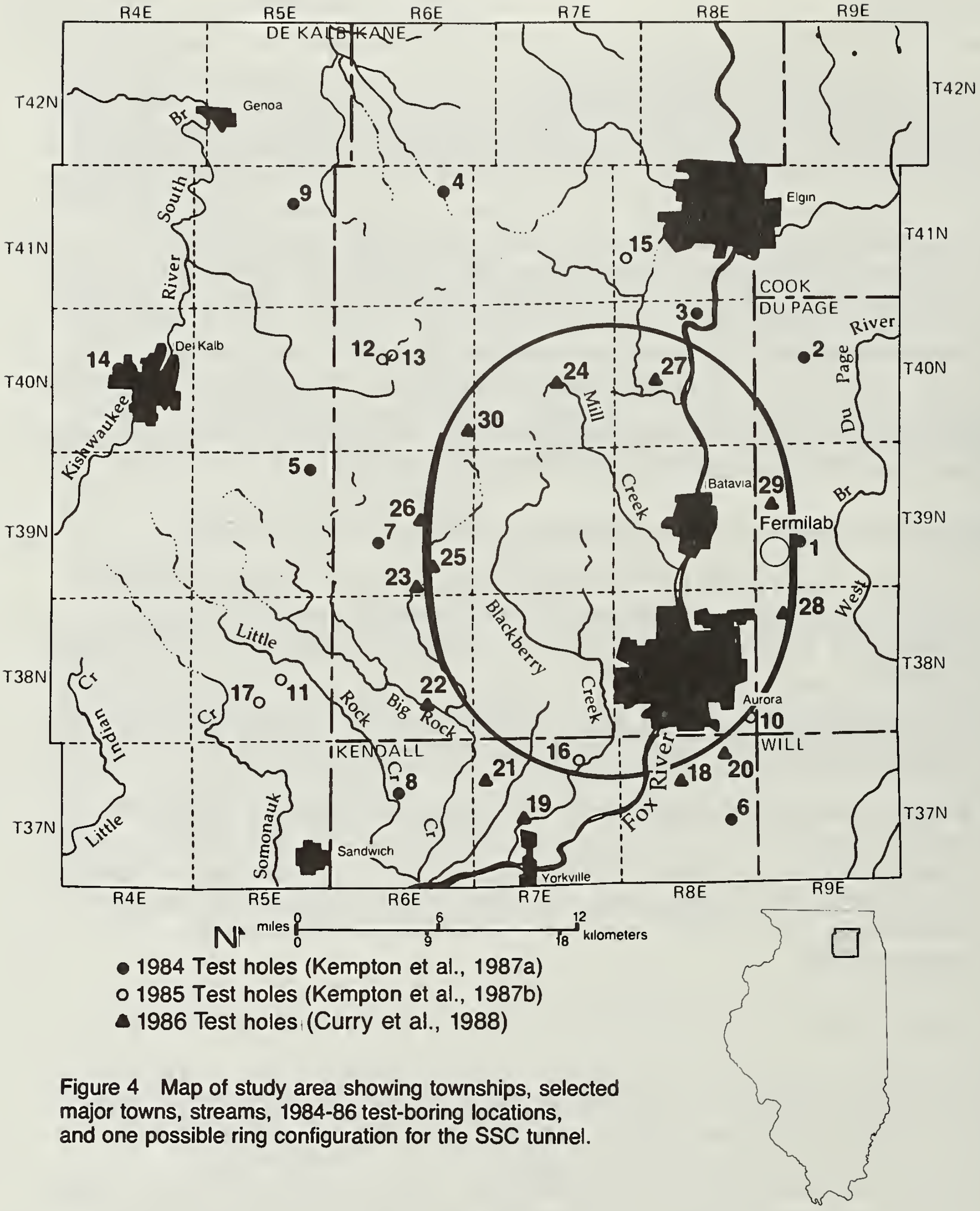


Figure 4 Map of study area showing townships, selected major towns, streams, 1984-86 test-boring locations, and one possible ring configuration for the SSC tunnel.

This regional summary--which includes data from investigations of the stratigraphy, structure, hydrogeologic characteristics, and geotechnical properties of the bedrock and drift in the regional study area--presents a broad overview of the geologic framework of the study region but concentrates on those factors most relevant to construction of the SSC. The summary covers work completed by the Survey's SSC Geological Task Force from June 1984 through April 1986; additional data from 1986 test drilling (Curry et al., 1988: Vaiden et al., 1988) were used to update the geological maps and cross sections. Final integration of all study data will be included in Kempton et al. (in preparation).

Principal findings show that

- the area studied is an excellent site geologically for the SSC;
- tunneling in the Galena-Platteville and Maquoketa bedrock would be safe, economical, and environmentally sound;
- this bedrock has ideal properties for tunnel construction; it consists of thick, nearly horizontal, relatively uniform and undeformed carbonate rocks and shales. Laboratory and in situ tests of rock properties indicate that (1) only spot bolting--no systematic support--would be required to support the tunnel, and (2) the rock is suitable for construction by use of a tunnel-boring machine, which is safer, faster, and less expensive than drill-and-blast methods. Advance rates of 180 feet per day (with two 10-hour shifts) can be anticipated, and cutter costs will be low because of the nonabrasive nature of the rock;
- groundwater inflow or seepage should not be a major problem during tunnel construction and operation of the SSC facility, and tunnel construction and operation should not adversely affect groundwater resources of the area (Kempton et al., 1987c).

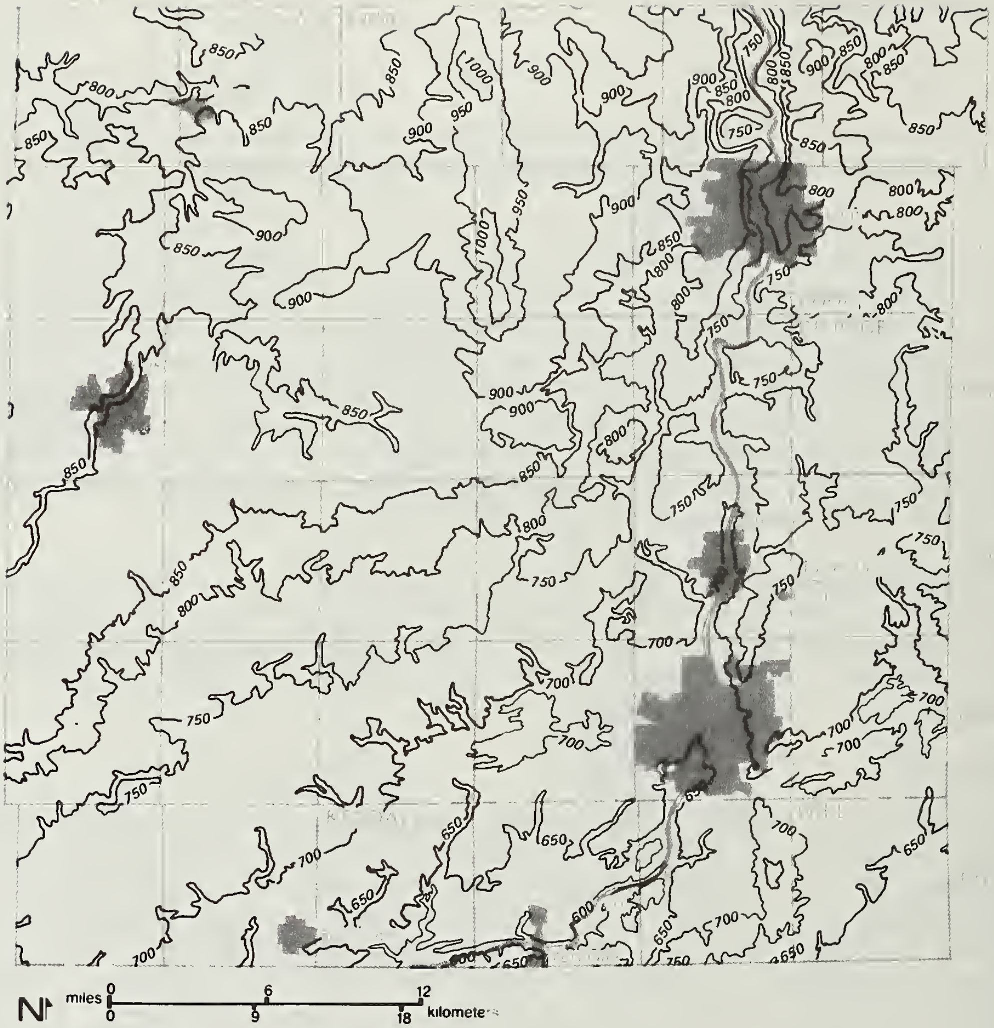
STUDY AREA

The study area, roughly 40 miles west of Chicago, covers approximately 1300 square miles (fig. 4). The size and location of this area was determined by (1) considering the size and shape of the SSC ring (first envisioned as up to 100 miles in circumference), (2) avoiding the inactive Sandwich Fault to the southwest because fractured rocks in this zone would offer poor tunneling conditions, and (3) including Fermi National Accelerator Laboratory in order to take advantage of existing land and facilities. The study region is primarily urban in the east and agricultural in the west (Hines, 1986; Dahlberg and Luman, 1985). The population of the area is concentrated in towns along the Fox River and in the towns of De Kalb and Sycamore in De Kalb County; the rest of the area includes smaller scattered communities and suburban developments but is still predominantly rural.

The topography of the area is characterized by gently rolling prairie interspersed with large and small river valleys, subtle glacial ridges, and rounded hills (fig. 5). Surface elevation ranges from 600 feet above mean sea level (m.s.l.) in northern Kendall County to more than 1,000 feet above m.s.l. in northern Kane County (Kempton et al., 1985; Hines, 1986).

DATA SOURCES

Detailed studies and extensive data sets provide the background for the geologic and hydrogeologic maps and discussions presented here: studies of the bedrock by Buschbach (1964), Hughes, Kratz, and Landon (1966), Willman (1973), Willman and Kolata (1978), and Kolata and Graese (1983);



contour interval 50 feet; datum is mean sea level

Figure 5 Generalized topography of the study area (modified from Kempton et al., 1985).

reports on the glacial deposits by Kempton (1963, 1966), Kempton and Hackett (1968a, 1968b), Gross (1969), Kempton and Gross (1971), Landon and Kempton (1971), Kemmis (1978, 1981), Wickham (1979), Wickham and Johnson (1981), Brossman (1982), Schmitt (1985), and Wickham, Johnson, and Glass (1988); other regional reports by Piskin and Bergstrom (1967, 1975), Willman and Frye (1970), and Willman et al. (1975); and county and regional studies relating geology to land-use planning, including discussions of aquifer distribution and engineering characteristics of glacial deposits by Gross (1970) for De Kalb County, Kempton, Bogner, and Cartwright (1977) for northeastern Illinois for the Northern Illinois Planning Commission (NIPC), and Gilkeson and Westerman (1976) for Kane County (NIPC). The preliminary feasibility study (Kempton et al., 1985) evaluated existing data to select potential sites for the SSC.

The ISGS maintains an extensive database of water-well logs and samples. More than 7,700 drilling records, mostly for shallow wells in the drift and upper bedrock in urban areas, were used to construct maps (see well location maps in Hines, 1986). In addition, test holes from controlled drilling programs (Landon and Kempton, 1971; Reed, 1972, 1975; and Wickham, 1979), and more than 200 seismic station sites were used to construct the bedrock topography map (Gilkeson and Heigold, 1985; Steven McFadden, ISGS, personal communication, 1987). More than 850 of the 7,700 drilling records (including 150 sample sets of well cuttings) were examined and plotted during preparation of the bedrock maps for this report. In addition, outcrops and quarry exposures within the area were examined.

An ISGS geologist examined more than 150 water-well sample sets provided by drilling contractors from within the study area to determine group/formation tops and lithologic variation in the rock units. These samples were examined thoroughly through the top of the Galena Group, but were studied in less detail below this depth because the rock types are similar. Samples from water wells were generally available in 5-foot intervals and in some instances in 10-foot intervals. Characteristics such as lithology, color, grain size, and presence of fossils and chert were noted in descriptions. Stratigraphic tops were then selected, with an accuracy of ± 5 feet due to sampling intervals. Colors of wet samples were compared with colors in the Rock-Color Chart (Geological Society of America, 1984).

The test-drilling program provided additional data. Researchers collected information on drift and bedrock lithology, soil and rock strength, water levels, bedrock fracturing and joint systems, in situ hydraulic conductivity, and downhole geophysical logging (Kempton et al. 1987a, 1987b). The location of each of the holes drilled is shown in figure 4. Total footage of the core obtained during the 1984-85 drilling (F Series) program was 7,013.6 feet (5,049.55 feet of bedrock and 1,964 feet of drift). All of the 1984-85 drillholes were vertical except for one angle boring (ISGS F-8) drilled 30 degrees from vertical to permit examination of joint strike orientations and spacing immediately northeast of the Sandwich Fault Zone (figs 4, 6). Most of the 1984-85 test holes were drilled to 400 feet above mean sea level, the initial target elevation of the bedrock tunnel to house the SSC. Further modification of this target elevation increased tunnel depth, placing the tunnel completely within the Galena-Platteville, and target elevations of 350 feet and later 320 feet above mean sea level were considered. Drilling in 1986 (S Series) (Curry et al., 1988; Vaiden et al., 1988) penetrated rocks at these deeper elevations.

PREPARATION OF GEOLOGIC MAPS

Geological maps for this study were prepared at a scale of 1:100,000. Maps at scales of 1:62,500 and 1:24,000 were used for some detailed mapping, and final versions of the large, detailed maps were photographically reduced and transferred to the 1:100,000 base.

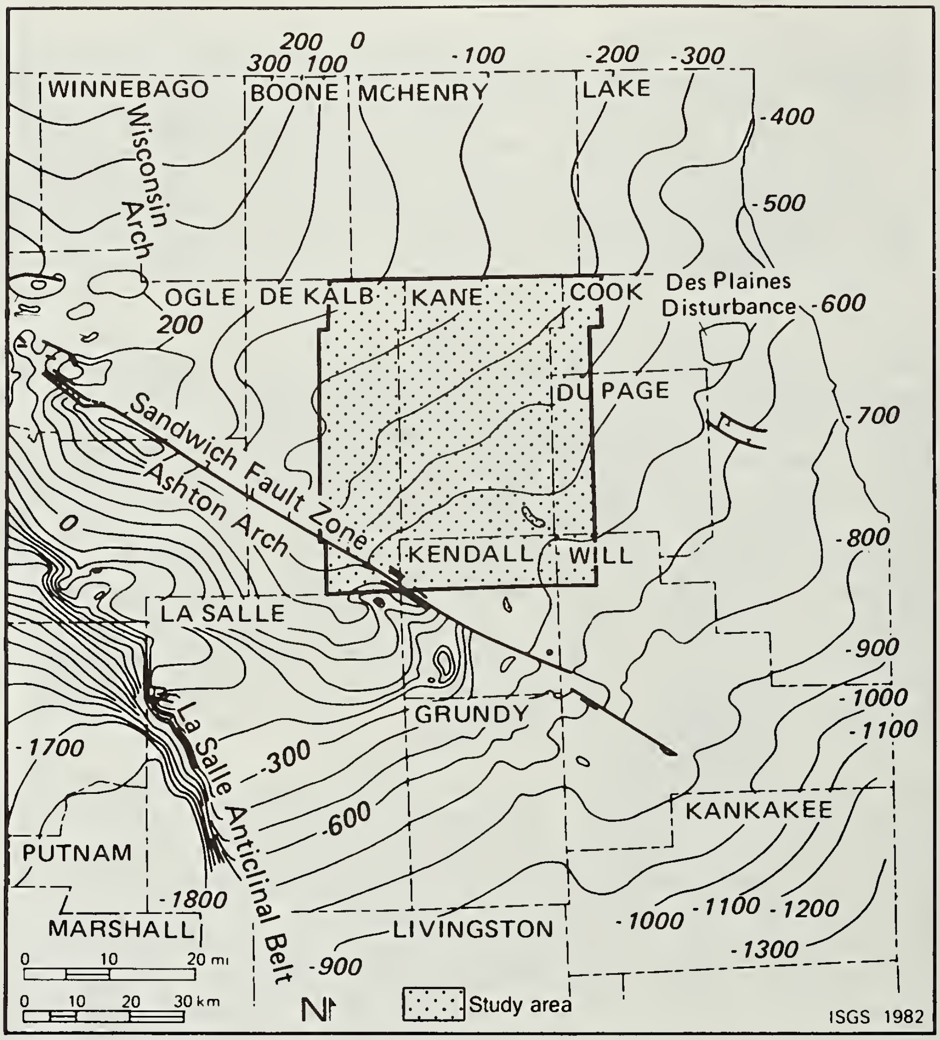


Figure 6 Major structural features in northeastern Illinois as indicated by the elevation of the top of the Franconia Formation in the Cambrian System; contour interval = 100 ft; datum is mean sea level (modified from Kolata and Graese, 1983).

Several maps presented in this report are revisions of those in the preliminary geological feasibility study (Kempton et al., 1985). The maps are based on restudy of all available data (as of April, 1986), including the 17 core holes drilled specifically for regional study; the bedrock maps have been modified by data acquired late in 1986 (Curry et al., 1988; Vaiden et al.; 1988, Laymon, 1987). Maps revised since the preliminary study include areal geology of the bedrock surface, elevation of the top of Galena Group, thickness of the Maquoketa Group, thickness of Silurian dolomite formations, combined thickness of the Galena-Platteville Groups, bedrock topography, drift thickness, and potential surficial and buried sand and gravel aquifers. In addition, new cross sections based on sample and core descriptions from the 1984-86 test drilling programs have been constructed.

Included in this publication but not in the preliminary report are a map of the elevation of the top of the Ancell Group (Glenwood Formation, St. Peter Sandstone), and a surficial deposits map.

GEOLOGY

A. M. Graese and B. B. Curry

The SSC regional study area in northeastern Illinois provides an excellent geologic setting for construction of the proposed Superconducting Super Collider. The relatively uniform and undeformed, nearly horizontal bedrock in which the tunnel to house the facility could be constructed is overlain by thick deposits of glacial drift. The Paleozoic bedrock underlying the region (fig. 7) was deposited between 420 million and 570 million years ago (Cambrian to Silurian age). These sedimentary rocks, consisting primarily of dolomite, limestone, sandstone, and shale, are as much as 4,000 feet thick in northeastern Illinois (Willman et al., 1975).

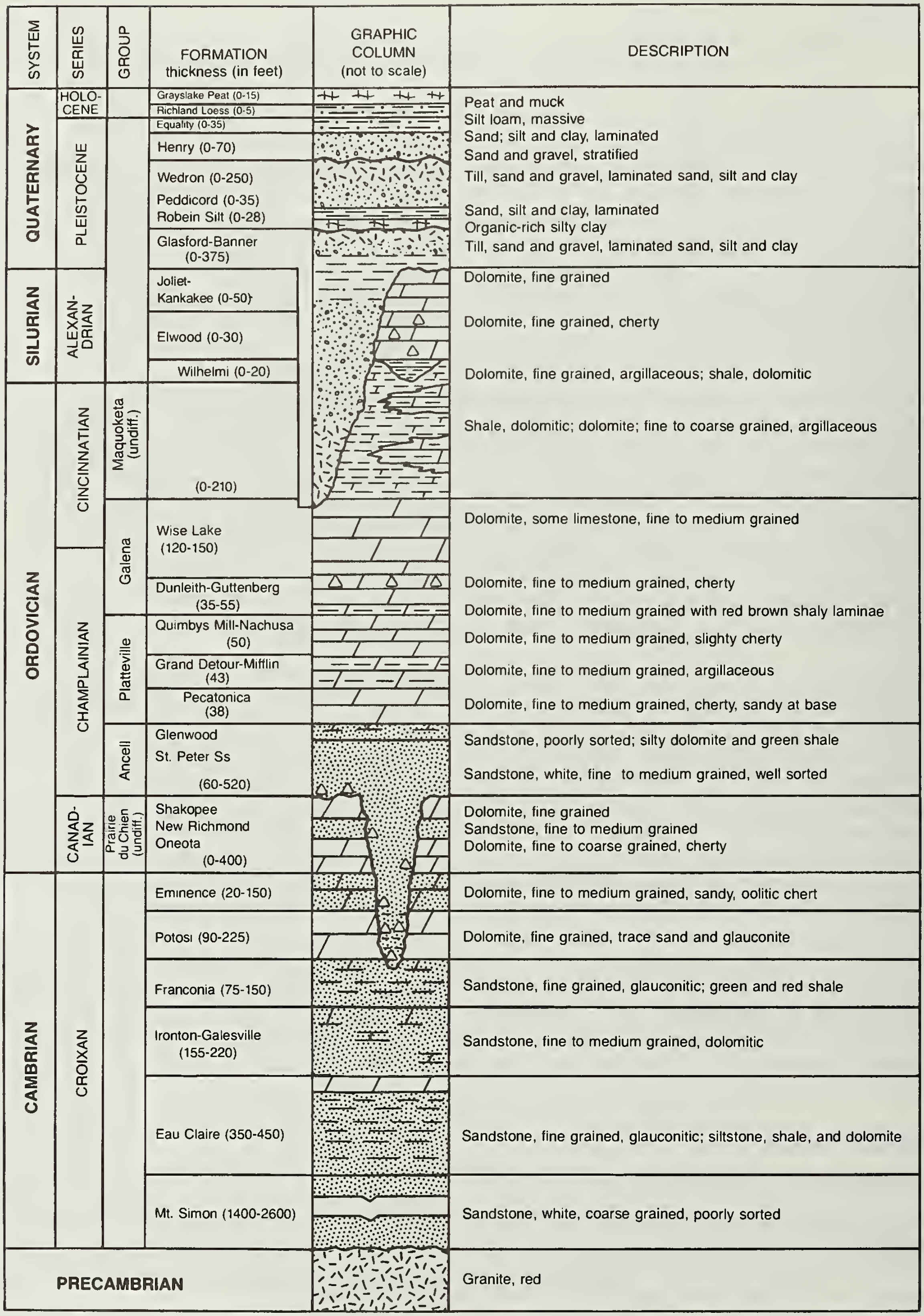
Overlying the bedrock are materials deposited during the Quaternary Period (from about 1.5 million years ago to the present). This sequence of deposits consists mostly of glacial drift (till, lake sediments, and coarse-textured outwash material), loess (windblown silt), and alluvial (river) sediments; it generally is 50 to 300 feet thick in northeastern Illinois but is more than 400 feet thick in northwestern De Kalb County. Along streams these deposits may be less than 50 feet thick; bedrock is exposed in some places along streams, in quarries, and roadcuts. Glacial deposits are usually thickest where they fill valleys cut into the bedrock surface and under some end moraines (Kempton et al., 1985).

Although the geology of the region is not structurally complex, the study area is located northeast of the Sandwich Fault Zone--a zone 85 miles long and 0.5 to 2.0 miles wide, extending from Will County on the south to Ogle County on the north--that is characterized by numerous northwest-trending, near-vertical faults. At the zone's midpoint in southeastern De Kalb County the rocks are displaced vertically by as much as 800 feet. Geologic relationships suggest that most displacement occurred in late Paleozoic time, approximately 250 to 300 million years ago. However, the stratigraphic record near the fault zone is incomplete from Silurian to Pleistocene time and it is therefore uncertain whether or not additional displacements occurred during this interval (Kolata, Buschbach, and Treworgy, 1978). This zone is considered seismically inactive. No historical earthquakes with epicenters along this fault zone have been recorded (Heigold, 1972); moreover, no displacement has occurred for at least 17,000 years where Wisconsinan-age till covers an exposure of the fault zone.

BEDROCK GEOLOGY

Succession and Distribution

This section focuses on the vertical and areal distribution and characteristics of the bedrock strata that would contain the proposed SSC tunnel, chambers, and shafts: the Galena, Platteville, and Maquoketa Groups of Ordovician age, and Silurian age formations.



SYSTEM	SERIES	GROUP	FORMATION thickness (in feet)	GRAPHIC COLUMN (not to scale)	DESCRIPTION
QUATERNARY	HOLOCENE		Grayslake Peat (0-15)		Peat and muck
			Richland Loess (0-5)		Silt loam, massive
	PLEISTOCENE		Equality (0-35)		Sand; silt and clay, laminated
			Henry (0-70)		Sand and gravel, stratified
			Wedron (0-250)		Till, sand and gravel, laminated sand, silt and clay
			Peddicord (0-35)		Sand, silt and clay, laminated
			Robein Silt (0-28)		Organic-rich silty clay
			Glasford-Banner (0-375)		Till, sand and gravel, laminated sand, silt and clay
SILURIAN	ALEXANDRIAN		Joliet-Kankakee (0-50)		Dolomite, fine grained
			Elwood (0-30)		Dolomite, fine grained, cherty
			Wilhelmi (0-20)		Dolomite, fine grained, argillaceous; shale, dolomitic
ORDOVICIAN	CINCINNATIAN	Maquoketa (undiff.)	(0-210)		Shale, dolomitic; dolomite; fine to coarse grained, argillaceous
		Galena	Wise Lake (120-150)		Dolomite, some limestone, fine to medium grained
	CHAMPLAINIAN		Dunleith-Guttenberg (35-55)		Dolomite, fine to medium grained, cherty Dolomite, fine to medium grained with red brown shaly laminae
		Platteville	Quimbys Mill-Nachusa (50)		Dolomite, fine to medium grained, slighty cherty
			Grand Detour-Mifflin (43)		Dolomite, fine to medium grained, argillaceous
			Pecatonica (38)		Dolomite, fine to medium grained, cherty, sandy at base
		Ancell	Glenwood		Sandstone, poorly sorted; silty dolomite and green shale
			St. Peter Ss (60-520)		Sandstone, white, fine to medium grained, well sorted
	CANADIAN	Prairie du Chien (undiff.)	Shakopee		Dolomite, fine grained
			New Richmond		Sandstone, fine to medium grained
			Oneota (0-400)		Dolomite, fine to coarse grained, cherty
CAMBRIAN	CROIXAN		Eminence (20-150)		Dolomite, fine to medium grained, sandy, oolitic chert
			Potosi (90-225)		Dolomite, fine grained, trace sand and glauconite
			Franconia (75-150)		Sandstone, fine grained, glauconitic; green and red shale
			Ironton-Galesville (155-220)		Sandstone, fine to medium grained, dolomitic
			Eau Claire (350-450)		Sandstone, fine grained, glauconitic; siltstone, shale, and dolomite
			Mt. Simon (1400-2600)		Sandstone, white, coarse grained, poorly sorted
PRECAMBRIAN					Granite, red

Figure 7 Stratigraphic column of bedrock and drift units in northeastern Illinois, northeast of the Sandwich Fault Zone (not to scale).

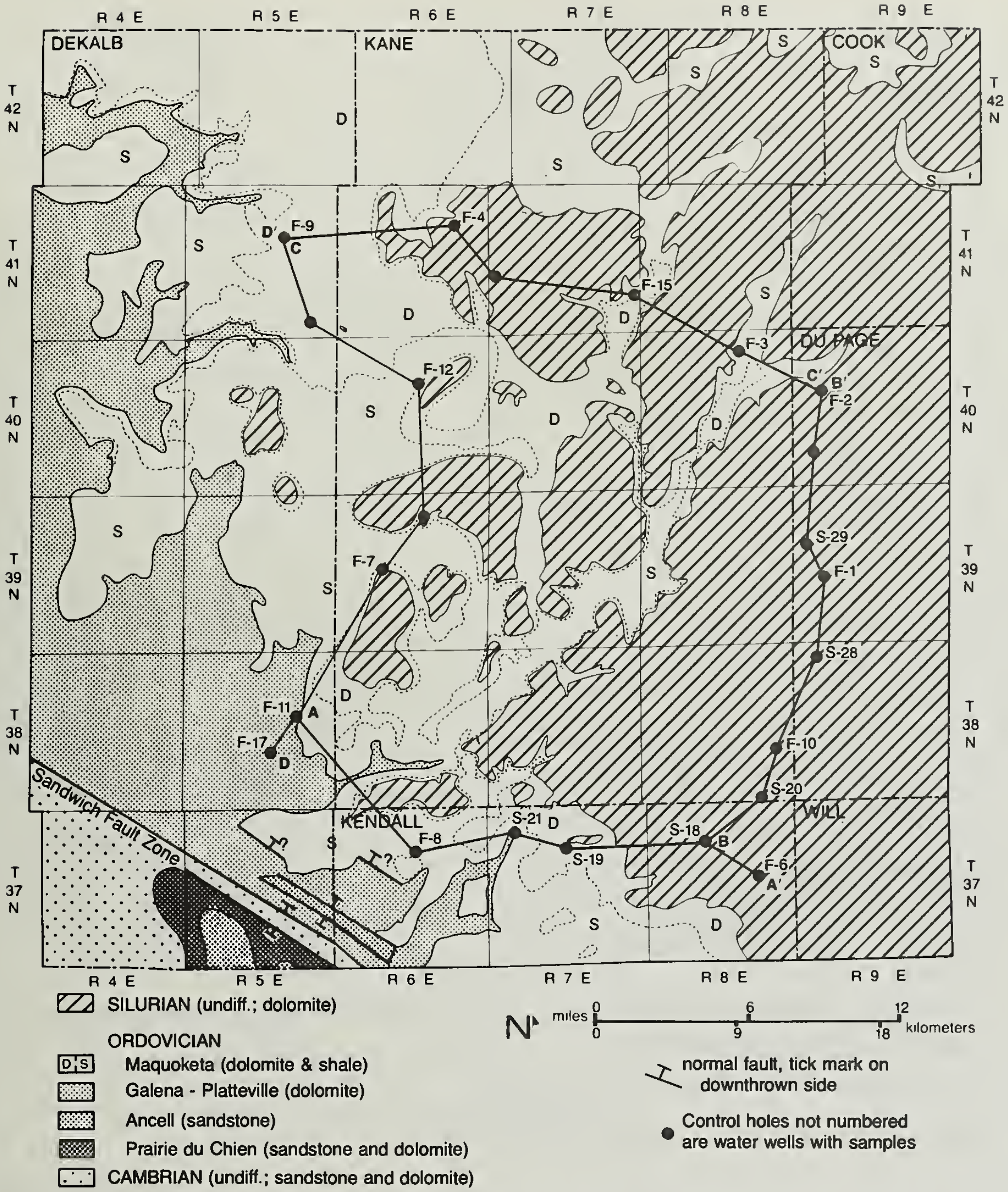


Figure 8 Areal geology of the bedrock surface; lines of bedrock cross sections (figs. 8-11) are shown.

Numerous formations and members are recognized in these Paleozoic strata (fig. 7), but figure 8 shows only the following divisions (from oldest to youngest): (1) Cambrian System (undifferentiated formations, primarily sandstone and dolomite); (2) Ordovician System: Prairie du Chien Group (dolomite and sandstone), Ancell Group (primarily sandstone, some shale and dolomite), combined Galena and Platteville Groups (dolomite and limestone), and Maquoketa Group (shale and dolomite, some limestone); and (3) Silurian System (undifferentiated formations, composed of dolomite and some limestone). The areal distribution of these rocks at the bedrock surface is related to regional structure and to Quaternary erosion. North of the Sandwich Fault Zone the distribution is controlled by the truncation of the southeasterly dipping rocks along

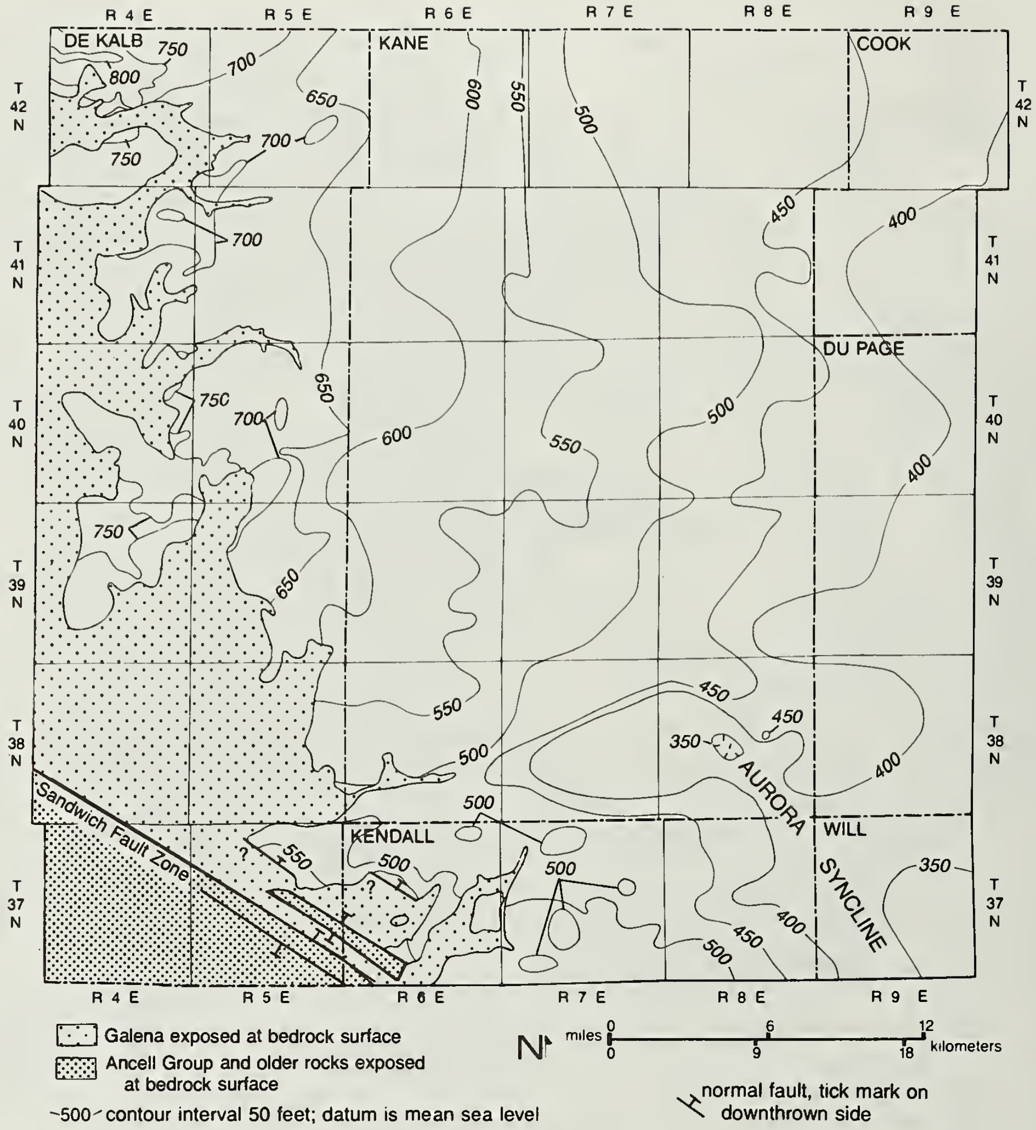


Figure 9 Structure on the top of the Galena Group.

the Wisconsin Arch (figs. 6, 8); the older Galena-Platteville Groups are present along the western margin of the study area (fig. 8) and the younger Silurian formations are the uppermost bedrock unit along the east side. Several bedrock valleys eroded into the Paleozoic rocks also control the bedrock distribution. Along the western margin (fig. 8) Galena-Platteville rocks are found along the deepest segments of east trending bedrock valleys. Along the eastern margin of the study area the Silurian-Maquoketa contact is controlled by the southwest trend of the "Newark Valley" (fig. 15, p. 19) and related tributary systems.

The Sandwich Fault Zone (fig. 8) juxtaposes the Ordovician Galena and Platteville Groups on the northeast against Cambrian-aged rocks of the Eminence, Potosi, and Franconia Formations (fig. 6) on the southwest. Additional discussion of the area southwest of the fault zone is included in Kolata, Buschbach, and Treworgy (1978) and Kempton et al. (1985).

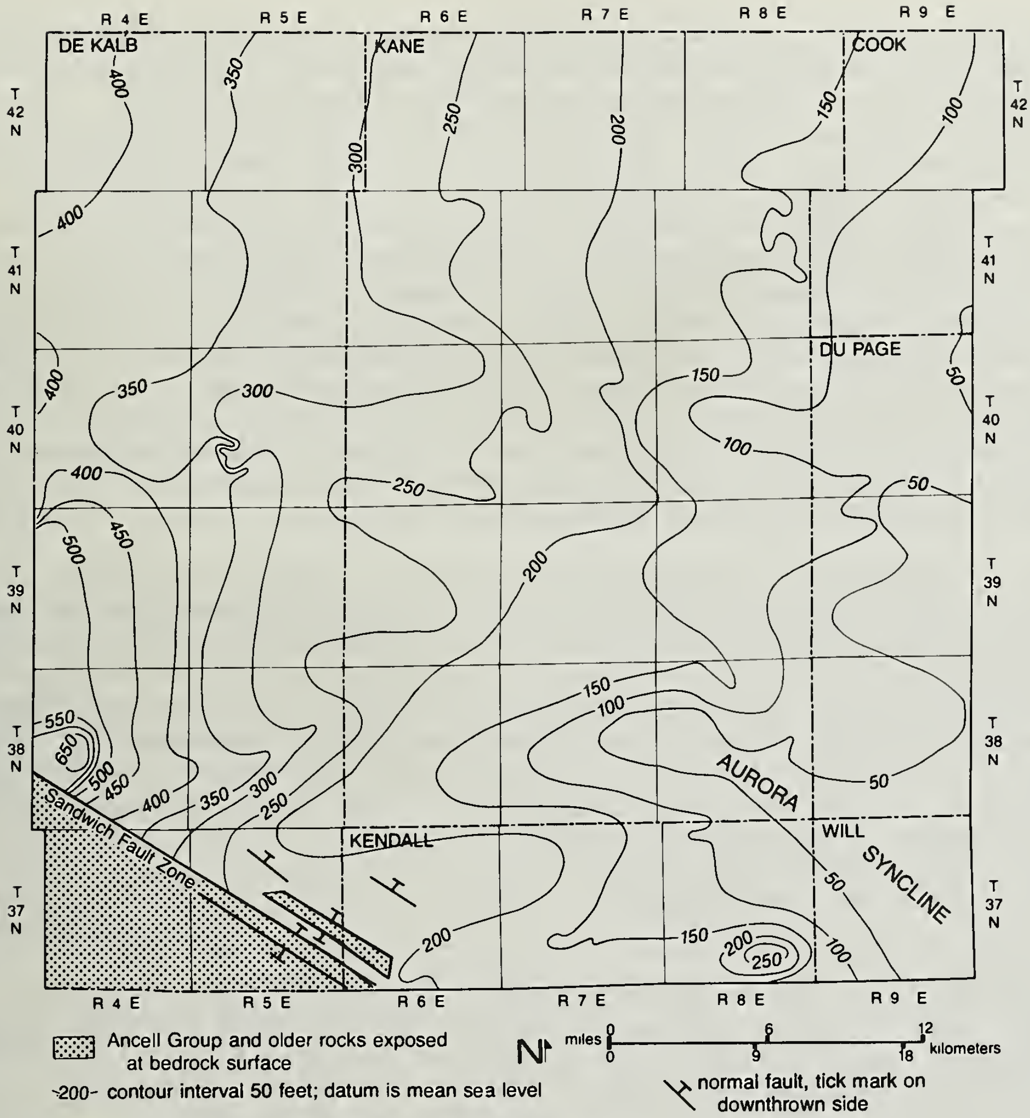


Figure 10 Structure on the top of the Ancell Group.

Structural Features

In the study area the strata dip to the southeast approximately 10 to 15 feet per mile (0.1° to 0.2°). Consequently, a given stratigraphic horizon (for instance, top of Galena Group) is approximately 350 feet higher on the northwest side of the area than on the southeast side (fig. 9). The top of the Galena Group (fig. 9) is a widespread, mappable surface; it is the most reliable structural datum within the study area. More than 850 deep water wells and test holes have penetrated the top of Galena. Data for this map (fig. 9) are concentrated primarily along the Fox River in eastern Kane and northern Kendall Counties; mapping is thus more accurate in these regions than in northern Kane and western Du Page Counties where there are fewer wells.

Superimposed on the southwest-trending regional dip are gentle east-west and northwest-southeast-trending folds, which are evident on maps of the top of the Galena (fig. 9) and the top of the Ancell Group (fig. 10). The northwest-trending structure in the southern third of both maps is the Aurora Syncline (Willman and Payne, 1942). A minor anticline and syncline shown on both maps in T40N-T41N to R5E-R7E may be related to an inferred basement fault interpreted by McGinnis (1966) on the basis of poor to fair reflection and gravity data. Displacement along the McGinnis Fault north of and parallel to the Sandwich Fault Zone is thought to have occurred before middle Ordovician time, 458 to 478 million years ago, prior to Galena-Platteville deposition. Although some existing well records and structure mapping confirm the existence of folding in younger rocks roughly parallel to the inferred basement fault, it is subtle, having an estimated relief of about 30 feet over a distance of 1 to 2 miles. Additional test drilling and seismic reflection data should determine whether or not the inferred basement fault exists.

Detailed mapping has revealed no major faults or major structural anomalies other than the Sandwich Fault Zone. During construction work for the Chicago Tunnel and Reservoir Plan (TARP) 40 miles to the east of the SSC study area, minor strike-slip offsets with vertical displacements ranging from inches to 50 feet were encountered. However, some elevation differences in mapped geologic contacts interpreted as offsets by Harza Engineering (1975) in preconstruction work for the TARP project were found during the tunnel construction to be caused by minor folding (Harza, 1984; Harza with ISGS, 1988).

Description of Bedrock Units

Structural and stratigraphic relationships from land surface down to the top of the Ancell Group, which underlies the Platteville Group, are shown in four cross sections (fig. 11a-d) based on core and sample studies and structure maps. The cross sections also show the thickness and gross lithology of the glacial drift. Of note on these cross sections are the bedrock valleys, the sand and gravel deposits within these valleys, facies relations within the Maquoketa Group, structural relief on the top of the Galena-Platteville Groups, and the thinning and complete removal (by pre-Quaternary erosion) of the Maquoketa and Silurian rocks along the western margin of the study area.

Ancell Group. The top of the Ancell Group (St. Peter Sandstone and Glenwood Formations) forms the lower limit of the bedrock units that would house the proposed SSC tunnel (fig. 10). The older St. Peter Sandstone is composed of white, fine- to medium-grained, friable sandstone that normally ranges in thickness from 150 to 250 feet in the study area (except where eroded at the bedrock surface). The younger Glenwood, which is as much as 75 feet thick, is highly variable in lithology; it consists of a poorly sorted sandstone with interbedded shale and silty dolomite.

Galena and Platteville Groups. Carbonate rocks of the Galena and Platteville Groups typically consist of pale yellow brown, fine- to medium-grained, pure (95 percent carbonate, 5 percent or less clay and silt-sized quartz), fine- to medium-bedded dolomite, and one region of limestone. The beds are generally 6 to 12 inches thick, very wavy, and separated by thin (less than 1/16 inch), commonly stylolitic, green or brown shale laminae. In some places the carbonate rocks contain chert nodules. The combined thickness of the Galena and Platteville Groups (fig. 12) generally ranges from 300 to more than 350 feet where overlain by the Maquoketa Group.

The Platteville Group, which lies below the Galena Group, comprises a number of formations and members; they are described in detail in Willman and Kolata (1978). The Platteville is composed of light gray to brown, very fine- to medium-grained, fossiliferous, pure to argillaceous, thin- to medium-bedded dolomite separated by thin, brown to gray, wavy, shaly laminae. In places (see figs. 11a, 11b) the dolomite grades into calcareous dolomite and very fine-grained limestone; the basal few feet are often sandy. Dark gray, mottled, argillaceous beds, and chert nodules (less than 3 inches in diameter) may be present in places. The Platteville ranges in thickness from 140 to 150 feet in the study area.

The Galena Group is subdivided into three formations in the study area: the Guttenberg, Dunleith, and Wise Lake Formations. The thickness of the Galena Group in the area ranges from 160 to 200 feet.

The Guttenberg Formation consists of pure dolomite separated by reddish brown shale laminae. Within the study area, the Guttenberg is approximately 2 feet thick and is often absent.

The Dunleith Formation is a medium-grained, vuggy dolomite approximately 45 feet thick. The upper 5 to 10 feet is commonly cherty; the remaining dolomite is similar but more vuggy than the overlying Wise Lake Formation.

Most of the Wise Lake Formation consists of pure, light brown, slightly vuggy dolomite. Generally thick bedded, the unit is separated by wavy, very thin, shaly laminae; within the study area it is generally 140 feet thick. The upper 5 to 10 feet is often very vuggy and occasionally oil stained. In a few places in the Aurora area of Kane County where the Dunleith and Wise Lake Formations cannot be readily differentiated from each other, the Wise Lake is a very fine-grained to coarse-grained limestone. A widespread, thin, mixed-layer illite-smectite clay bed--the Dygerts K-bentonite bed (Willman and Kolata, 1978) less than 2 inches thick--has been noted 80 to 100 feet below the top of the Wise Lake; the composition of the clay fraction is roughly 80 percent illite and 20 percent smectite.

Maquoketa Group. The rocks lying conformably above the dolomites of the Galena and Platteville Groups are the shales, dolomites, and minor limestones of the Maquoketa Group. The thickness of the Maquoketa (fig. 13) ranges from 0 to 210 feet in areas where overlying Silurian rocks have been removed and 130 to 210 feet if covered by Silurian rocks. Pre-Silurian erosion on the surface of the Maquoketa may have partly controlled the thickness of the Maquoketa Group, producing channels that were subsequently filled by the Silurian Wilhelmi and Elwood Formations (Kolata and Graese, 1983).

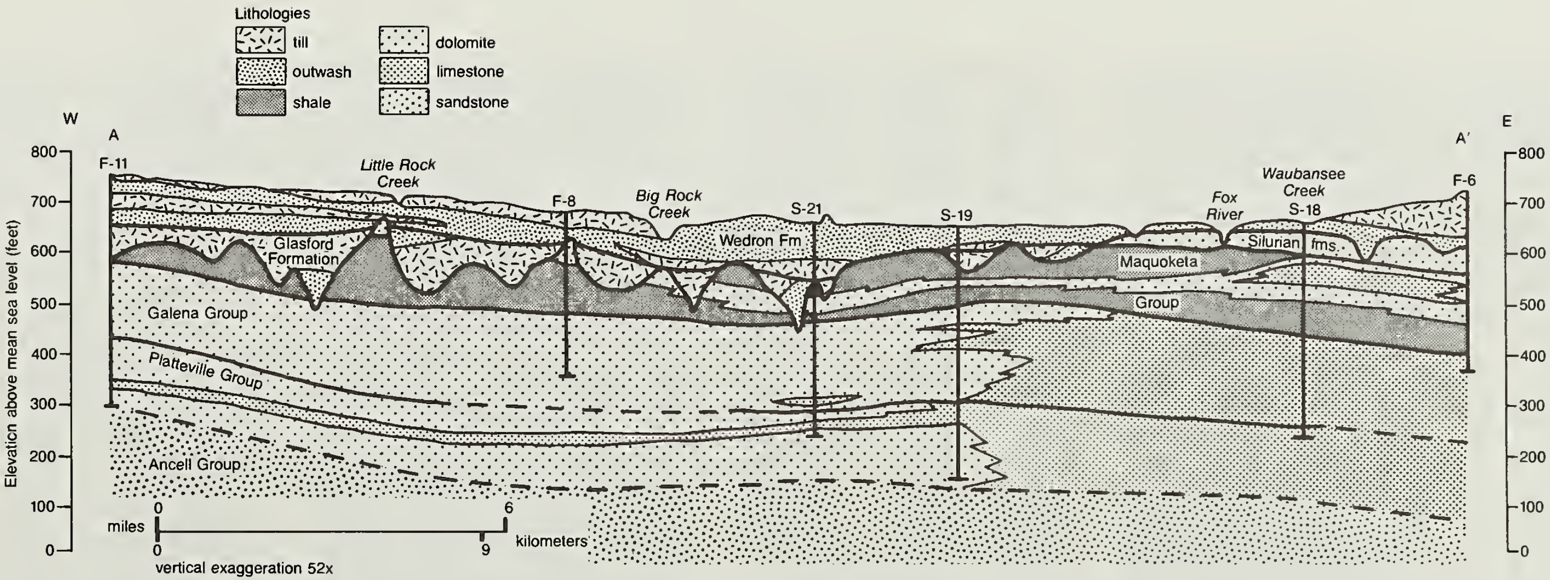


Figure 11a Southern west-east cross section A-A′ (see location map, fig. 8).

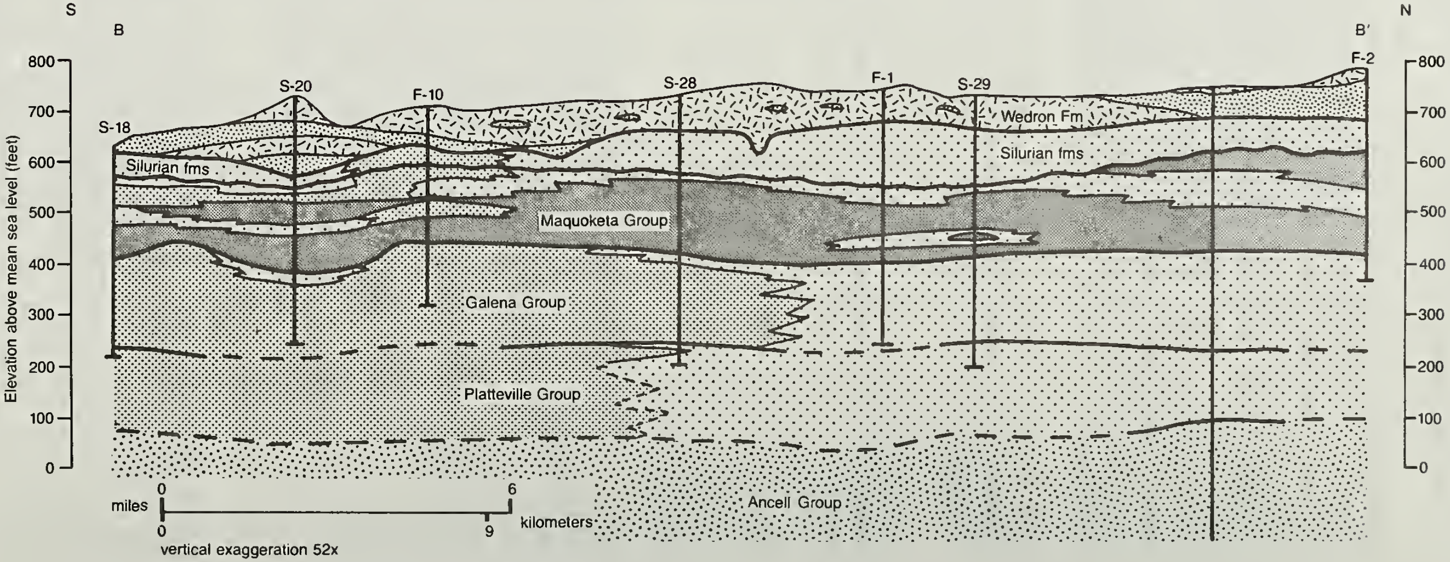


Figure 11b Eastern south-north cross section B-B′.

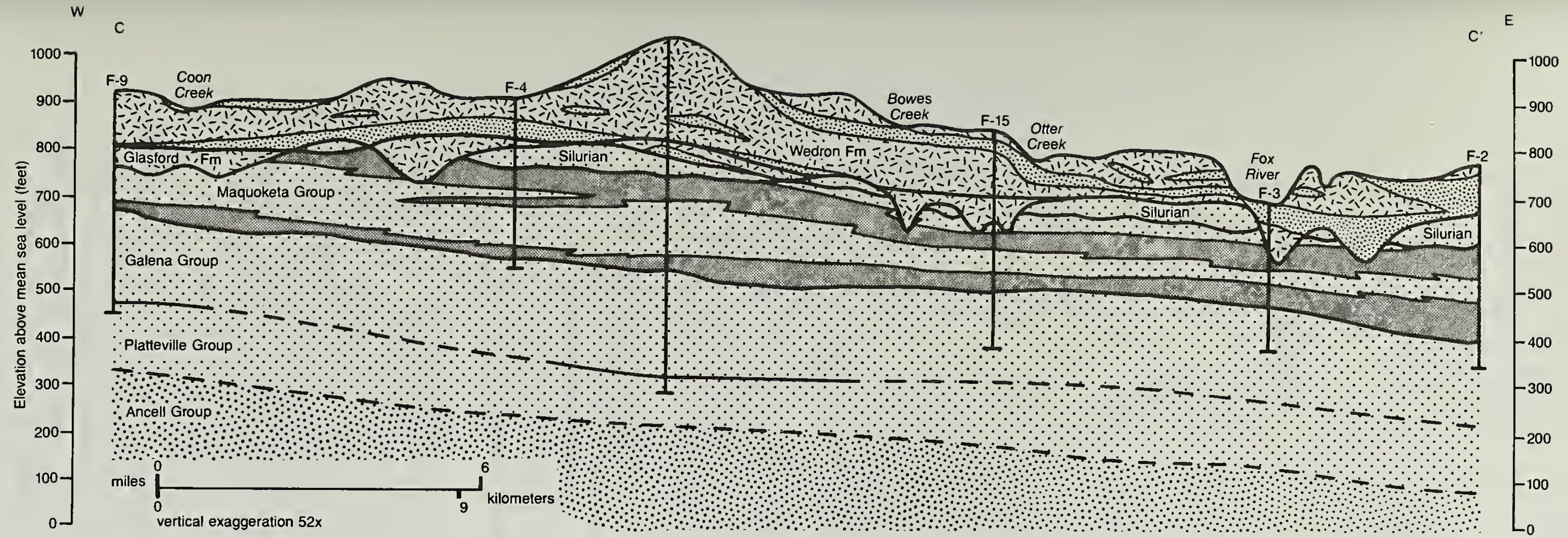


Figure 11c Northern west-east cross section C-C′.

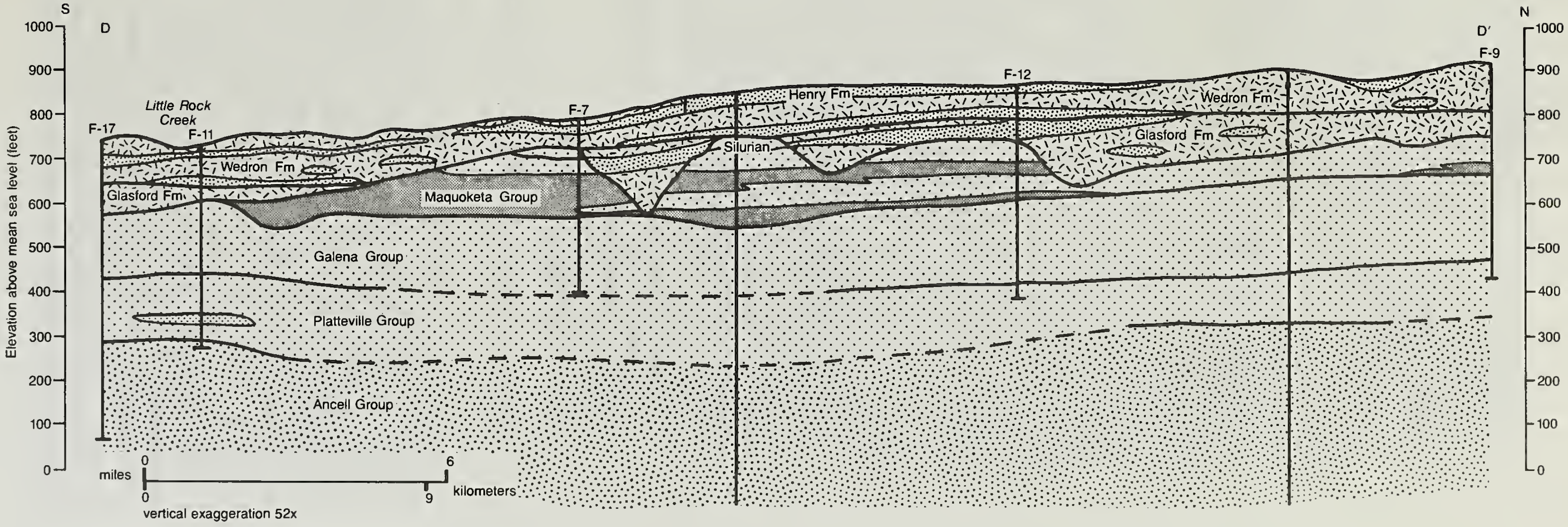


Figure 11d Western south-north section D-D′.

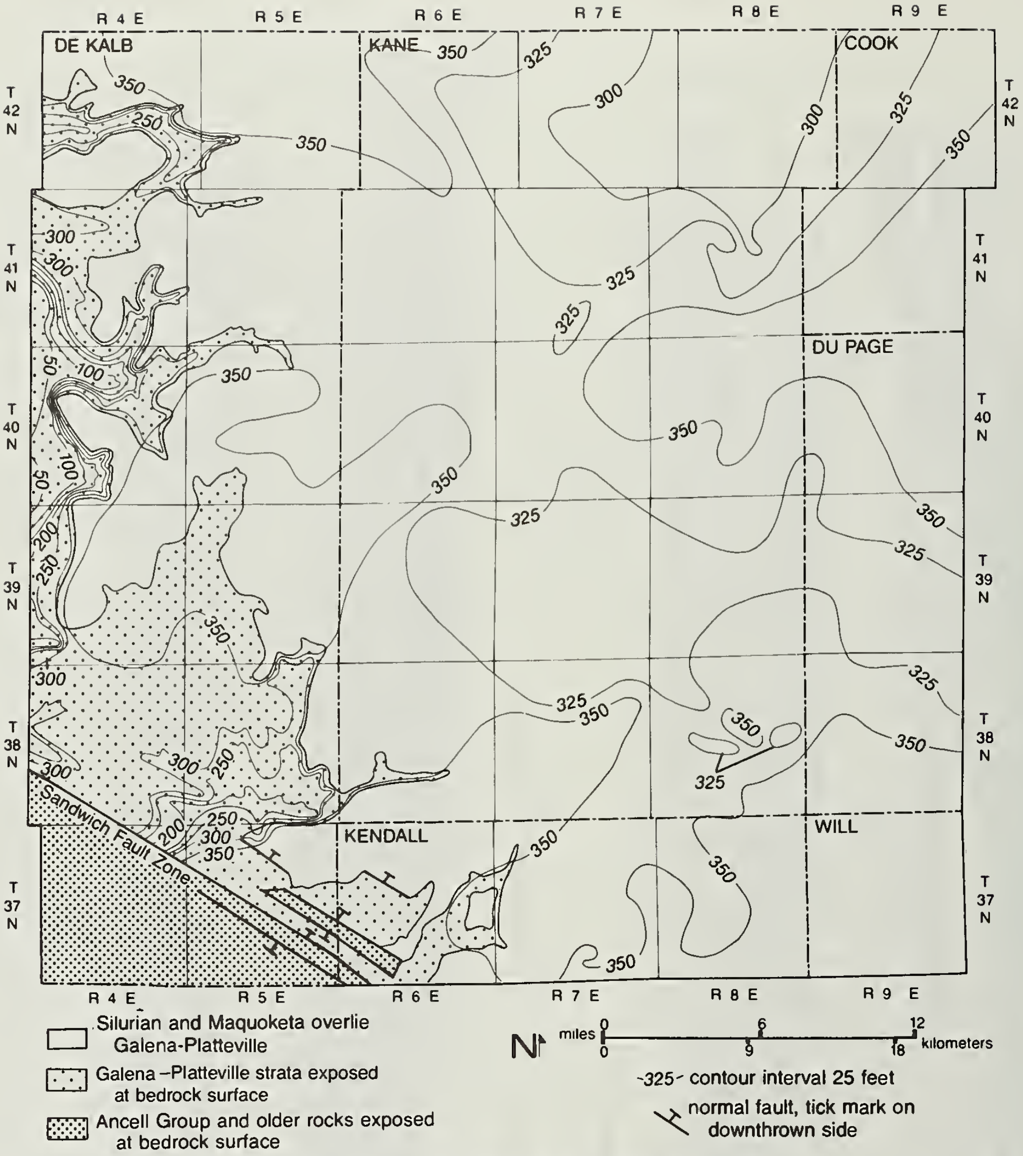


Figure 12 Combined thickness of the Galena and Platteville Groups.

In the Chicago area to the east, the Maquoketa Group shales and carbonates are subdivided into the following formations, listed in ascending order: (1) Scales Shale, an olive gray, laminated, dolomitic shale; (2) Fort Atkinson Dolomite, a light olive gray, crinoid-bryozoan-brachiopod dolomite; (3) Brainard Shale, a greenish gray, silty, fossiliferous, dolomitic, burrowed shale containing thin interbeds of dolomite; and (4) Neda Formation, a red, silty, hematitic shale containing flattened iron-oxide spheroids. Within the study area the Maquoketa lithologies vary considerably over short distances, unlike those of the underlying Galena-Platteville Groups, which are laterally consistent. The Maquoketa formations in this area are difficult to distinguish from one another because of their complex facies relationships. There are two shale-carbonate sequences, and the thickness and distribution of these lithologies vary considerably over the area (Graese and Kolata, 1985; Graese, 1988).

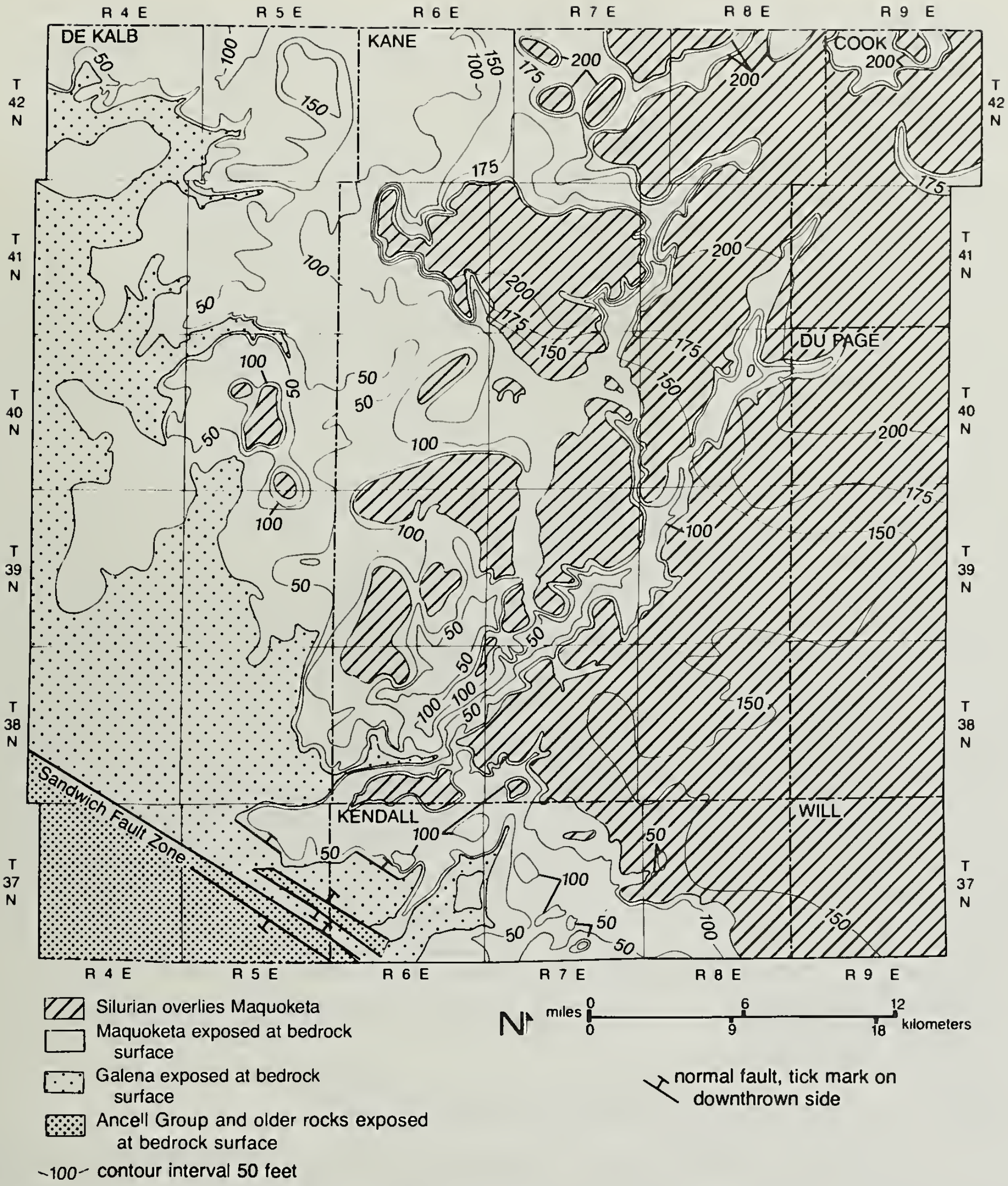


Figure 13 Thickness of the Maquoketa Group.

Silurian Formations. The Silurian-age dolomites and limestones within the study area are primarily light gray to pinkish gray and greenish gray, fine grained, and have thin (less than 0.01-foot thick) greenish gray, wavy, shaly laminae every 0.2 to 0.6 foot. The oldest Silurian rocks of the Wilhelmi Formation may be present in places where the top of the Maquoketa is deeply eroded.

The oldest Silurian unit exposed at the bedrock surface in the area is typically the Elwood Formation, which is a cherty (nodules and layers, up to 3 inches thick), slightly argillaceous, light gray, fine-grained dolomite. This unit is generally 20 to 30 feet thick where it has not been eroded; it grades upward into the noncherty, relatively pure dolomite of the Kankakee Formation, which is generally 20 to 50 feet

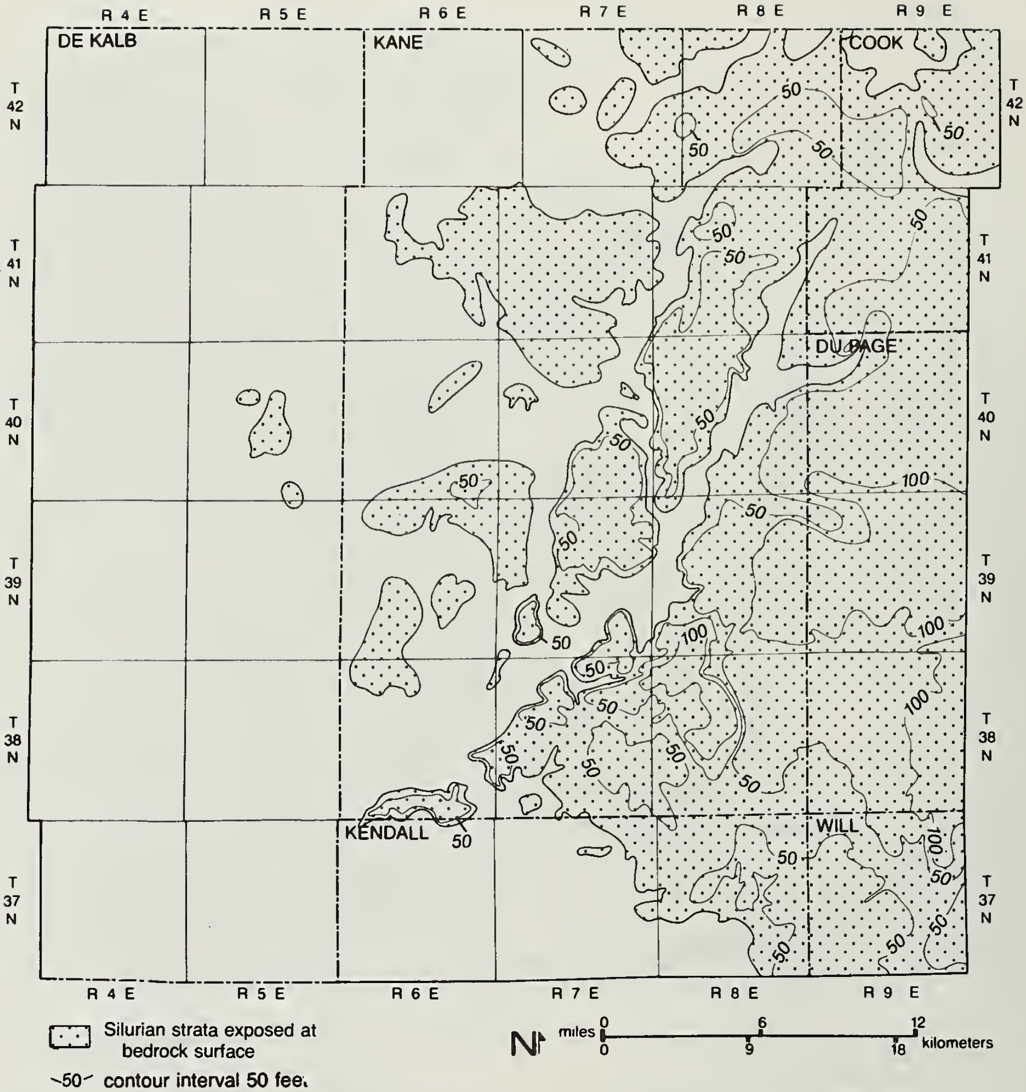


Figure 14 Thickness of the Silurian formations (undifferentiated).

thick where not eroded. Within the study area the Kankakee is missing or partly eroded except at the ISGS F-1 test hole (figs. 8, 11b) and along the eastern margin of the study area (fig. 14, Kempton et al., 1987a) where it is overlain by the Joliet Formation. The Joliet has not been differentiated from the Kankakee in this report because of its similarity to the Kankakee. The distribution and thickness of the Silurian dolomites and included minor limestones are shown on figure 14. The Silurian thickens from an erosional featheredge in Kane and Kendall Counties to more than 300 feet in the Chicago area to the east.

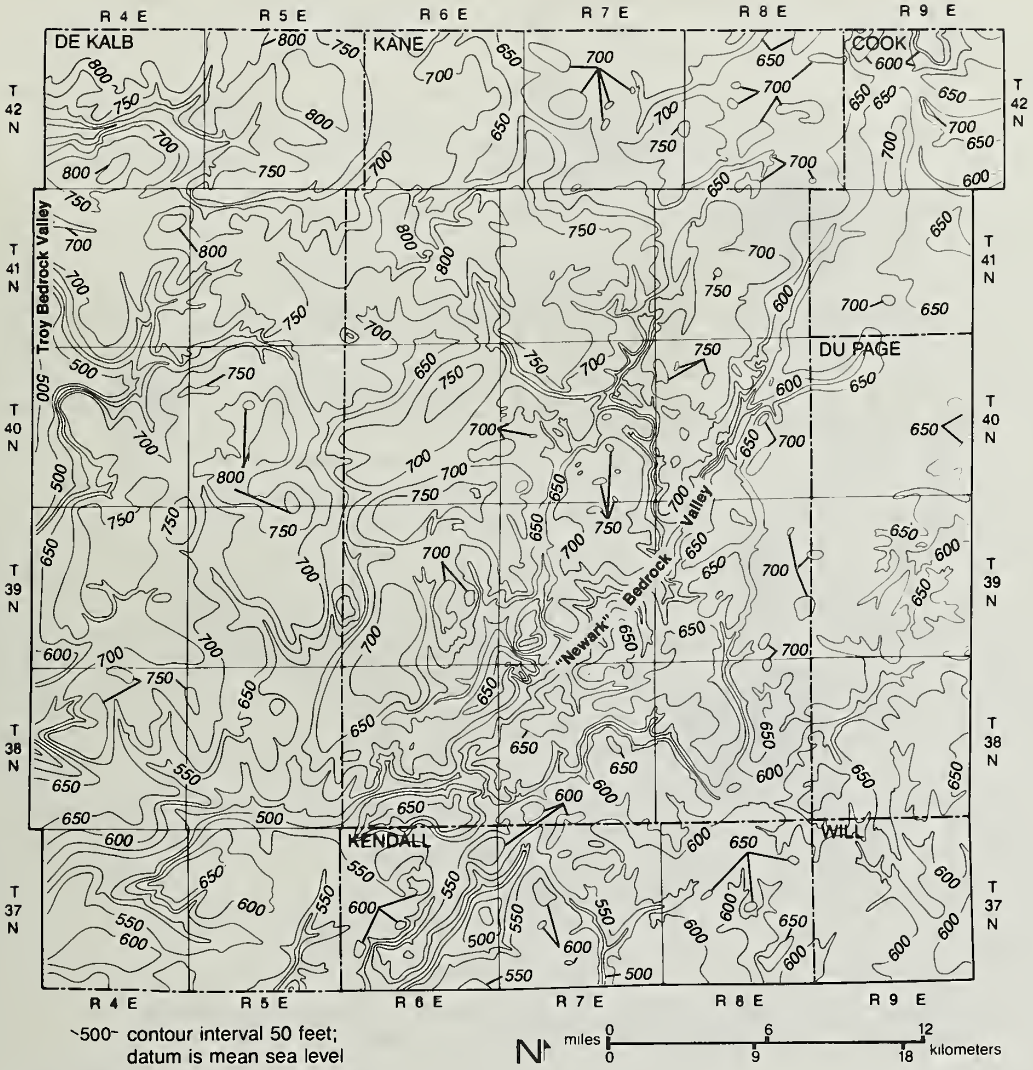


Figure 15 Bedrock topography.

BEDROCK TOPOGRAPHY AND CHARACTERISTICS OF THE BEDROCK SURFACE

The bedrock surface (fig. 15) is characterized by gently sloping highlands (local slopes of about 0.1 percent) that are cut by bedrock valleys having maximum valley wall slopes of about 25 percent. Maximum relief across the area is about 350 feet. The mean elevation of the bedrock uplands is between 700 and 800 feet above mean sea level in the central and northern parts of the study area and between 550 to 650 feet above mean sea level in the southern part.

The Troy Bedrock Valley near the study area's western boundary is the deepest bedrock valley. Water-well log data suggest that the lowermost part of this valley bottom is 475 feet above mean sea level. Another prominent feature is the "Newark" Bedrock Valley (see fig. 15), which extends southwest from Cook County diagonally across the lower half of Kane and De Kalb Counties. Drainage of the lower "Newark" Bedrock Valley may have been oriented either south (joining the major bedrock valley indicated in T37N, R6E) or west (as indicated in fig. 15); it is

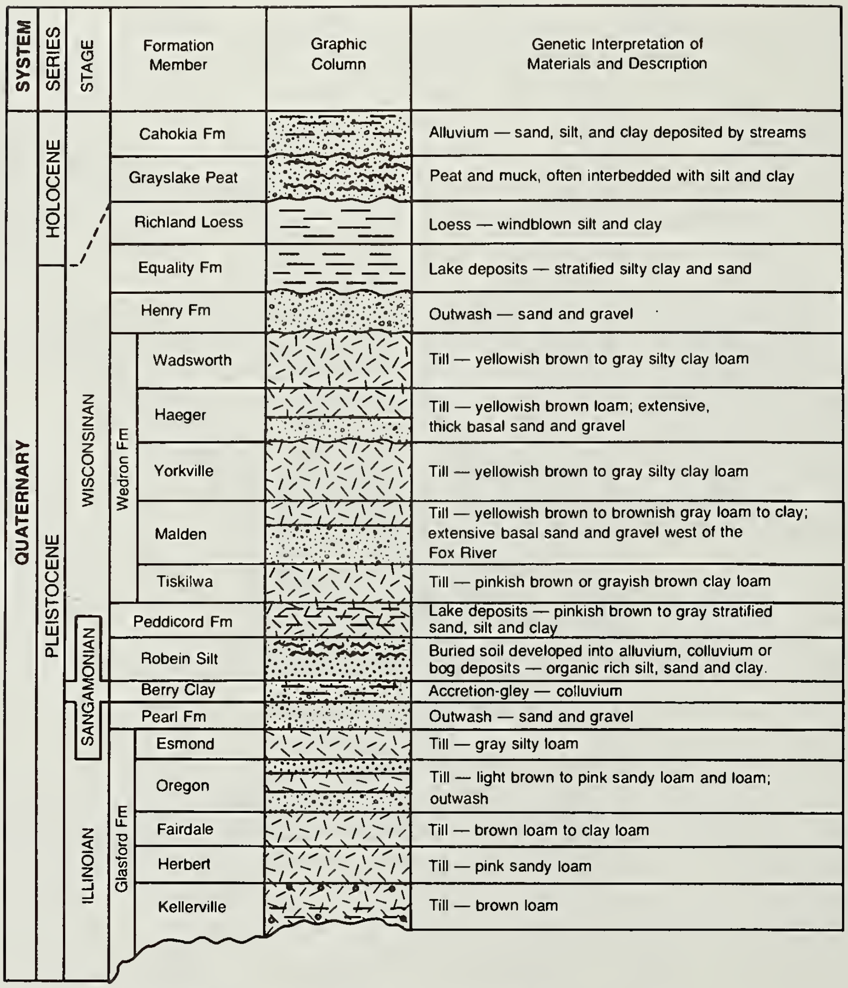


Figure 16 Stratigraphic column of drift (Quaternary) deposits in northeastern Illinois, not to scale (modified from Kempton et al., 1985).

possible that both routes have been used. The lowermost part of this valley bottom is less than 450 feet above mean sea level in T37N R6E. The SSC tunnel will not intersect these bedrock valleys; the tunnel will lie approximately 130 feet below the lowest parts of the bedrock valleys.

The bedrock topography map (fig. 15) is a revision of earlier interpretations (Kempton et al., 1985; Wickham, Johnson, and Glass, 1988). The location and width of some valleys shown in figure 15 have been modified from previous interpretations on the basis of new information obtained from seismic refraction data (Gilkeson et al., 1987; Laymon, 1987) and test drilling.

GLACIAL DRIFT AND SURFICIAL DEPOSITS

Because construction of the SSC tunnel and surface facilities will include excavating shafts through surficial deposits to provide access to the tunnel in the bedrock, it was important to provide details on the distribution and characteristics of the deposits overlying the bedrock in the study area.

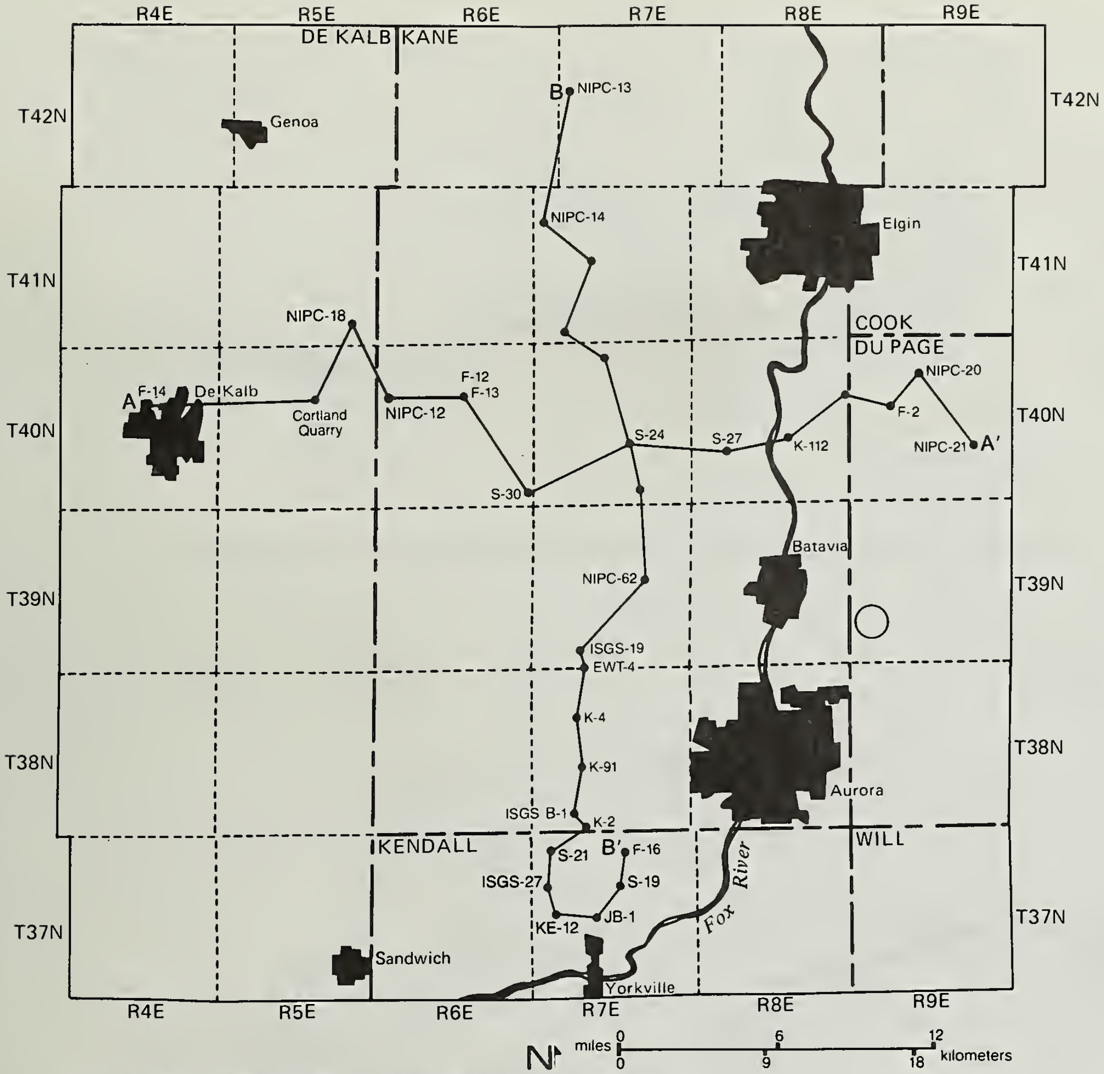


Figure 17a Location map for drift cross sections (figs. 17b, 17c) and drill hole locations; unmarked sites are water wells.

Succession, Distribution, and Thickness

Most of the Quaternary deposits in northeastern Illinois (Willman and Frye, 1970) were deposited by continental glaciers. There is evidence in the study area for two major ice sheet advances with an intervening period of warmer climate (interglacial) that allowed soil development. The older Illinoian-age ice sheet deposited the Glasford Formation from about 400,000 to 130,000 years ago (fig. 16); the interglacial Sangamon Soil and interstadial Robein Silt were developed in or deposited on the Glasford about 130,000 to 25,000 years ago. These paleosols (buried soils) and proglacial lacustrine (lake) sediment (Peddicord Formation) were partly overridden by a younger Wisconsinan-age ice sheet that deposited the Wedron Formation from about 25,000 to 14,000 years ago. As the last glacier melted the following sediments were deposited: glaciofluvial sand and gravel (Henry Formation); lacustrine sand, silt, and clay (Equality Formation); slope wash (Peyton Colluvium); aeolian (windblown) dust (Richland Loess); and organic-rich sediment (Grayslake Peat). The Cahokia Alluvium is sediment deposited by modern streams and rivers. The sequence, thickness, distribution and surface features of these deposits are shown in figures 16 to 20.

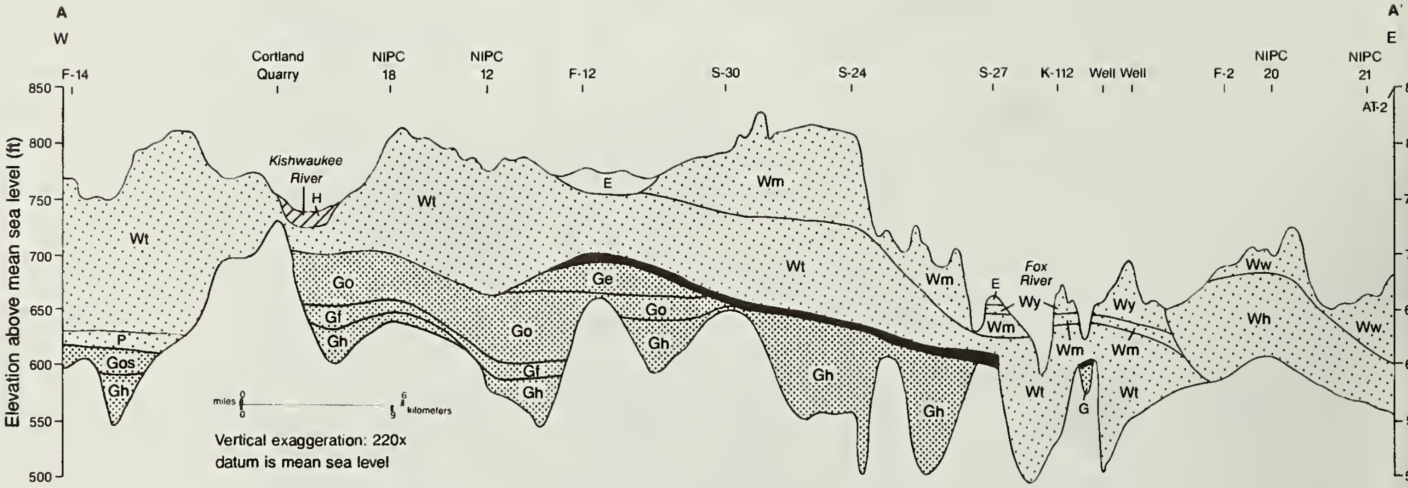


Figure 17b Cross section of glacial drift showing lithostratigraphic units from west to east.

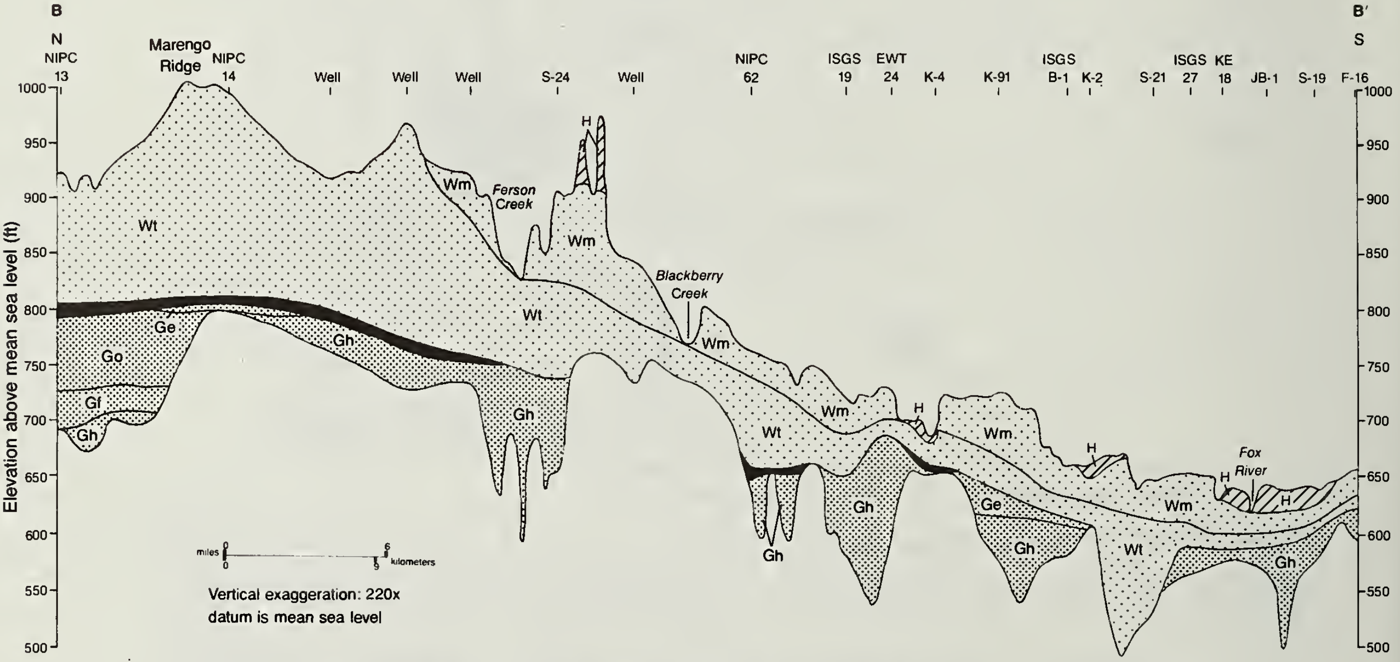


Figure 17c Cross section of glacial drift showing lithostratigraphic units from north to south.

E Equality Formation

H Henry Formation

P Peddicord Formation

■ Robein Silt

Wedron Formation

- Ww Wadsworth Till Mbr
- Wh Haegar Till Mbr
- Wy Yorkville Till Mbr
- Wm Malden Till Mbr
- Wt Tiskilwa Till Mbr

Glasford Formation

- G Undifferentiated
- Ge Esmond Till Mbr
- Gos Oregon Till Mbr, silty facies
- Go Oregon Till Mbr
- Gf Fairdale Till Mbr
- Gh Herbert Till Mbr

Figure 18 Drift thickness.

Most of the Quaternary deposits are till, outwash, and lacustrine sediment. A mappable till unit is characterized by its particle-size distribution, moisture content, color, clay mineral assemblage, and relation to landforms. Most tills can also be characterized by the degree of sediment variability found in them. The Tiskilwa Till Member of the Wedron Formation (figs. 16, 17a, 17b, 17c), for example, contains mostly till and small amounts of intra-till outwash and lacustrine sediment (Wickham, Johnson, and Glass, 1988). The Malden Till Member, on the other hand, has abundant coarse-grained sediment.

The drift thickness map (fig. 18) is derived from the bedrock topography map (fig. 15) and 7.5-minute quadrangle topographic maps. Drift thickness varies from about 0 (where rock is exposed at land surface) to more than 400 feet (where deep bedrock valleys are filled). The greatest thickness is in the Troy Bedrock Valley on the western edge of the study area and in places under the Marengo Moraine (fig. 19). Drift thickness between 150 and 200 feet generally is found in shallow bedrock valleys adjacent to major bedrock valleys and along the Marengo Moraine. Remaining areas generally have between 100 and 150 feet of drift, with substantial areas of drift less than 100 feet thick, particularly in the southern part of the study area. The drift is thin or absent where bedrock is locally exposed along the Fox River from South Elgin to Aurora, along Big Rock Creek, in the southeastern part of the study area, and along the Kishwaukee River west of Genoa.

Description of Units

Glasford Formation. The Glasford Formation, as much as 375 feet thick in the Troy Bedrock Valley, lies above bedrock and below the Robein Silt, the Wedron Formation, or the Peoria Loess. The Banner Formation, stratigraphically below the Glasford, has not been identified in the study area. The Glasford pinches out toward the east and is very thin, patchy or absent east of the Fox River. The Glasford is apparently absent in the main trunk of the "Newark" Bedrock Valley, which is filled with till and outwash of the Tiskilwa Till Member of the Wedron Formation. A major tributary of the "Newark" that extends under Aurora, Montgomery, and the Fox River is filled with Glasford sediments. The valley fills of Illinoian and Wisconsinan age include significant sand and gravel deposits.

The stratigraphic units of the Glasford Formation are tentatively correlated with those in Boone and Winnebago Counties (Berg et al., 1985). Several of the till members, including the Herbert, Fairdale, Oregon, and Esmond Till Members, appear to be present in the study area. In some places, the basal Illinoian unit is the Kellerville Till Member (Kempton et al., 1987a, 1987b).

Sangamon Soil/Robein Silt. The Sangamon Soil and the Robein silt form a diagnostic stratigraphic marker (where present) that separates the Glasford and Wedron Formations. The top of the Sangamon and the Robein are usually within 5 feet of one another. Fragments of the Robein are often incorporated into overlying till or sand and gravel.

Wedron Formation. The Wedron Formation, as much as 270 feet thick, consists chiefly of till interbedded with outwash sand and gravel and lacustrine silt and clay. Five principal till members have been identified in the Wedron and mapped throughout the region: in ascending order, the Tiskilwa, the Malden, the Yorkville, the Haeger, and the Wadsworth Till Members.

- **Tiskilwa Till Member**, the thickest drift unit, is as much as 270 feet thick in some places. The character and depositional history of this unit are described in detail by Wickham, Johnson, and Glass (1988).

The Tiskilwa is a remarkably homogeneous, calcareous, loam to clay loam till; when unoxidized it is brown to grayish brown with a pink cast. Although it is generally uniform, it has a weak to moderately strong blocky structure and may contain thin, discontinuous layers of gravel, sand, and silt.

The upper part of the Tiskilwa often contains variably textured till interbedded with thin layers of sorted gravel, sand, silt, and clay.

These sediments are thought to have been deposited at the margin or on top of the ablating (melting) glacier and are called ablation till. Ablation deposits are frequently coarser and less massive than underlying, more homogeneous till interpreted to have been deposited at or near the base of an active glacier.

The Tiskilwa is a wedge-shaped deposit; it is thinnest along the Fox River, thickens toward the northwest to more than 150 feet below the Bloomington Morainic System, and to more than 270 feet below the Marengo Moraine (fig. 19). Toward the southeast, the Tiskilwa thins or is absent where it is buried by younger drift; this thinning may be attributed to either fluvial or glacial erosion (Wickham, Johnson, and Glass, 1988). When present east of the Fox River, the Tiskilwa may be found as bedrock valley fill; it may also occur in patches less than about 45 feet thick on highland surfaces buried by younger tills.

- **Malden Till Member** is the most lithologically and mineralogically heterogenous till member in the area. In comparison to the Tiskilwa, it is relatively thin, averaging little more than 35 feet thick. The Malden usually is associated with stratified gravel, sand, and silt deposits.

- **Yorkville Till Member** overlies the Malden or Tiskilwa Till Member. It is a gray till composed of 45 percent clay, 45 percent silt, and 10 percent sand (Kemmis, 1981). Its color varies from brown or grayish brown where oxidized to dark gray where unoxidized. The Yorkville may be more than 50 feet thick but generally is from 20 to 30 feet thick.

- **Haeger Till Member** is found in the northeastern corner of the study area. It is characterized as a sequence of bouldery and cobbly sand and gravel as much as 60 feet thick, overlain by loam till about 25 feet thick. Haeger till pinches out to the south where it is overlain by thin deposits of Wadsworth Till Member. Hansel and Johnson (1986) believe that the basal outwash is continuous with the outwash extending beneath and west of the West Chicago Moraine. Below the West Chicago Moraine the Haegar has been interpreted to occur beneath the Wadsworth Till Member; the character of these materials is similar to that of some units assigned to the Malden Till Member underlying Fermilab (Landon and Kempton, 1971).

- **Wadsworth Till Member** is mapped chiefly by its association with the prominent West Chicago Moraine (fig. 19). Schmitt (1985) indicates that Wadsworth till is identical to the Yorkville in particle-size distribution, lithic heterogeneity, clay mineralogy, and engineering properties. The Wadsworth is generally less than 50 feet thick along the West Chicago Moraine; it overlies thick sequences of sand and gravel, lacustrine sediment, and till having variable texture interpreted to be Haegar Till Member (Hansel and Johnson, 1986).

Henry Formation consists of glacial outwash deposits up to about 70 feet thick composed mostly of sand and gravel. The Henry occurs at or near ground surface and in some places is overlain only by loess, alluvium, colluvium, and lacustrine deposits. Sand and gravel deposits covered by another formation are considered part of that formation, not part of the

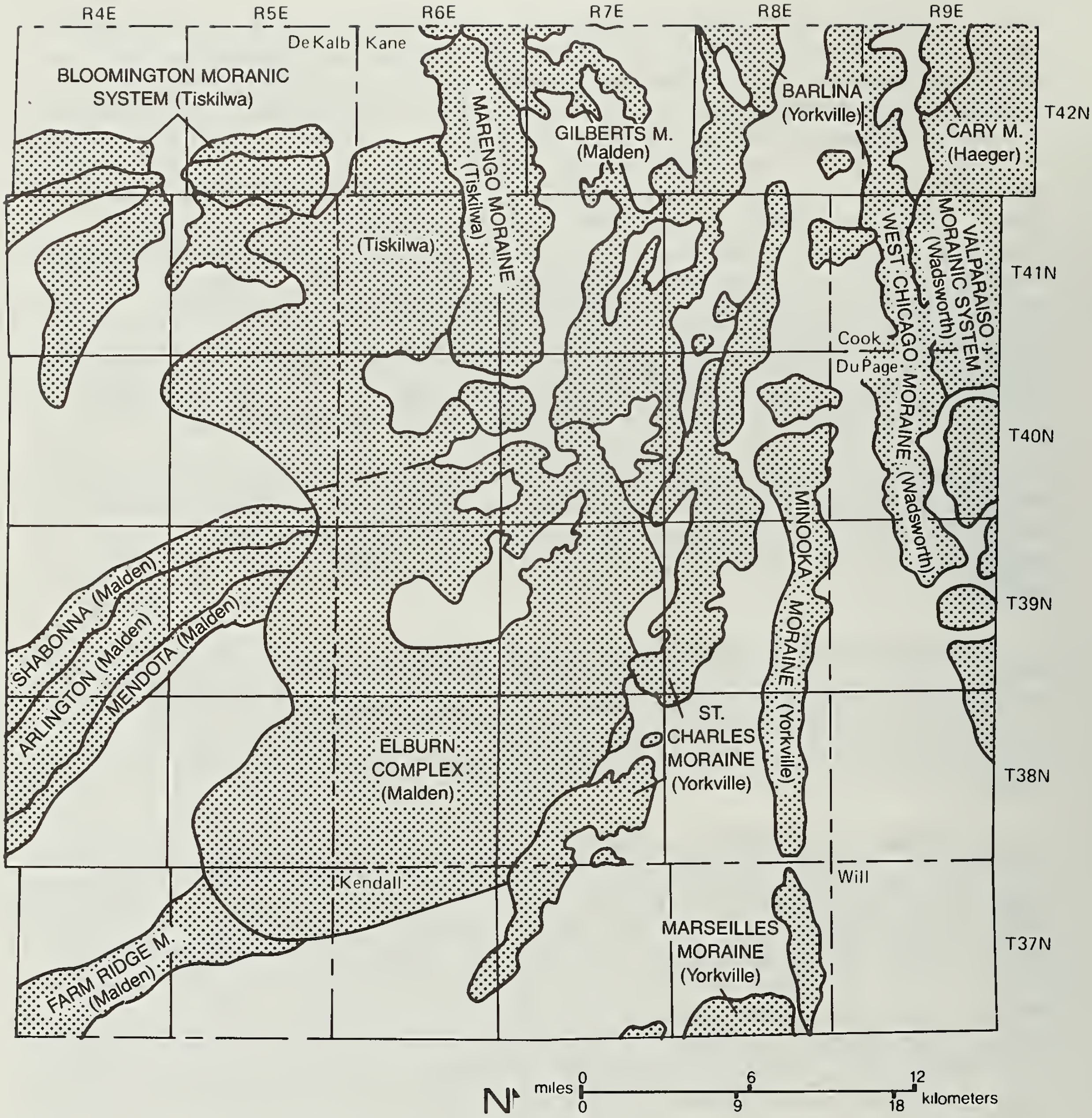


Figure 19 Locations of moraines (modified from Willman and Frye, 1970). (Surficial till member indicated in parentheses.)

Henry. The Henry Formation may vary from thin, well-sorted, sandy, sheetlike deposits to hills of poorly sorted silt, sand, and gravel. The hills are generally ice-contact deposits formed within or under the glacier and are generally limited in distribution in the area. Several of these features are prominent kames in the Elburn Complex (fig. 19).

Thin, glacial outwash plain and valley train deposits mapped as the Henry formation are relatively continuous and widespread. Extensive deposits of Henry are present near the eastern and southern edges of the

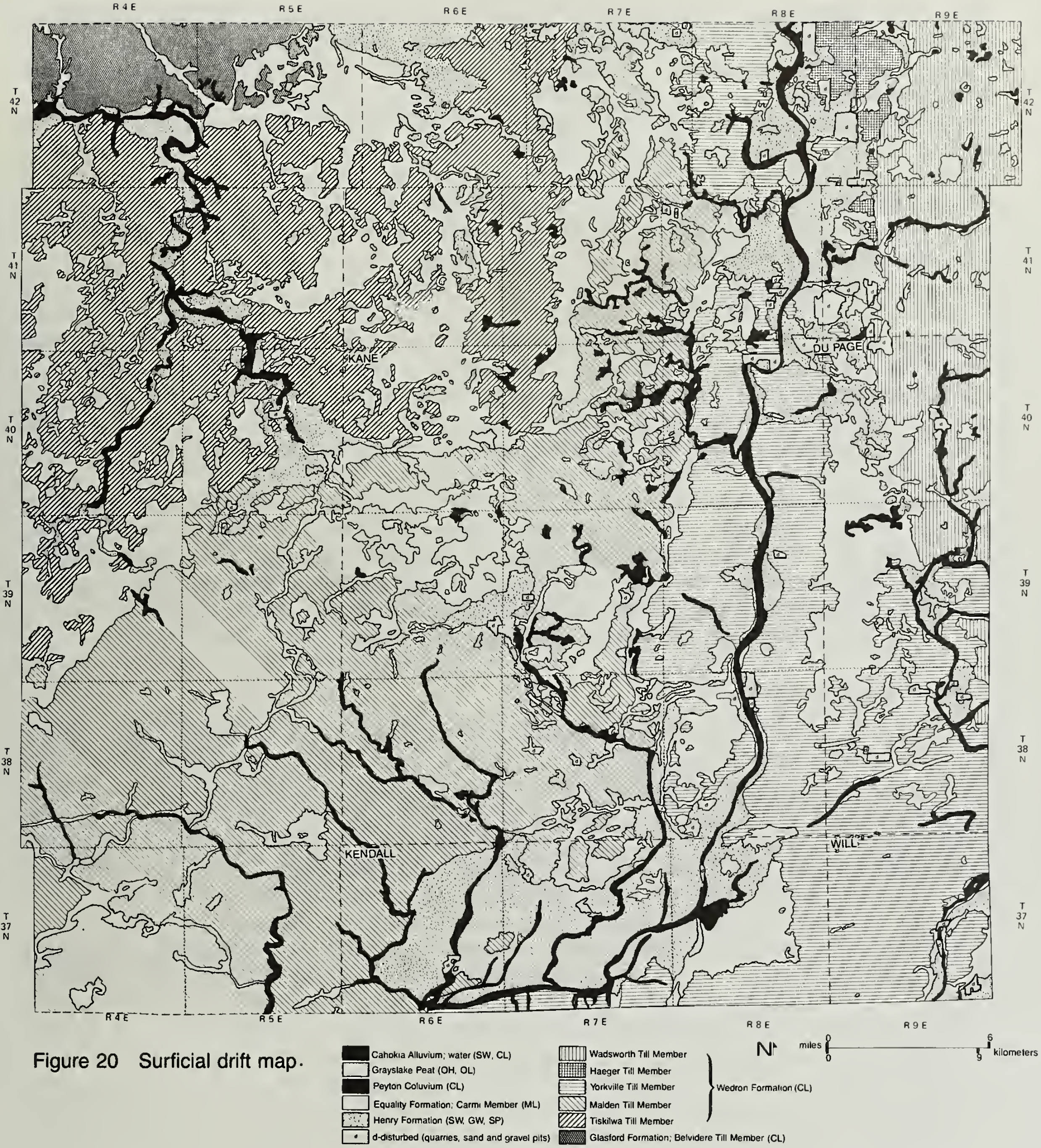


Figure 20 Surficial drift map.

study area on either side of the Fox River as well as near the northern and northeastern edges along the Kishwaukee River valley (fig. 20).

Because Henry and Equality Formation deposits were often deposited simultaneously or alternately, they are commonly interbedded. Extensive areas covered by these deposits, mapped as the Henry Formation (generally less than 20 feet thick), are present in the southeastern part of the study area west of the Fox River and in the northern part of the study area near the Kane-De Kalb County boundary.

Equality Formation is composed of sediments deposited in lakes formed during melting of Wisconsinan glaciers. The deposits consist mainly of laminated silt and clay. Lacustrine deposits within till units or below the Henry Formation are not considered Equality Formation; they are instead mapped as part of the formation in which they occur (Willman and Frye, 1970).

The Equality is generally less than 20 feet thick, but in some places it is 35 feet thick; it often overlies sand and gravel. Along the Tiskilwa-Malden contact are extensive lacustrine deposits, resting primarily on the Tiskilwa.

Cahokia Alluvium is the formation name for Holocene and late Wisconsinan deposits in the flood plains and channels along modern rivers. The alluvium is generally composed of silt containing discontinuous sand and gravel lenses; in the study area it may be less than 10 feet thick. The Cahokia overlies Henry and Equality deposits in many places.

Richland or Peoria Loess mantles much of the study area characterized by gentle slopes; on most moraines or on flood plains this unit is thin or not present. The Richland Loess covers Wisconsinan-age Wedron deposits, whereas the Peoria covers Illinoian-age sediments or bedrock (Willman and Frye, 1970). Each loess is usually less than 5 feet thick. The deposits are modified by soil-forming processes.

Surficial Features

The distribution of surficial Quaternary deposits is complex (fig. 20), but the areal extent of all till units is limited by the position of their associated end moraines (fig. 19; Willman and Frye, 1970). Most moraines are ridges often composed largely of till. However, the Elburn Complex is an exception: it is a large area, characterized by hummocky topography, that includes abundant kames and one esker. On the south end of the Elburn complex thin Malden till overlies thick sand and gravel; the north end is associated with ablation deposits of the Tiskilwa Till Member. The areas between moraines are commonly covered by extensive, thin, lacustrine deposits or by valley trains of outwash.

HYDROGEOLOGY

R. C. Vaiden, J. P. Kempton, A. M. Graese, B. B. Curry, and W. G. Dixon, Jr.

Investigations of the potential impact of (1) tunnel construction on groundwater resources in the study region and (2) groundwater on construction of and operation within the tunnel were conducted as part of the study to assess the suitability of the 36-township area in northeastern Illinois for construction of the SSC.

This overview of the hydrogeologic setting of the study region--incorporating data on water levels and hydraulic conductivity obtained from the 1984-86 drilling programs--indicates that

- construction of the tunnel should have almost no impact on water resources. The low heads and low hydraulic conductivities measured in the relatively impermeable Galena-Platteville rocks in which the tunnel could be constructed confirm that these units have little or no potential as a major source of groundwater.

- water seepage and inflow are expected to be minimal and should not pose any unusual or serious problems during tunnel construction. A drainage system in the tunnel would collect inflow and pump it to the surface, where it may be used for cooling or other purposes.

- adequate water resources are available in the study region for operation of the facility.

The information on regional groundwater conditions and monitoring wells provided in this study can be used as baseline data for comparison with site-specific data (Curry et al., 1988, Vaiden et al., 1988) obtained prior to, during, and following tunnel construction.

REGIONAL HYDROGEOLOGIC SETTING

The pattern of surface drainage in the study area is shown in figure 4. Drainage in the eastern and southwestern part of the study area is generally toward the south; numerous small streams drain east and south into the Fox River (the main drainageway in the area), which flows south and southwest. At the extreme eastern edge of the study area, the West Branch of the Du Page River also flows south. In the northwest part of the area, the south branch of the Kishwaukee River generally flows north before turning west to the Rock River. These streams are groundwater discharge areas. The area has a few small man-made lakes and some natural ponds. There are no large man-made reservoirs (Hines, 1986, p. 36).

Hydrogeologic properties of the rock and drift units, topographic relief, and amount of water (precipitation) in the area dictate the amount of infiltration and the rate and direction of groundwater movement. The geologic materials can be broadly classified as high-permeability or low-permeability. Permeability may be primary (as in

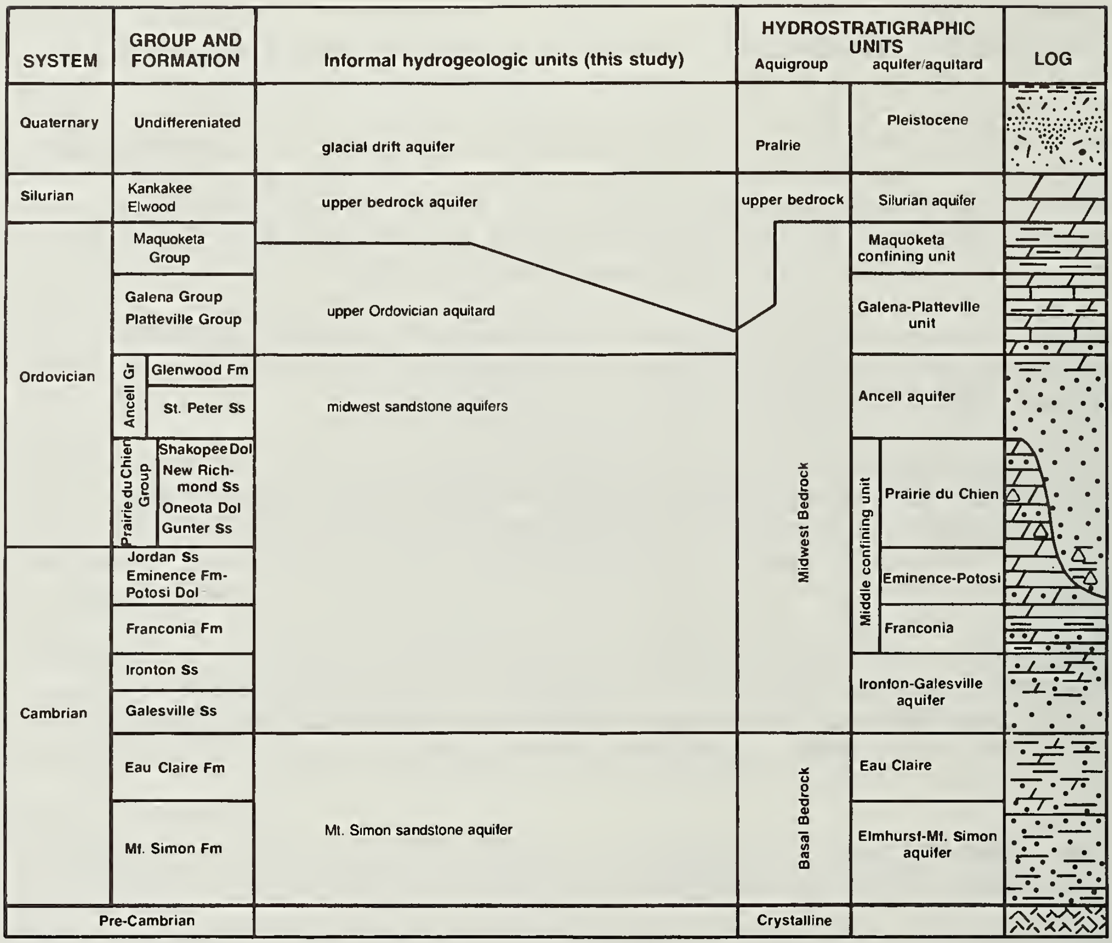


Figure 21 Comparison of formal hydrostratigraphic units and informal classification used in this study (modified from Visocky, Sherrill, and Cartwright, 1985).

porous materials such as sandstone, sand, and gravel) or secondary, where fractures, joints, and other openings permit water movement. Only highly permeable materials yield sufficient water for industrial, municipal, and most domestic uses; such materials include sand and gravel associated with glacial tills and sandstones in the Ancell Group. Moderate to high secondary permeability has developed within the upper 50 feet of Silurian bedrock where joints and fractures have been enlarged by solution. In the study area, glacial till, shale, and dolomite of the Maquoketa Group, and dolomite of the Galena-Platteville are relatively impermeable.

HYDROSTRATIGRAPHIC UNITS

Classification

The subsurface materials are informally subdivided for this report into five hydrogeologic units on the basis of lithology and hydraulic conductivity. From land surface down, they are (1) glacial drift aquifers (sand and gravel deposits within the low-permeable glacial till); (2) upper bedrock aquifer, primarily fractured and weathered dolomite and shale immediately below the drift; (3) upper Ordovician aquitard, composed of the Maquoketa and Galena-Platteville Groups, which together act as a confining bed that restricts water movement; (4) midwest sandstone aquifers (Ancell and Ironton-Galeville sandstones); and (5) the Mt. Simon Sandstone aquifer, including the basal sandstone member of the Eau Claire Formation (fig. 21).

The equivalent formal hydrostratigraphic units are defined and described in detail by Visocky, Sherrill, and Cartwright (1985). These and related geologic units are shown in figure 21. The formal hydrostratigraphic divisions are used mainly from an aquifer-water resource perspective; our primary objective in this report was to focus on the aquitards additionally from an engineering perspective: to investigate the suitability of the Galena-Platteville and Maquoketa (the upper Ordovician aquitard) for constructing the SSC tunnel and chambers.

Additional background information and significant portions of the data provided here are included in Kempton et al. (1985, 1987a, 1987b), Visocky and Schulmeister (1988), Curry et al. (1988), and Vaiden et al. (1988). Information on groundwater quality and projected groundwater use in the study area are included in Visocky and Schulmeister (1988). Background radioactivity in the rocks and groundwater is addressed in Gilkeson, Cahill, and Gendron (1988).

Glacial Drift

The glacial drift aquifers include all of the separate water-yielding sand and gravel bodies within the glacial drift. Although the drift is saturated below the water table (top of zone of saturation), only permeable materials that yield groundwater in a usable quantity are considered aquifers. Since the top of the zone of saturation nearly parallels the land surface and is usually within 5 to 20 feet of it, most sand and gravel beds within the drift are saturated and yield at least small amounts of groundwater, even though surrounded by relatively impermeable till (aquitards).

Drift aquifers can be broadly subdivided into three catagories: surficial, buried, and basal. Large quantities of sand and gravel are present as surficial deposits (fig. 20), particularly in the southeastern part of the study area. In a few areas, mainly along the Fox River and locally north of the Fox River in the southwest quadrant of the study area, these surface deposits may be locally continuous from land surface to bedrock. Some of these deposits are used locally to provide water for municipal or domestic needs. The buried aquifers often occupy the bedrock valleys (fig. 22). Some of these coarse-grained bodies are now deeply buried--as much as 400 feet in the Troy Valley at the western edge of the area (fig. 15). Those that rest directly on bedrock (basal aquifers) may interact with the bedrock aquifer and together may operate as a single hydrologic unit. Because the full extent and continuity of deep drift aquifers in the study area are not as yet completely mapped, their depiction on figure 22 is only approximate.

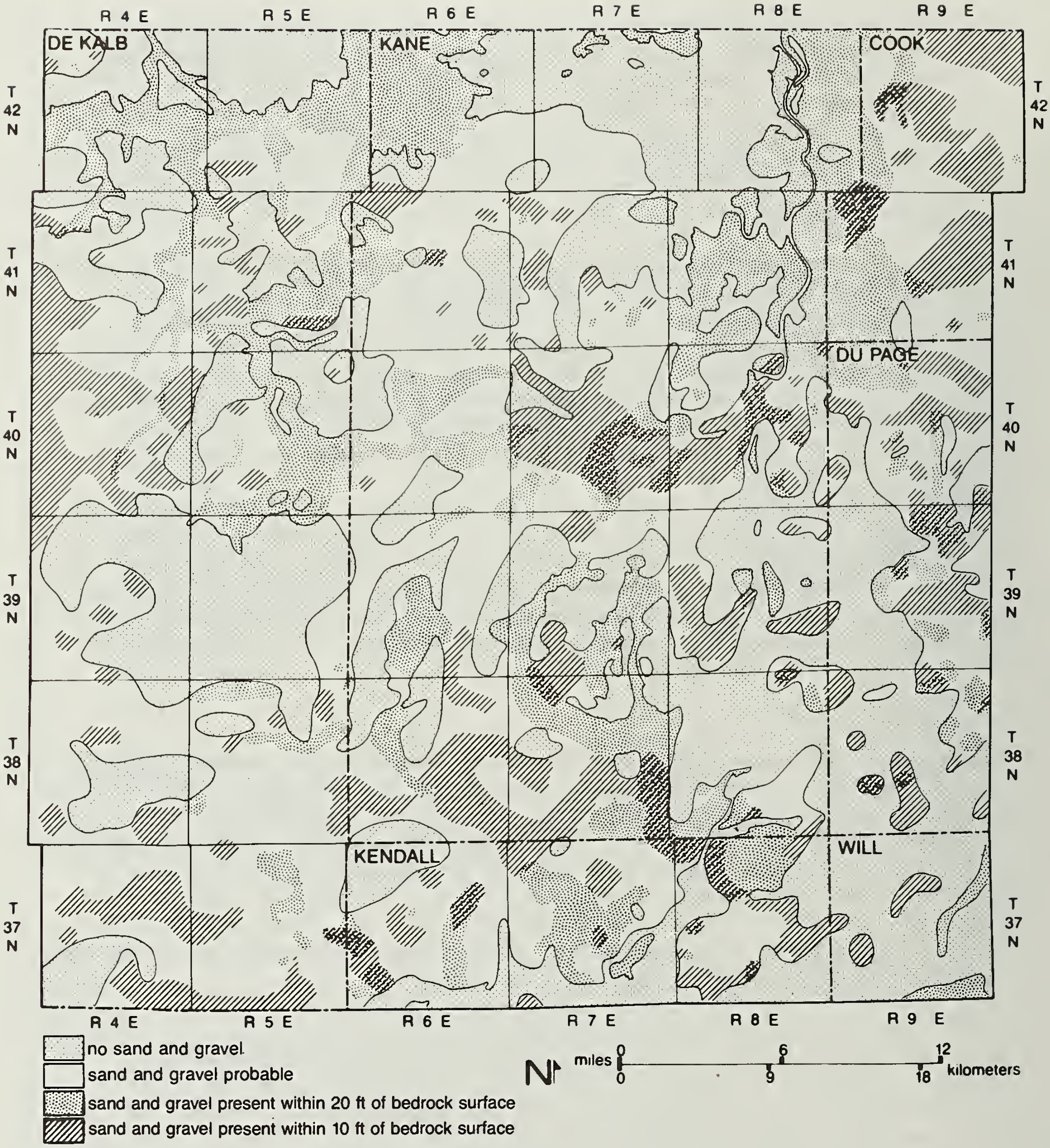


Figure 22 Potential drift aquifers.

Upper Bedrock Aquifer

The upper bedrock aquifer within this area is largely contained within the uppermost 50 feet of bedrock, irrespective of the formations present (fig. 23a). Near the bedrock surface, carbonate solution has enlarged fractures and joints in the otherwise low-permeability bedrock; most groundwater flow is along these fractures and joints. Fracture width and frequency generally decrease with depth. Shale, resistant to solution, shows measurable permeability only where fractures are present. The upper bedrock aquifer is commonly confined where overlain by glacial till and unconfined where overlain by sand and gravel deposits or at land surface (fig. 22).

The aquifer is most permeable and productive within the Silurian and Maquoketa dolomite, primarily east of the Fox River. The Maquoketa is the upper bedrock aquifer west of the Fox River where it lies beneath the glacial deposits; here water yields are much lower and less predictable because of the lower permeability of the shale and the shaly nature of the dolomite.

Upper Ordovician Aquitard

The upper Ordovician aquitard is composed of the Maquoketa and Galena-Platteville strata where they are more than about 50 feet below the bedrock surface. The aquitard comprises the Maquoketa and Galena-Platteville in the eastern part of the study area and consists wholly of the lower Galena-Platteville along the western edge of the study area. Thus the Galena and the Maquoketa are part of both the upper bedrock aquifer and the upper Ordovician aquitard, depending upon their position in relation to the top of bedrock. The Maquoketa and Galena-Platteville also form confining beds for the midwest sandstone aquifers. The water within these confining units is slowly moving toward the potentiometric level of the midwest sandstone aquifer. Groundwater flow modeling suggests that flow direction follows the midwest sandstone aquifer--nearly horizontal to the east (D. Schumacher, personal communication, 1988).

Midwest Sandstone Aquifers

The midwest sandstone aquifers are composed of the Ancell Group sandstones (Glenwood and St. Peter Formations) and the Ironton-Galesville Sandstones. The system is confined at the top by the upper Ordovician aquitard (Galena-Platteville and Maquoketa). Relatively thin dolomite, shale, and sandstone of the lower Ordovician and upper Cambrian separate the two thick sandstone units (fig. 21), and probably act as minor confining beds. Wells finished in the lower aquifer are generally open to both aquifers, so only a combined piezometric head can be measured from them. The two individual aquifers are therefore generally treated as one unit from a water resources perspective; however, if piezometers were installed separately into these units, different water levels would probably be obtained.

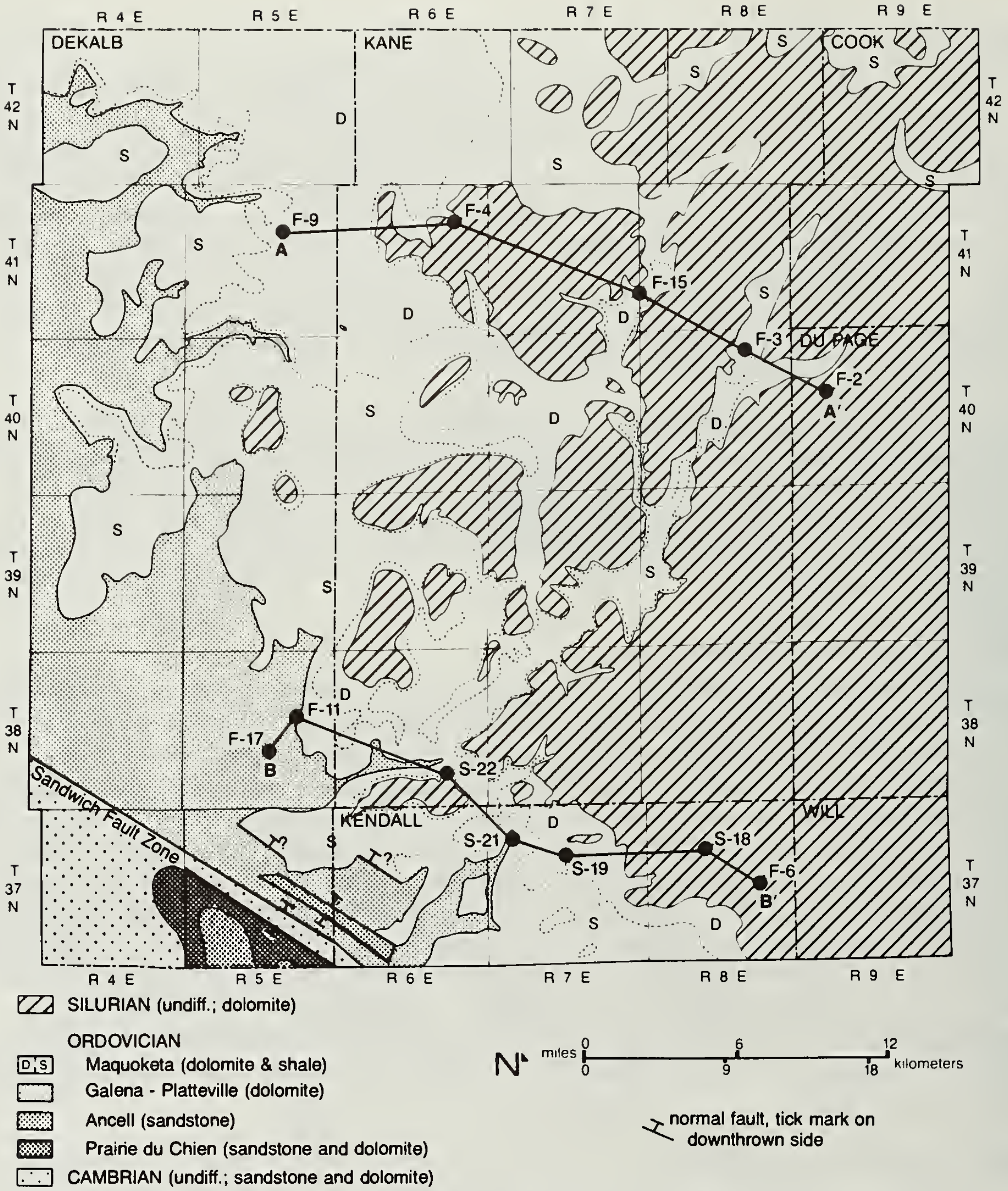


Figure 23a Map of bedrock surface showing locations of hydrogeologic cross sections A-A′ and B-B′ (figs. 23b, c).

HYDRAULIC CONDUCTIVITY

Lateral hydraulic conductivities were obtained from a pressure (packer) testing apparatus in all test holes except F-8 and S-25. Testing was conducted on the bedrock, primarily the Maquoketa and Galena Groups. Fewer tests were conducted on the Platteville Group and Silurian dolomite formations in the first 17 holes. Commercially available pressure testing equipment was used, in test intervals of 21 feet (20 ft for the S test-hole series). Calibration tests of the equipment

Table 1. Summary of hydraulic conductivity values of rock and drift aquifer units

Stratigraphic unit	Hydrogeologic unit	Hydraulic conductivity (cm/sec)
Drift	Glacial drift aquifer	
	Outwash sands and gravels	1 x 10^{-2} to 1 x 10^{-4}
	Glacial tills	1 x 10^{-5} to 1 x 10^{-8}
Silurian	Upper bedrock aquifer	1 x 10^{-2} to 1 x 10^{-6}
Maquoketa	Upper bedrock aquifer	1 x 10^{-2} to <1 x 10^{-6}
Maquoketa	Upper Ordovician aquitard	1 x 10^{-5} to <1 x 10^{-6}
Galena-Platteville	Upper Ordovician aquitard	1 x 10^{-3} to <1 x 10^{-6}
Ancell	Midwest sandstone aquifer	3 x 10^{-3}

Sources: Kempton et al., 1987a, 1987b; Vaiden et al., 1988; Curry et al., 1988.

indicated that the equipment is most accurate between $1.0x10^{-6}$ and $5.0x10^{-4}$ centimeters per second (cm/sec) (Kempton et al., 1987b).

The general hydrogeologic conditions in the study area are shown on two cross sections based on data from the SSC borings (figs. 23a, b, c). These cross sections indicate the current interpretation of the subsurface relationships of hydraulic conductivity and water levels among the various rock units. The transition from upper Ordovician aquifer to upper bedrock aquitard is illustrated by the difference in hydraulic conductivities (figs. 23b, c). Although the Silurian has high hydraulic conductivity near the bedrock surface, the Maquoketa typically has lower hydraulic conductivity even when it is at the bedrock surface (fig. 23b). The Maquoketa therefore may not be a reliable water source in all areas, even when it is part of the upper bedrock aquifer. Figure 23b shows the Galena (in the west) as a part of the upper bedrock aquifer and the upper bedrock aquitard to the east. Table 1 summarizes hydraulic conductivities for rock and aquifer units for the study area. Hydraulic conductivities of $1x10^{-6}$ cm/sec in the table represent values of $1x10^{-6}$ cm/sec or less.

Glacial Drift

No tests were performed in the glacial drift during this project, but on the basis of previous work, hydraulic conductivities are assumed to range (low to high) from about $1x10^{-8}$ to $1x10^{-2}$ cm/sec. The matrix hydraulic conductivity determined in the laboratory on the Tiskilwa Till Member of the Wedron Formation is low, averaging about $2.0x10^{-8}$ cm/sec (Jennings, 1987), whereas the hydraulic conductivity along joints to depths of as much as 30 feet below land surface in till is probably on the order of $1x10^{-5}$ to $1x10^{-6}$ cm/sec (Berg, Kempton, and Cartwright, 1984). The hydraulic conductivity of outwash sands and gravels is higher, ranging from $1x10^{-2}$ to $1x10^{-4}$ cm/sec (Williams and Farvolden, 1967).

Bedrock

Silurian Formations and Maquoketa Group. Packer test results for the Silurian formations in exploratory boreholes indicate hydraulic conductivities ranging from $1x10^{-2}$ to $1x10^{-6}$ cm/sec. Hydraulic conductivities of the Maquoketa differed greatly, depending on the depth, geographic location, and lithology of the rock tested. Where the Maquoketa consists of jointed shale at the bedrock surface, the hydraulic conductivity in the upper few feet was moderate to low ($1x10^{-4}$ to $1x10^{-6}$ cm/sec) or less. In areas where the Maquoketa shale was not jointed, its hydraulic conductivity generally was between $1x10^{-5}$ to $1x10^{-6}$ cm/sec. Within the Maquoketa dolomite, values were higher--generally $1x10^{-4}$ to $1x10^{-6}$ cm/sec but sometimes were as much as $1x10^{-3}$ cm/sec (in test hole F-4), presumably because of enlarged fractures or vugs due to some solution of carbonate. The greatest hydraulic conductivity was measured in Maquoketa dolomite near the bedrock surface ($1x10^{-2}$ cm/sec; Curry et al., 1988).

Galena-Platteville Groups. Hydraulic conductivity in the Galena-Platteville (where overlain by the drift), ranged from $1x10^{-4}$ to $1x10^{-5}$ cm/sec in the interval near or at the bedrock surface. At greater depths, or where covered by overlying units, the Galena-Platteville generally has lower values ($1x10^{-5}$ to $1x10^{-6}$ cm/sec, often less). Localized areas of higher permeability ($1x10^{-3}$ to $1x10^{-4}$ cm/sec) have been encountered at depth in test holes F-11, F-12, S-19, and S-21 (fig. 4) (Curry et al., 1988).

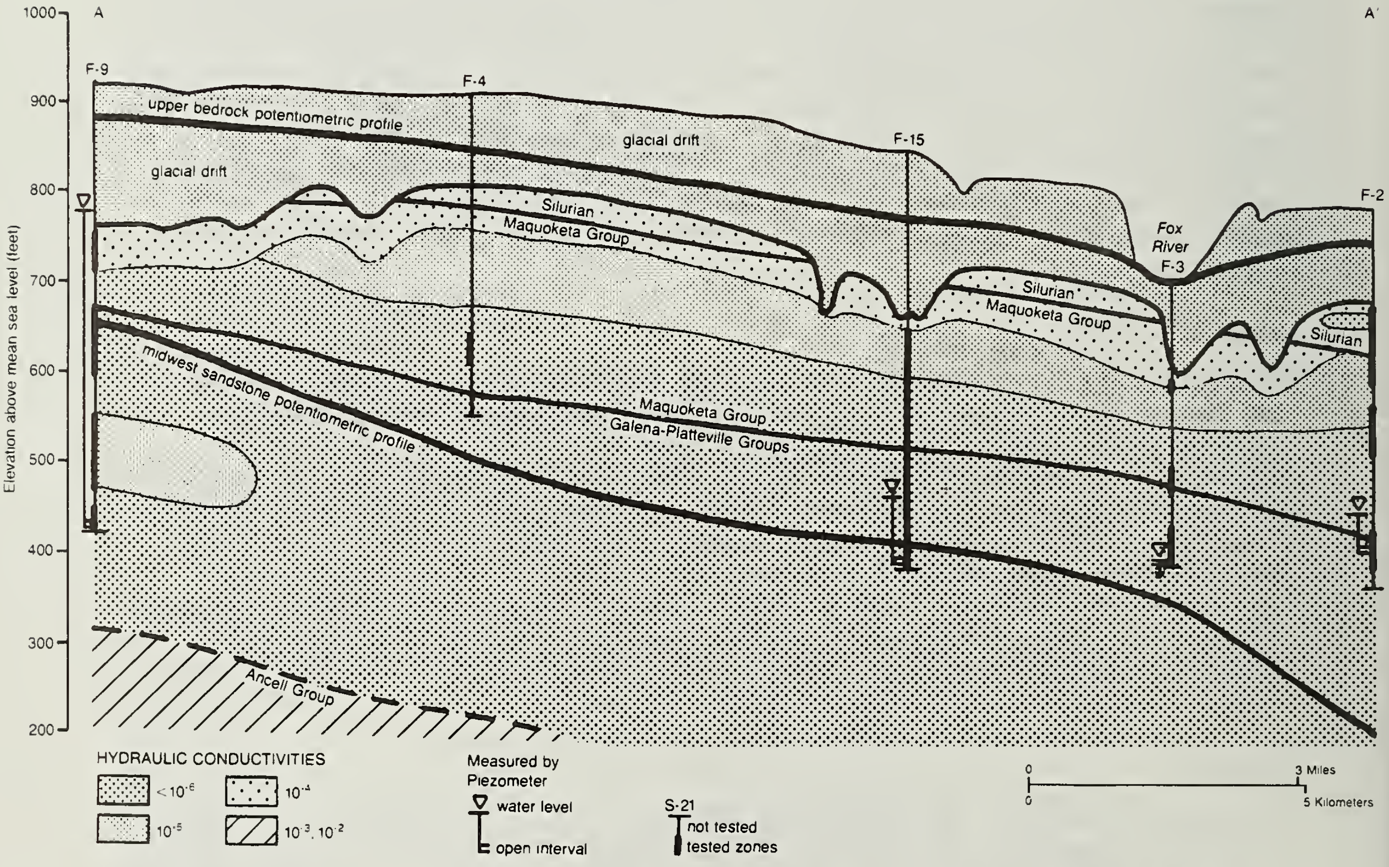


Figure 23b Cross section A-A′, showing generalized rock hydraulic conductivities, approximate elevations of the potentiometric surface of the upper bedrock aquifer and the midwest sandstone aquifers, and water levels measured in borehole piezometers.

POTENTIOMETRIC LEVELS

The potentiometric surface of an aquifer represents the hydraulic head within pores and discontinuities in the aquifer. The head is measured (in a discrete interval) in a piezometer, generally a PVC pipe; the height along the water column represents the pressure head at that point in the aquifer. The type of piezometer used was a standing level Casagrande piezometer. A strict usage of the term "piezometer" should refer to a well open at a point; from a practical standpoint, however, the term "piezometer" is used in this report because the open interval of each well is small in comparison with the thickness of the geologic unit penetrated. It is important to note here that water level measurements of the aquitards were made from 5- and 20-foot rock intervals from piezometers, and aquifer water levels were recorded from open wells, which may have open intervals of hundreds of feet. When water level elevations from wells or piezometers are plotted on a map and contoured, a potentiometric surface map is constructed (figs. 24, 25).

The cross sections in figures 23b and 23c depict the potentiometric surfaces of the upper bedrock and midwest sandstone aquifers, water levels in the aquitard, and hydraulic conductivity zones within the rock units. Measurements of water levels in piezometers began in December 1984 following the completion of test hole F-9 (fig. 4). Actual data from piezometers installed in test holes are presented in Kempton et al. (1987a, 1987b) and Curry et al. (1988). Subsequent readings show some variation in water levels, but most water levels have become stable. Exceptions are in test holes F-12 and F-10, in which the levels have continued to drop steadily since the installation of the piezometer. The readings from the piezometer at test hole F-1 are questionable because of difficulties experienced during installation. All other piezometers show minor fluctuations that may be seasonally related.

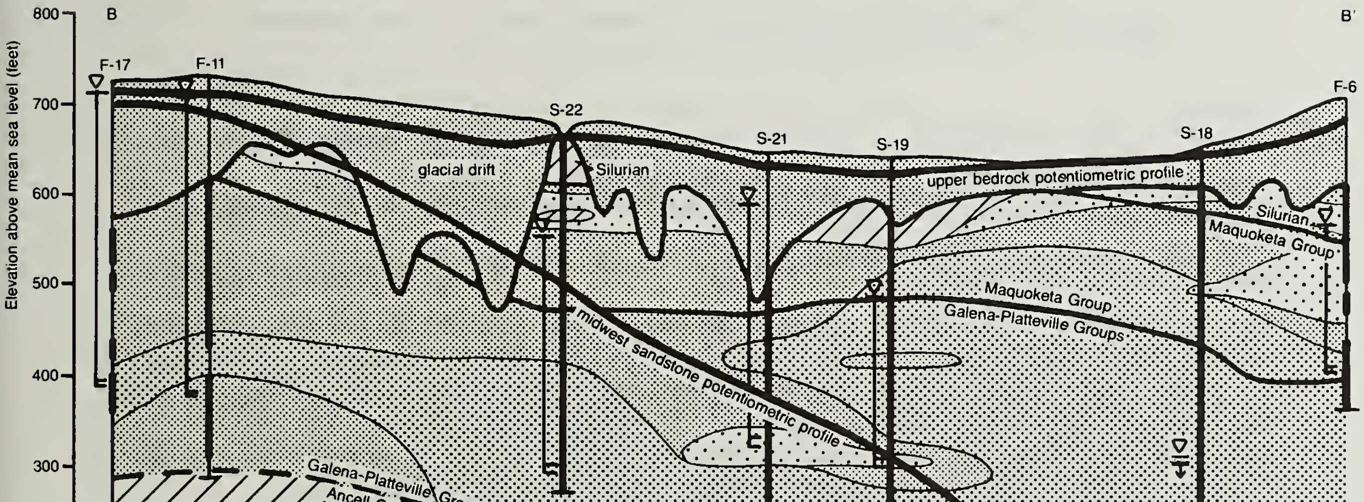


Figure 23c Cross section B-B′, showing generalized rock hydraulic conductivities, approximate elevations of the potentiometric surface of the upper bedrock aquifer and the midwest sandstone aquifers, and water levels measured in borehole piezometers.

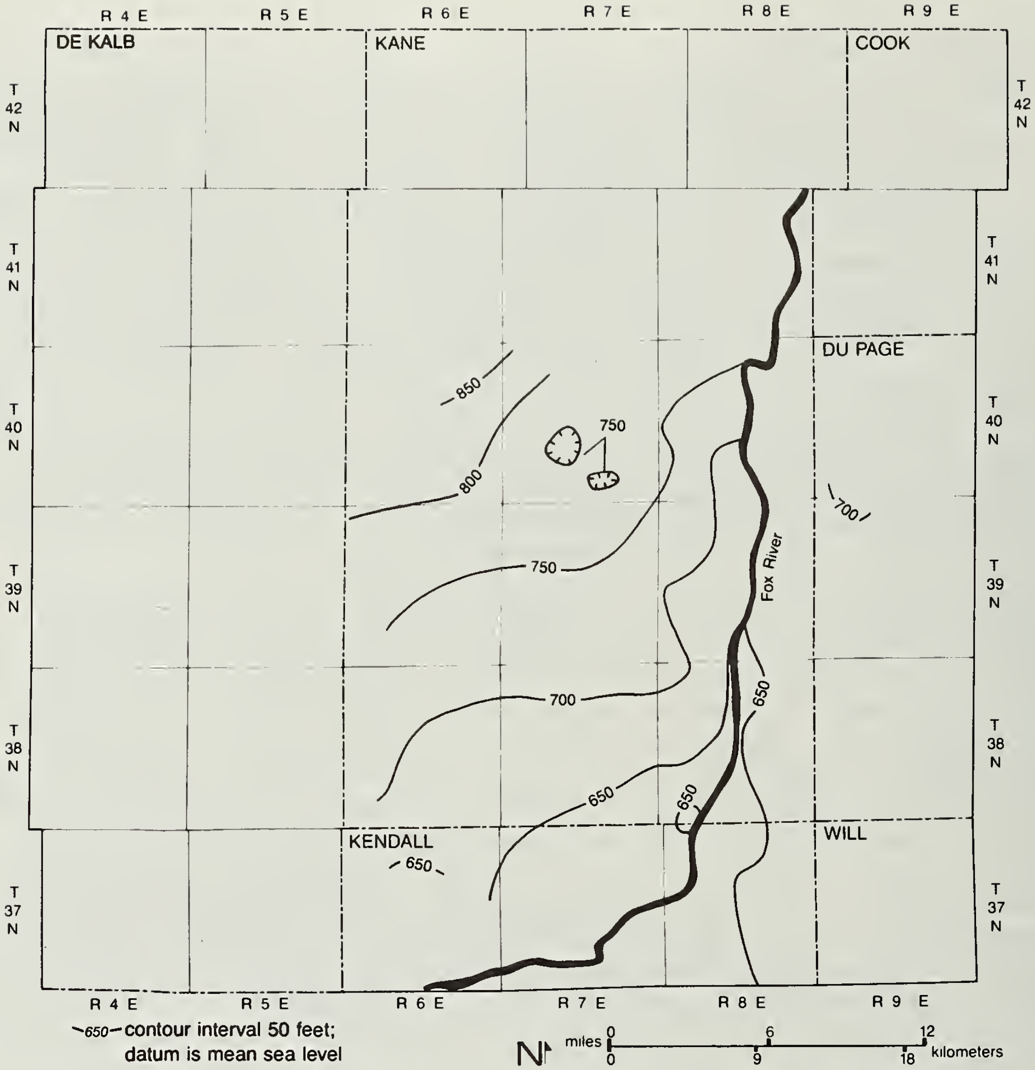


Figure 24 Potentiometric surface of the upper bedrock aquifer (water levels measured in 1986, modified from Visocky and Schulmeister, 1988).

Visocky and Schulmeister (1988) discuss the interpretations of these fluctuations in detail. The vertical bars in figures 23b and 23c represent values obtained from long-term monitoring at several elevations; they do not represent the same stratigraphic intervals.

Water Levels in Aquifers

Glacial Drift. The water table (the top of the zone of saturation) is generally 5 to 20 feet below land surface but may fluctuate by 10 or more feet during a normal year. The water table intermittently intersects the land surface in depressions and along valleys to form ponds and streams, respectively (discharge areas). Although the water table generally parallels the surface topography, the depth to groundwater may be affected by the particle-size distribution of drift. Depending on particle-size distribution and local topography, areas may be exceptionally well drained if they overlie sand or gravel substrata or poorly drained if they overlie a clay substratum (Kempton and Cartwright, 1984). A potentiometric surface map of the drift aquifers is available in Visocky and Schulmeister (1988).

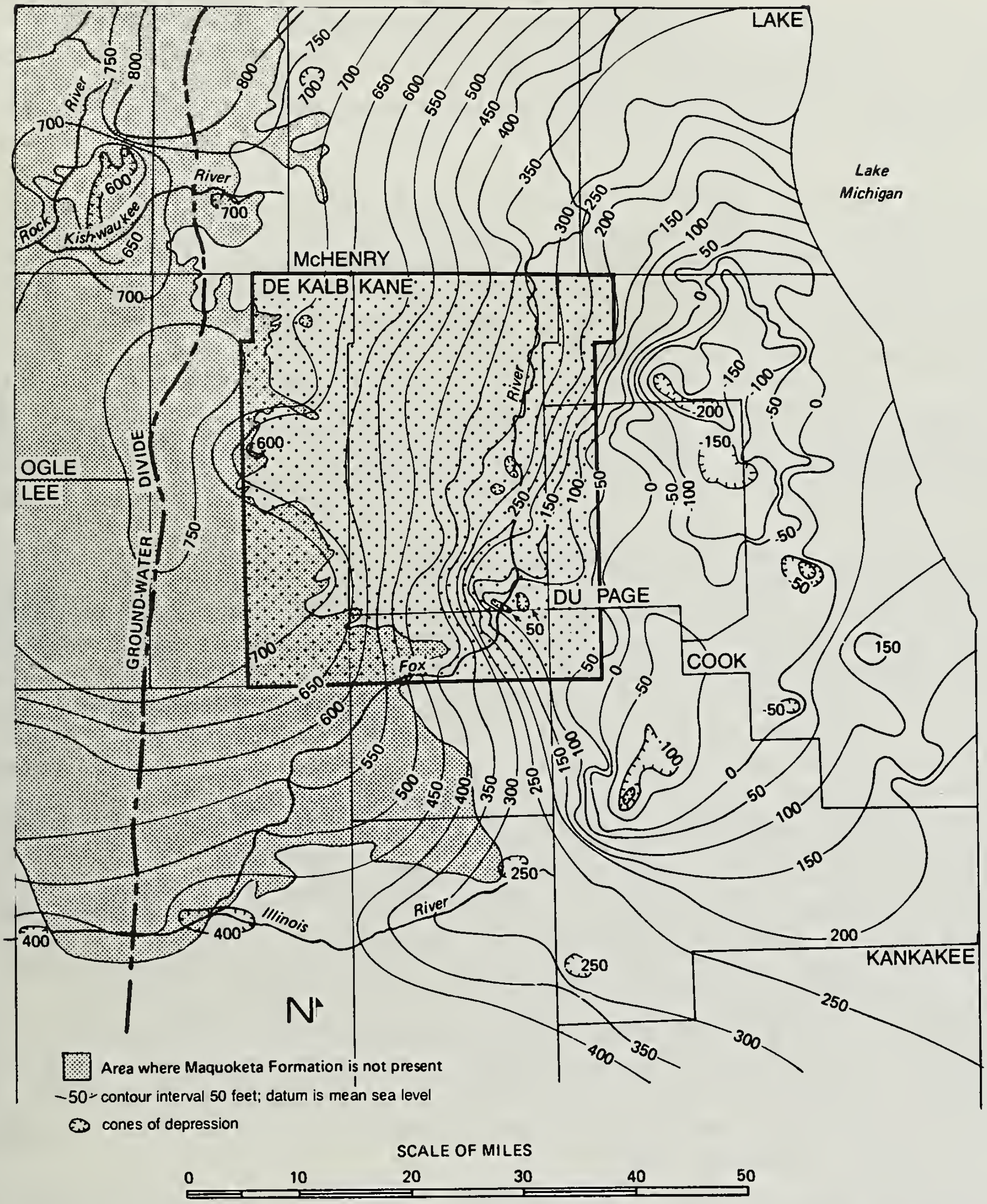


Figure 25 Potentiometric surface of the midwest sandstone aquifers (water levels measured in 1985, Sasman et al., 1986).

Bedrock. A comparison of water levels in wells open only to the upper bedrock aquifer and water levels in wells finished in the midwest sandstone aquifers indicates head differences from about 10 to 600 feet or more (figs. 23b, c). Water level elevations in the upper bedrock aquifer rise (fig. 24) from 625 feet above mean sea level near the Fox River to more than 850 feet above mean sea level in the central part of the study area, indicating a northwest to southeast flow direction (fig. 24). Water levels in the upper bedrock aquifer are higher throughout the area than the elevation of the river, and in most places water within the upper bedrock aquifer discharges to the river. The potentiometric surface of the upper bedrock aquifer is depressed along the Fox River, primarily because of low surface topography. Shallow pumping in urban centers along the Fox River (fig. 24), and in T40N, R7E in subdivisions in north-central Kane County have also contributed to the lowering of water levels in these areas.

The potentiometric surface of the midwest sandstone aquifer (Sasman et al., 1986) (fig. 25) suggests a general west to east flow direction because the surface is as much as 700 feet above mean sea level in De Kalb County and decreases to 100 feet or less in eastern Kane and western Du Page counties. Cones of depression resulting from heavy municipal and industrial pumping in the Chicago region result in a general flow direction to the east of the study area, although the flow direction is partly related to the easterly dip of the rock units. Some of these waters are intercepted by pumping centers noted in figure 25 at Elgin, Geneva-St. Charles, and Aurora (Sasman et al., 1986).

Water Levels in Aquitards (Confining Beds)

A comparison of the potentiometric surfaces of the upper bedrock aquifer and the midwest sandstone aquifer indicates that the volume of water that flows through the aquitard is minimal; this is confirmed by pressure packer test data. Water levels measured in the Galena-Platteville piezometers are always above those measured in the midwest sandstone aquifers but appear to follow the general slope of the midwest sandstone aquifers and are below and apparently unrelated to those of the upper bedrock aquifer. The potentiometric surface of the midwest aquifers has a greater slope than that of the upper bedrock and Galena-Platteville water levels. Elevations of representative Galena-Platteville water levels noted in figures 24 and 25 range between 600 and 800 feet in De Kalb County and 400 to 600 feet in much of Kane County. A map of the Galena-Platteville potentiometric surface in Visocky and Schulmeister (1988) shows a general west to east flow direction. Because flow through discontinuities in the Galena-Platteville is very slow, interpretation of a potentiometric surface is difficult. However, water levels in the Galena-Platteville indicate a general downward and eastward movement toward the potentiometric surface of the midwest sandstone aquifer.

Placement of the SSC tunnel and chambers within the Galena-Platteville (upper Ordovician aquitard) between the upper bedrock and midwest sandstone aquifers should not significantly affect groundwater resources. Groundwater inflow from this non-aquifer unit should be minimal--even though hydraulic heads may lie above anticipated tunnel depth--because of the associated low hydraulic conductivities (see Evaluation of Construction Conditions section). The tunnel, however, may intersect localized jointed zones of slightly higher hydraulic conductivity that may produce initial larger flows and require grouting to reduce long-term inflow rates.

GROUNDWATER RESOURCES

Most groundwater used in the study area comes from the midwest and basal Cambrian and Ordovician strata. Approximately 250.6 million gallons per

Table 2. Groundwater pumpage by county in 1986

County		1986 pumpage (million gallons per day)
Cook		66.8
De Kalb		13.1
Du Page		97.7
Kane		34.2
Kendall		4.5
Will		49.2
	Total pumpage	265.5

Source: Kirk, 1987.

day is pumped from the bedrock; a relatively smaller, but increasing, amount of groundwater is obtained from the glacial drift in a six-county area (Kirk, 1987; Visocky and Schulmeister, 1988). The greatest demand for water within the study area occurs along the Fox River Valley, where the major population centers are concentrated; here most of the water is obtained from the near-surface drift and upper bedrock aquifers and from the deeper midwest sandstone aquifers. Allocations of Lake Michigan water for communities east of the Fox River may ease dependence on deep aquifers and allow limited recovery of piezometric heads in the area. Total groundwater pumpage for the region is shown in table 2.

Glacial Drift

Some of the groundwater supplies for domestic, farm, and small industrial uses are obtained from sand and gravel bodies located in the glacial drift. Yields from domestic wells developed in drift aquifers usually range from 50 to 500 gallons per minute, but some municipal wells in thick, near-surface deposits near the Fox River may have yields as large as 1,000 to 3,000 gallons per minute (Schict, Adams, and Stall, 1976). Aurora and Elgin are now developing or have developed municipal well fields in drift deposits in the Newark valley and its tributaries (fig. 18). These supplies will supplement those currently obtained from the bedrock and surface water (Gilkeson et al., 1987).

Bedrock

Groundwater is pumped primarily from two aquifer units: the Silurian dolomites (upper bedrock aquifer) and the Ancell and Ironton-Galesville Sandstones (midwest sandstone aquifers). Where present, the Silurian dolomite is commonly used for domestic and industrial supplies and yields up to 1,000 gallons per minute. West of the Fox River, where the Maquoketa is the upper bedrock aquifer, yields are generally small to moderate.

The Galena-Platteville yields little water east of the Maquoketa subcrop boundary and is not used as a water source in most areas. The Galena-Platteville is used for small-volume water supplies along the western margin of the study area in De Kalb County. Wells obtaining water primarily from the upper bedrock aquifer may extend into the generally impermeable Galena to provide additional storage capacity to the well.

Yields from the midwest sandstone aquifers vary among the stratigraphic units. The St. Peter and Glenwood sandstones may yield small to moderate quantities of groundwater (50 to 200 gallons per minute) and are often used for domestic, small industrial, and municipal supplies. Yields from the Ancell are generally too low to provide large municipal water supplies. The Ancell is more extensively used south of the Sandwich Fault, where it is at or close to the bedrock surface. The Ironton-Galesville is a more uniform and productive aquifer, yielding more than 500 gallons per minute; it is commonly used for municipal and industrial supplies (Visocky, Sherrill, and Cartwright, 1985). Pumpage of the midwest sandstone aquifers has lowered water levels east of the study area hundreds of feet. Increasing use of Lake Michigan water could ease demand on groundwater in the eastern part of the study area.

GEOTECHNICAL PROPERTIES OF GEOLOGIC UNITS

R. A. Bauer and B. B. Curry

Much of the information provided in this section was obtained specifically to determine construction feasibility for the proposed SSC; however, some of the data can be used to evaluate general construction conditions throughout the region. This section also provides baseline data for relating to site-specific data currently being developed for the SSC location (Curry et al., 1988; Vaiden et al., 1988; Kempton et al., in preparation; Bauer, Hasek, and Su, in preparation).

The principal requisites for general construction and surface facilities for the SSC are adequate bearing strength to support surface structures, lack of liquefaction potential, and good drainage conditions. Important engineering considerations for the SSC tunnel in bedrock are (1) geotechnical properties of the rock (including strength, hardness, quality of the rock mass, and in situ stress); (2) geologic structures (including bedding and joint characteristics, faults, and diagenetic structures); (3) seismicity; and (4) hydrogeologic conditions. Data on the geotechnical characteristics of the geologic units encountered in the area are useful for estimating rock mass quality, ease of excavation, excavation rates, excavation equipment needed, support requirements for underground construction, and ultimately, construction costs.

General information on the drift and bedrock units is provided in Kempton et al. (1985); additional information obtained during the SSC drilling program included data on rock and drift lithology, thickness, and distribution (discussed in the geology section of this report), drilling rate (time to drill 1 foot of rock), Rock Quality Designation (RQD) (quantification of joint spacing greater than 4 inches), core recovery (amount of core recovered per core run), fracture frequency (number of fractures per feet drilled), and distance between horizontal core separations. A description of these engineering properties and drilling and rock mechanics data obtained from drilling and laboratory testing in 1984 and 1985 (Kempton et al., 1987a, 1987b) can be found in the appendixes and tables. Laboratory procedures are explained in appendix B. Although data and interpretations in this section are based primarily on the F Series boreholes, the S Series boreholes show similar trends (Kempton et al., and Bauer, Hasek, and Su, in preparation).

GLACIAL DRIFT

Four basic lithic elements of the drift--till, lacustrine sediment, outwash, and organic-rich sediment--govern the range of engineering characteristics likely to be encountered. None of the above materials should pose problems that would result in higher-than-normal excavation costs. On the basis of the bearing strength data, as well as the experience gained during construction of surface structures in the area, no unusual settlement is expected for conventionally designed foundations. On the basis of the material properties, neither the sand and gravel nor clayey lacustrine materials in the area are considered to be liquefiable according to standards presented by Seed and Idriss (1982).

Table 3. Summary of geotechnical characteristics and properties of the drift

Unit		Standard Penetration Test (N) (blows/ft)	Compressive strength (Qp) (TSF)	Moisture content (W) (%)	Dry density (dd) (lbs/ft^3)	Particle size determination			
						Gravel (% of whole sample)	< 2-mm fraction		
							Sand (%)	Silt (%)	Clay (%)
Cahokia Alluvium	$\bar{x}$	8	1	26	107	6	29	45	26
	n	25	15	23	7	44	48	48	48
	R**	2-25	0-3	11-51	100-117	0-51	0-59	16-73	6-49
Grayslake Peat	$\bar{x}$	2	<1	112	52	2	8	52	40
	n	20	10	20	5	6	10	10	10
	R	0-5	<1	34-265	30-74	0-3	0-23	26-72	22-61
Richland Loess	$\bar{x}$	12	2	24	101	1	7	50	43
	n	6	10	10	5	8	8	8	8
	R	9-19	<1-4	20-31	94-104	0-3	0-15	40-61	35-53
Equality Formation	$\bar{x}$	20	1	29	96	1	8	60	32
	n	70	133	145	65	172	198	198	198
	R	3-68	<1-4	11-145	43-131	0-10	0-30	9-94	2-84
Henry Formation	$\bar{x}$	22	2	17	-	29	53	32	15
	n	251	4	19	-	112	113	113	113
	R	3-119	<1-2	11-23	-	0-76	5-91	2-92	0-53
Wadsworth Till	$\bar{x}$	24	2	17	-	6	14	43	43
Member	n	55	39	43	-	54	54	54	54
	R	-	-	-	-	-	-	-	-
Haegar Till	$\bar{x}$	36	2	12	-	21	38	49	13
Member	n	19	7	10	-	27	27	27	27
	R	-	-	-	-	5-41	16-53	39-65	5-24
Yorkville Till	$\bar{x}$	20	3	13	126	12	26	42	32
Member n	29	48	55	25	80	80	80	80	
(ablation facies)	R	11-26	<1-8	10-24	114-136	2-40	7-53	17-66	15-90
Yorkville	$\bar{x}$	28	4	17	117	4	10	46	44
Till Member	n	569	927	1,469	608	379	987	987	987
(till facies)	R	3-106	<1-10	6-35	92-138	0-29	0-54	18-83	13-68
Malden Till Member	$\bar{x}$	17	2	13	128	13	36	43	21
	n	33	37	44	13	54	54	54	54
	R	5-100	<1-4	9-25	119-135	0-32	4-57	23-63	6-38
Malden Till Member	$\bar{x}$	32	-	11	104	5	55	34	11
(outwash facies)	n	44	-	3	1	13	13	13	13
	R	6-100	-	8-13	-	0-23	3-83	4-80	0-29
Tiskilwa Till	$\bar{x}$	28	2	10	-	17	43	39	18
Member	n	132	12	105	-	41	43	43	43
(ablation facies)	R	6-77	1-6	6-30	-	5-70	16-62	18-54	8-37
Tiskilwa Till	$\bar{x}$	35	3	11	124	7	35	38	27
Member	n	533	370	364	84	315	315	315	315
(till facies)	R	3-600	<1-11	8-16	83-156	0-25	4-52	28-71	6-45
Robein Silt/	$\bar{x}$	258	4	17	98	8	36	32	32
Sangamon Soil	n	7	8	7	1	3	3	3	3
	R	152-440	3-4	12-23	98	<1-16	30-44	26-38	17-40
Glasford Formation	$\bar{x}$	57	4	11	144*	11	38	36	26
undivided	n	58	49	59	8	71	77	77	77
	R	22-106	1-5	6-18	124-150	<1-57	10-58	23-56	11-50

$\bar{x}$ = mean
n = number of samples
R = range
* = moist density

Sources: Landon and Kempton, 1971; Schmitt, 1985; Kempton et al., 1987; a,b; and data on open file at the ISGS

Till consists of overconsolidated, very poorly sorted clay, silt, sand, and larger particles; it is used extensively as foundation material. The upper till at a site may be weathered (oxidized) and jointed, which generally affects water movement but not necessarily gross engineering "strength" (Kemmis, 1978).

Lacustrine material overlain by till has characteristics similar to those of till: it is overconsolidated and has high strength and low permeability. Where the uppermost drift is lacustrine material (Equality Formation) it may be organic-rich (up to 5 percent organics) and may have considerable moisture content (up to 100 percent) and low strength.

Organic-rich sediment may also occur at the surface in small areas, generally in bogs (Grayslake Peat) or in the subsurface (Robein Silt). The Grayslake Peat, which may consist entirely of organic matter, generally has extremely low compressive strength, and its moisture content may be as high as 700 percent, making it undesirable as foundation material. Peat occurring at the surface is often removed prior to foundation construction.

Outwash is mostly sand and gravel and contains generally less than 15 percent silt and finer particles. Most outwash, buried or surficial, is dense or very dense and is generally suitable foundation material; it may be less desirable for shaft construction.

The engineering properties for the drift units that would be encountered in tunnel construction are listed in table 3. Included are blow count (N), the number of blows per foot; unconfined compressive strength by pocket penetrometer (Q_p) in tons per square foot; natural moisture content (W) in dry weight percent; and dry density (dd) in pounds per cubic foot.

Richland or Peoria Loess

These units have low bearing strength when saturated but medium to high strength when dry (Bergstrom, Piskin, and Follmer, 1976). The clay mineral fraction of the loess contains about 75 percent expandable clay minerals, indicating moderate shrink-swell potential. The Richland and Peoria are generally less than 5 feet thick.

Equality Formation

The Equality Formation is normally consolidated, and this is reflected in the mean engineering properties: moisture content, 29 percent, blow counts, 20, and unconfined compressive strength, 1 ton per square foot. Organic-matter content may increase from the bottom to the top of a thick sequence of the Equality, which accounts for the widely variable moisture content and blow counts in this formation.

Wedron Formation

Yorkville Till Member. The most uniform regional data for the Yorkville is particle-size distribution (10-46-44; sand-silt-clay, respectively, table 3) and moisture content (mean, 16.5 percent, fig. 26a). In

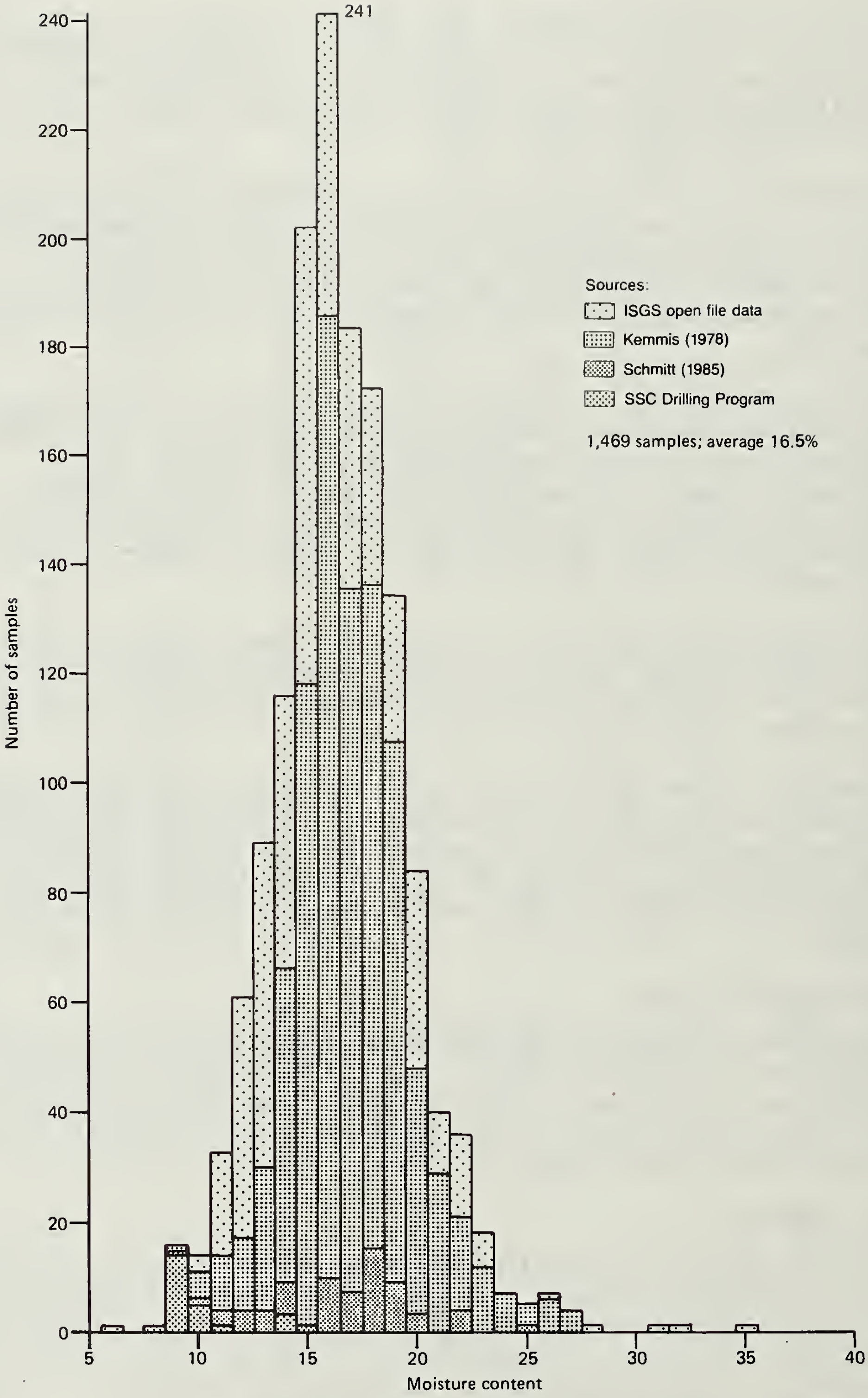


Figure 26a Moisture content of the Yorkville Till Member, Wedron Formation.

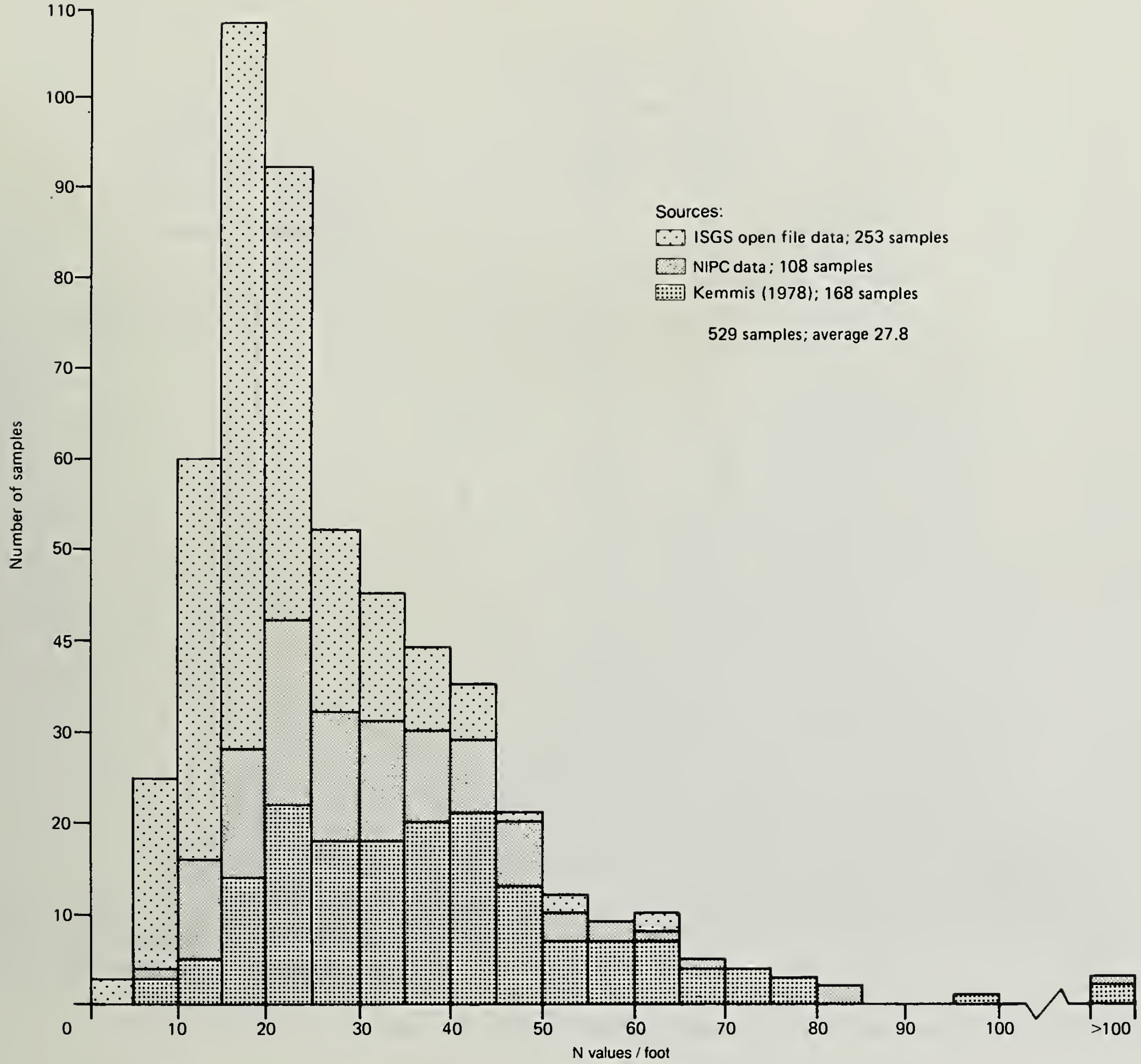


Figure 26b N (blow count) values for the Yorkville Till Member.

addition, N values show little variability (mean, 27.8 blows/foot, fig. 26b). The higher average N value for the Tiskilwa (fig. 27c), as compared with that of the Yorkville, can be attributed to the Tiskilwa's lower moisture content and higher sand and gravel content. The average moisture content of the Yorkville is higher than that of the Tiskilwa chiefly because of its higher silt and clay content, and perhaps also because of its lower density. Unconfined compressive strength (Q_p) of the Yorkville varies widely (fig. 26c); the associated bearing strength ranges from medium to high.

Malden Till Member. The Malden can be separated into two regional types in the study area (Landon and Kempton, 1971). One type is present east of and along the Fox River, and is found beneath the Fermilab Accelerator site where the Malden occurs beneath Yorkville deposits. Here the till has a very high bearing capacity but is associated with sand and gravel layers up to 15 feet thick, as well as with stratified silt, fine

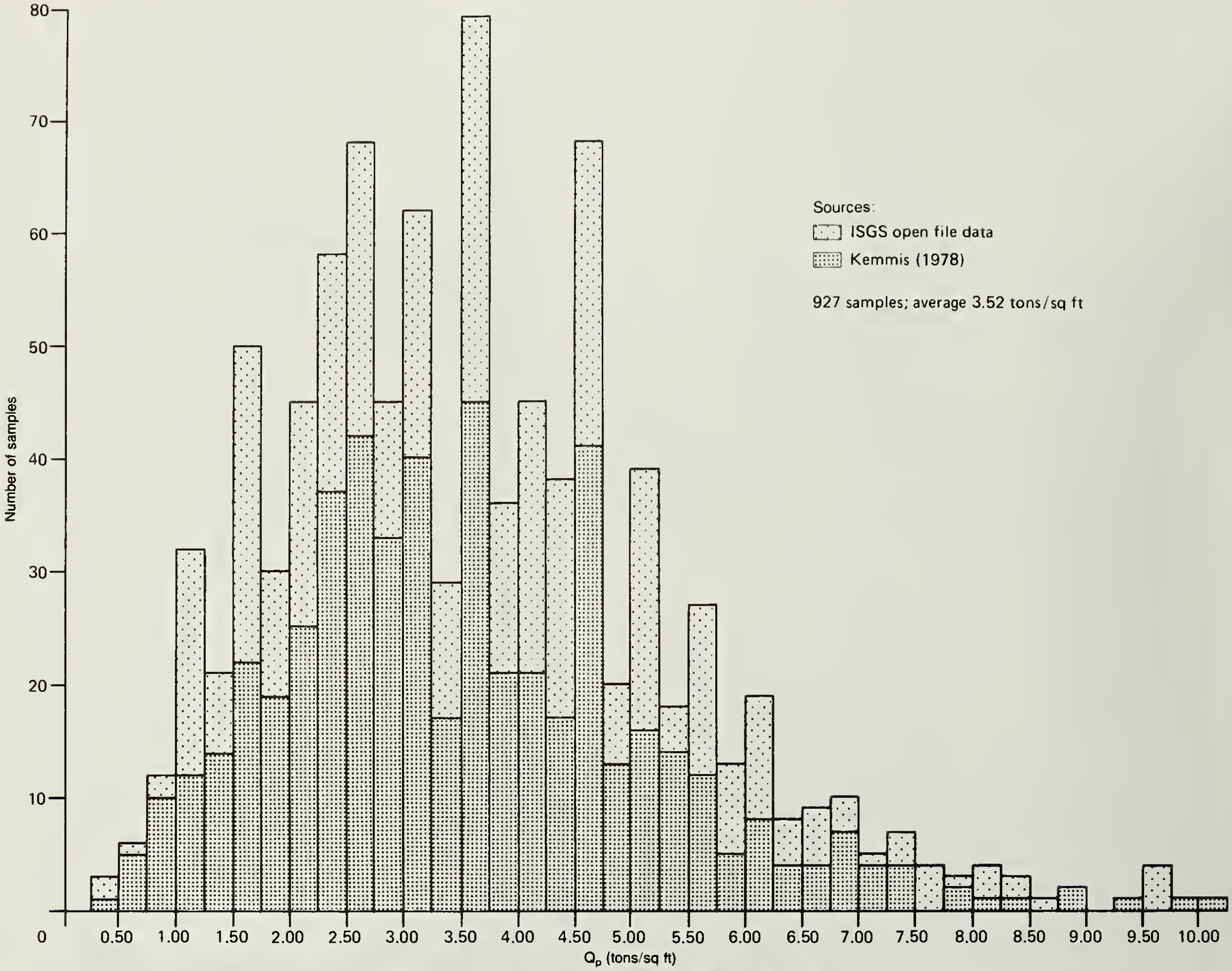


Figure 26c Unconfined compressive strength (Q_p) of the Yorkville Till Member.

sand, and clay beds (Unit C and D in Landon and Kempton, 1971). The other regional type occurs at or near the surface in the Elburn Complex (fig. 19). Here the Malden is a surficial deposit and the till is associated with abundant, poorly sorted sediment and deposits of dense sand and gravel up to 70 feet thick. Engineering properties of the Malden east of the Fox River are summarized in Landon and Kempton (1971).

Tiskilwa Till Member. The particle-size distribution data are remarkably uniform for what are interpreted as Tiskilwa basal till (35-38-27 sand, silt, and clay, table 3); this uniformity probably accounts for the equally uniform moisture content, which has a mean value of 10.6 percent (fig. 27a). Unconfined compressive strength (Q_p) and blow count (N) data vary more than do texture and moisture content (figs. 27b and 27c). The mean blow count is 45.3; values greater than 100 probably represent encounters during test drilling with boulders or smaller pebble-sized clasts that blocked split spoon penetration; eliminating these values, the mean blow count is 34.9. Unconfined compressive strength commonly exceeds 4.5 tons per square foot.

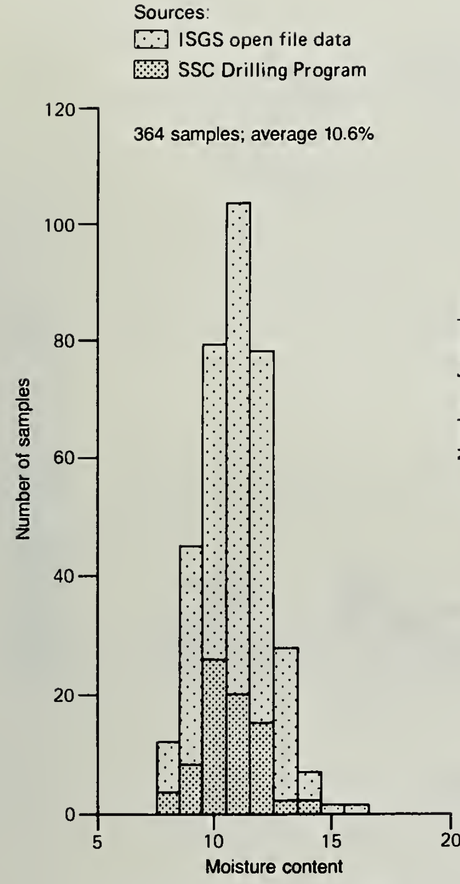


Figure 27a Moisture content of the Tiskilwa Till Member, Wedron Formation.

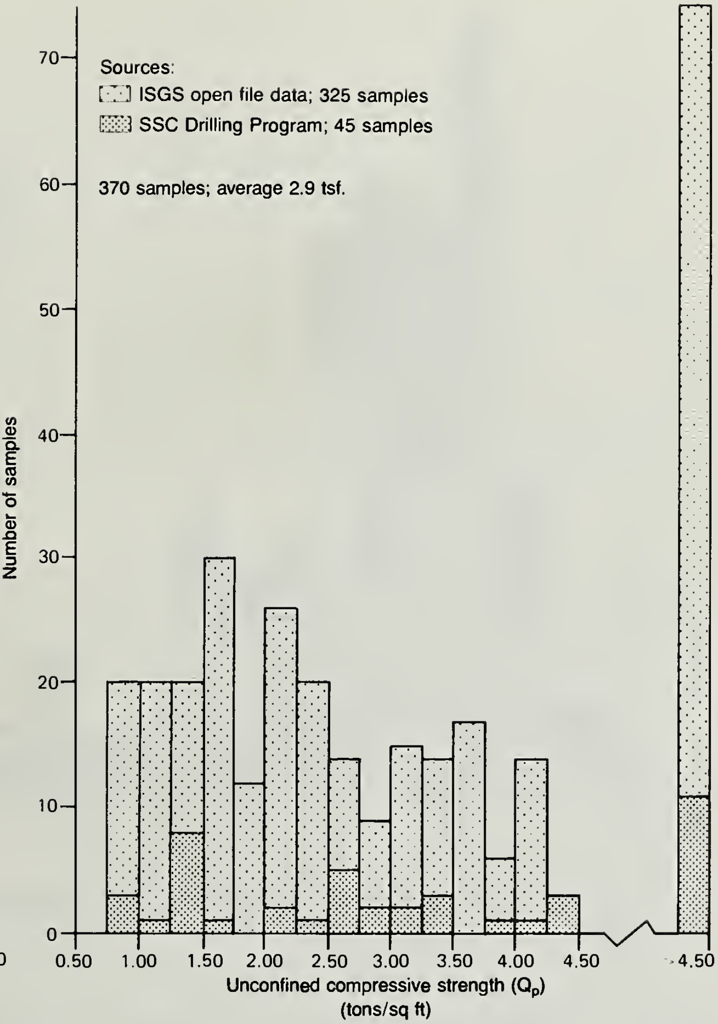


Figure 27b Unconfined compressive strength (Q_p) of the Tiskilwa Till Member.

Sangamon Soil--Robein Silt

The organic matter content of these deposits is generally 1 percent or less, but the Robein contain up to about 16 percent organic matter. The clay fraction of the Robein may also contain about 60 percent expandable clay minerals, indicating some shrink-swell potential. At test hole F-17 (fig. 4), an unusually thick sequence (28 feet) of interbedded organic-rich silty clay and clay loam occurs between a depth of 122 and 150 feet. At this site the Sangamon Soil-Robein Silt deposits have unconfined compressive strength much greater than 4.5 tons per square foot, and the maximum organic matter content is 0.98 percent (R.A. Cahill, ISGS, personal communication, 1987).

Glasford Formation (Undifferentiated)

In general, loamy till having high to very high bearing strength (table 4) and silty loam till having high bearing strength are common. Stratified gravel, sand, and silt are also present.

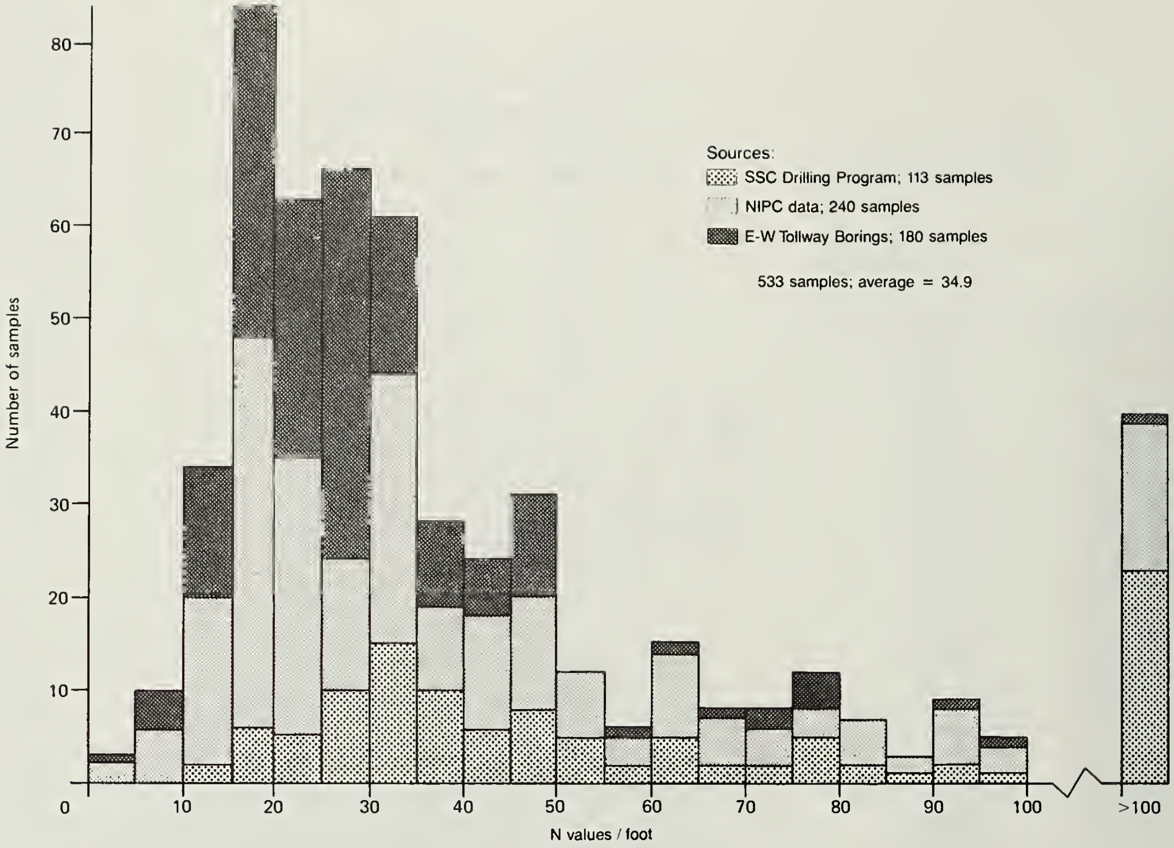


Figure 27c N (blow count) values for the Tiskilwa Till Member.

Table 4. Groupings of approximate bearing strengths of glacial materials

		Till and lacustrine sediment		Sand and gravel	
Bearing strength	Relative strength	Unconfined compressive strength (tsf)	Standard penetration test blow count*	Standard penetration test blow count*	Relative density
Low	Very soft	0.25	2		
	Soft	0.25-0.5	2-4	4	Very loose
Medium	Medium	0.5-1.0	4-8	4-10	Loose
	Stiff	1.0-2.0	8-15	10-30	Medium
High	Very stiff	2.0-4.0	15-30	30-50	Medium
Very high	Hard	>4.0	>30	>50	Very dense

*Blow count for 12-inch penetration (each blow is from a 140-pound hammer dropped from height of 30 inches).

Source: Bergstrom, Piskin, and Follmer, 1976; after Terzaghi and Peck, 1967.

BEDROCK-DRIFT INTERFACE

Glacial deposits (till, lacustrine, and outwash) overlie the bedrock surface. The rocks below this surface may in some places have retained residual soils and other weathering features such as fractures and joints. In some areas, these joints and fractures developed near or at the erosional surface were widened and enlarged by solution. These enlarged fractures, which also yield water, may have to be grouted before or during shaft construction. Glaciers that moved across the area locally distorted, shoved, or otherwise began to incorporate the rocks and residual soils into the ice, in some places completely removing the weathered debris and leaving a flat, often striated or grooved surface on relatively fresh bedrock. In other areas rubble or blocks are present at the bedrock surface (Johnson and Hansel, 1986). In the study area this interface can be seen only in quarries and in cores.

The Silurian rocks are the most intensely jointed in the uppermost 40 feet. Horizontal and especially vertical joints at the Podschwit Quarry (fig. 28) are either filled with clayey silt deposits up to 0.4 to 0.75 inch thick or have reddish brown to orange oxide stains. The stains indicate groundwater flow through fractures; the clayey silt deposits suggest downward translocation of fine-grained material facilitated by groundwater movement. The clay joint fillings are nearly pure illite, suggesting that their shrink-swell potential is low. At the Van Acker Pit (fig. 28), near-vertical crevices up to 1.5 feet across and 5 feet deep occur in bedrock and are filled with dark brown, silty clay (Robein Silt). The silty clay is composed of 50 percent smectite and 0.8 percent organic matter, suggesting some shrink-swell potential. This creviced zone on the bedrock surface, which was quarried and removed, originally covered about 40,000 square feet in a broad, shallow depression. A more significant portion of the bedrock surface at this site covered 150,000 square feet and was flat and unweathered.

Ice-shove blocks of Silurian dolomite in the Avery and Boughton Quarries (fig. 28) are generally rectangular prisms measuring up to 10 feet x 10 feet x 15 feet long. Most blocks appear to rest on the bedrock surface, but some lie on up to 5 feet of drift. The drift is composed of matrix-supported bedrock rubble (Johnson and Hansel, 1986). Rock rubble has also been noted in 5 of the first 17 test holes drilled (F Series).

The bedrock surface of the Maquoketa Group is variable because of the lithologic diversity of this unit. One exposure of the Maquoketa at and below the bedrock surface is at the Floit Pit (fig. 28), where interbeds of shale and argillaceous dolomite are relatively fresh and unweathered. However, some of the lowest RQD and core recovery values and highest fracture frequency values were encountered at or near the bedrock surface, suggesting poorer rock conditions than are encountered deeper in the bedrock (table 5). Where the lithology is dolomite or limestone, the contact is generally sharp, and rock rubble is absent above the bedrock surface.

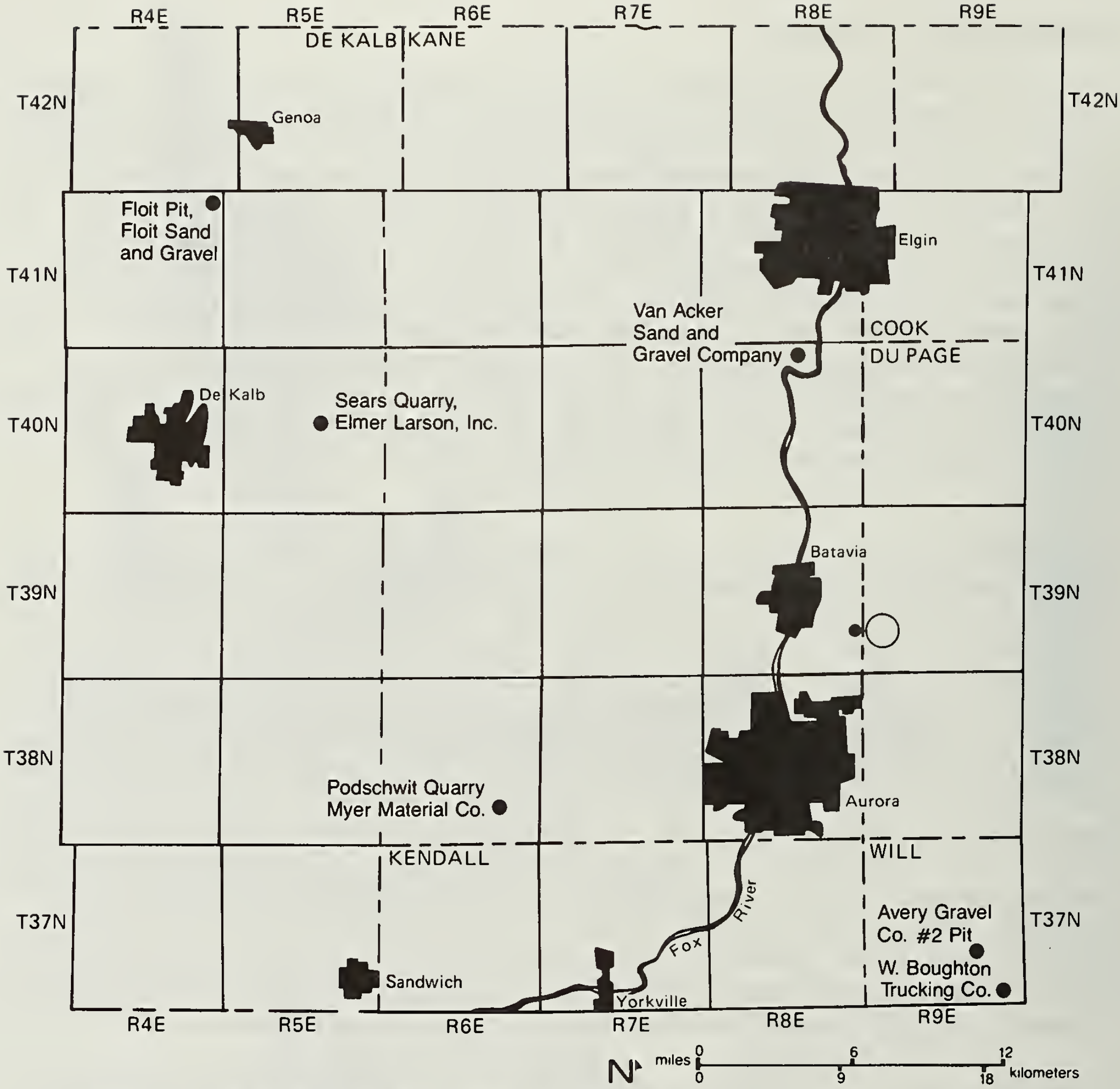


Figure 28 Quarries and sand and gravel pits noted in text.

BEDROCK

Material properties analyzed in the following discussion are average core recovery, average rock quality designation (RQD), compressive strength, and modulus ratio. Results of these analyses used to assess the rock quality were for those units housing the tunnel and chambers (Galena-Platteville) and the shafts (Silurian, Maquoketa, and Galena-Platteville).

General Characteristics

Silurian Formations. Average core recovery and average RQD of these formations are excellent (99.7 and 98.9 percent, respectively) and compressive strength and modulus ratio values are medium to high (table 6; fig. 29a). Average unconfined compressive strength is 16,065 pounds per square inch (psi). Average triaxial strength (see appendix C) is 48° phi angle, and average cohesive strength (see appendix C) is 1,640 psi.

Table 5. Summary of geotechnical conditions at or near the bedrock surface (results from first core runs in bedrock)

Borehole number	Rock type	Core recovery (%)	RQD (%)	Depth below top of bedrock* (ft)	Fracture frequency (#/10ft)
F-1	Silurian	85	70	3.3	5
F-2	Silurian	100	100	6.6	0
F-3	Maquoketa	96	96	6.1	4
F-4	Silurian	100	100	17.3	3
F-5	Maquoketa	100	84	2.5	2
F-6	Silurian	100	100	3.0	6
F-7	Silurian	100	100	3.5	0
F-8	Maquoketa	94	93	12.3	2
F-9	Maquoketa	99	91	8.9	5
F-10	Silurian	100	100	5.0	1
F-11	Galena	100	98	0.7	8
F-12	Maquoketa	70	70	14.1	0
F-13	Maquoketa	56	24	0.0	2
F-14	Maquoketa	100	100	1.0	3
F-15	Maquoketa	100	100	0.0	4
F-16	Maquoketa	100	100	0.0	0
F-17	Galena	100	88	0.0	6
Averages per rock type					
	Silurian	98	95	6.5	3
	Maquoketa	91	84	5.0	2
	Galena	100	93	0.4	7

*Top of first core run.

Maquoketa Group. Average core recovery and average RQD are excellent (98.5 and 97.2 percent, table 6). A relatively low value of 64 percent RQD resulted from an increase in the number of fractures in some shale sections; these sections, having fracture frequencies as high as 30 fractures per 10 feet, are soft-sediment deformation features, not part of a joint or fault system. Slickensided, randomly oriented fractures have been found in 4 of the 17 boreholes.

The physical properties of strata within the Maquoketa vary widely because the Maquoketa consists of interbedded dolomitic shale and dolomite. Compressive strength ranges from very low to medium; modulus ratio is low to average (table 6 and fig. 29a). On the basis of triaxial strength testing, the average phi angle is 32° and average cohesion strength is 996 psi. Average unconfined compressive strength is 4,405 psi for the shaly sections and 8,998 psi for the dolomite sections.

Slake durability (fig. 30) and clay mineral analysis were performed on the shale sections. The slake test results showed that the shale has a medium to medium-high resistance to slaking. Clay mineral analysis of disintegrated shale samples by X-ray diffraction showed that the shale is composed predominantly of illite with some chlorite, indicating no significant swelling potential.

Galena-Platteville Groups. Wise Lake Formation dolomites possess excellent average core recovery and RQD values of 99.9 and 99.1 percent, respectively. Compressive strength ranges from low to high, with most values in the medium range (fig. 29b; table 6). The modulus ratio is

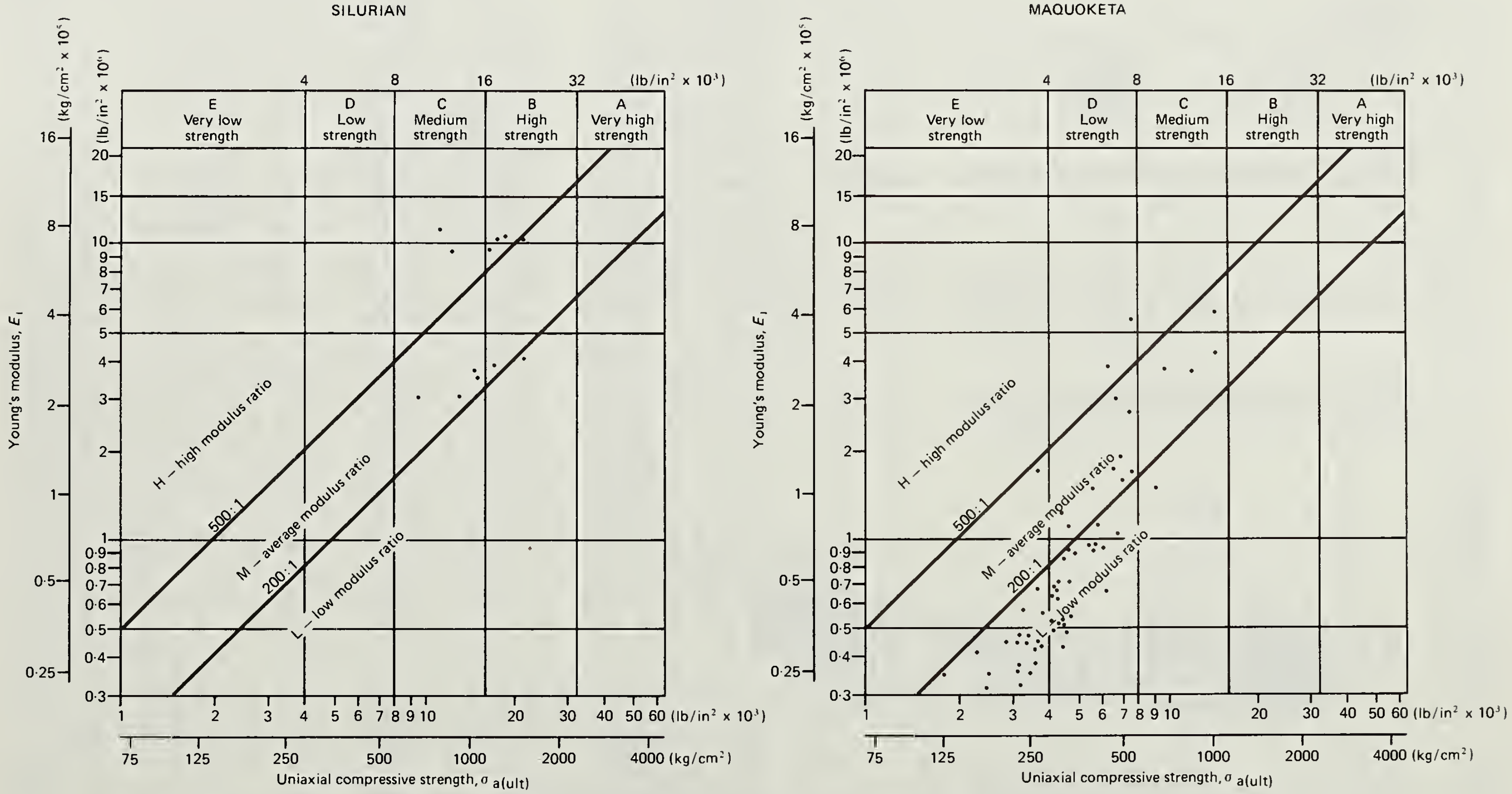


Figure 29a Strength test data for Silurian and Maquoketa bedrock samples, showing compressive strength and modulus ratios.

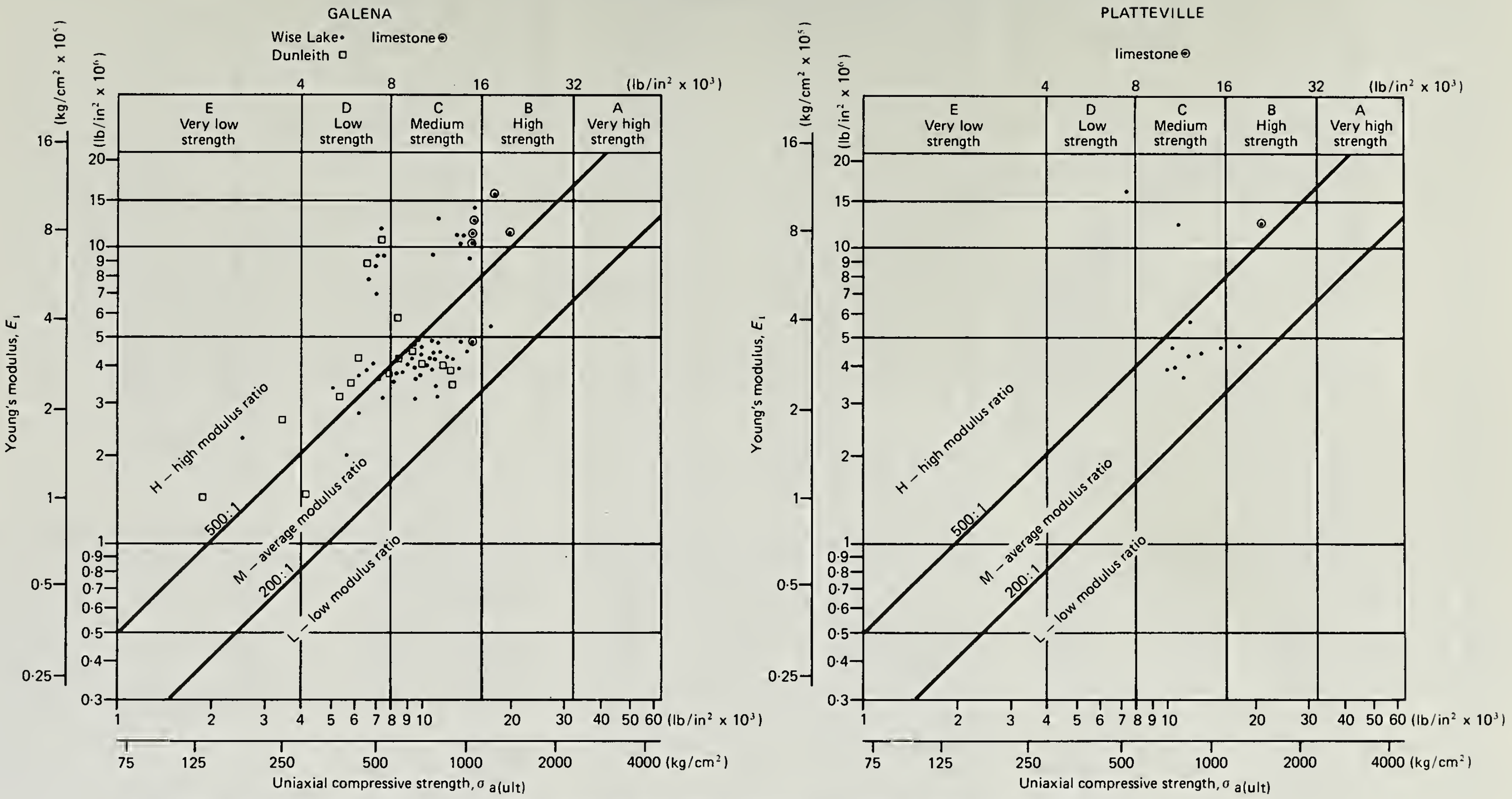


Figure 29b Strength test data for Galena and Platteville samples, showing compressive strength and modulus ratios.

Table 6. Average rock property values and in situ conditions

Unit	Core recovery (%)	RQD (%)	Triaxial		Unconfined compressive strength (psi)	Tangent modulus (psi x 10^6)	Indirect tensile strength (psi)	Compressive classification (fig. 28)	Modulus ratio (fig. 28)	Rock mass classification		Taber abrasion	Total hardness
			Phi angle	Cohesion (psi)						Q-system	RMR		
Silurian	99.7	98.9	48°	1,640	16,065	7.13	1,159	medium-high	avg-high	98	80-92		
Maquoketa	(98.5	97.2	32°	996)*									
Shale					4,405	0.77	523	very low-avg	low-avg	14	52-64	0.304	15.38
Dolomite					8,998	3.13	817	very low-avg	low-avg	14	55-67	0.532	
Galena													
Wise Lake													
Dolomite	99.9	99.1	49°	1,555	10,034	5.62	841	low-med	avg-high	98	75-87	0.897	30.74
Limestone	99.6	99.6	53°	2,842	16,148	11.72	1,089	med-high	high	98	80-92	1.153	36.19
Dunleith	99.4	97.6	42°	1,161	7,600	4.63	635	very low-med	avg-high	96	75-87	0.900	32.28
Platteville													
Dolomite	93.4	89.6	53°	1,884	12,169	6.56	1,034	medium	avg-high	88	72-84	0.841	37.20
Limestone	100.0	99.7	53°	3,054	22,775	6.30	1,411	high	high	98	77-89		

*Undifferentiated dolomite and dolomitic shale

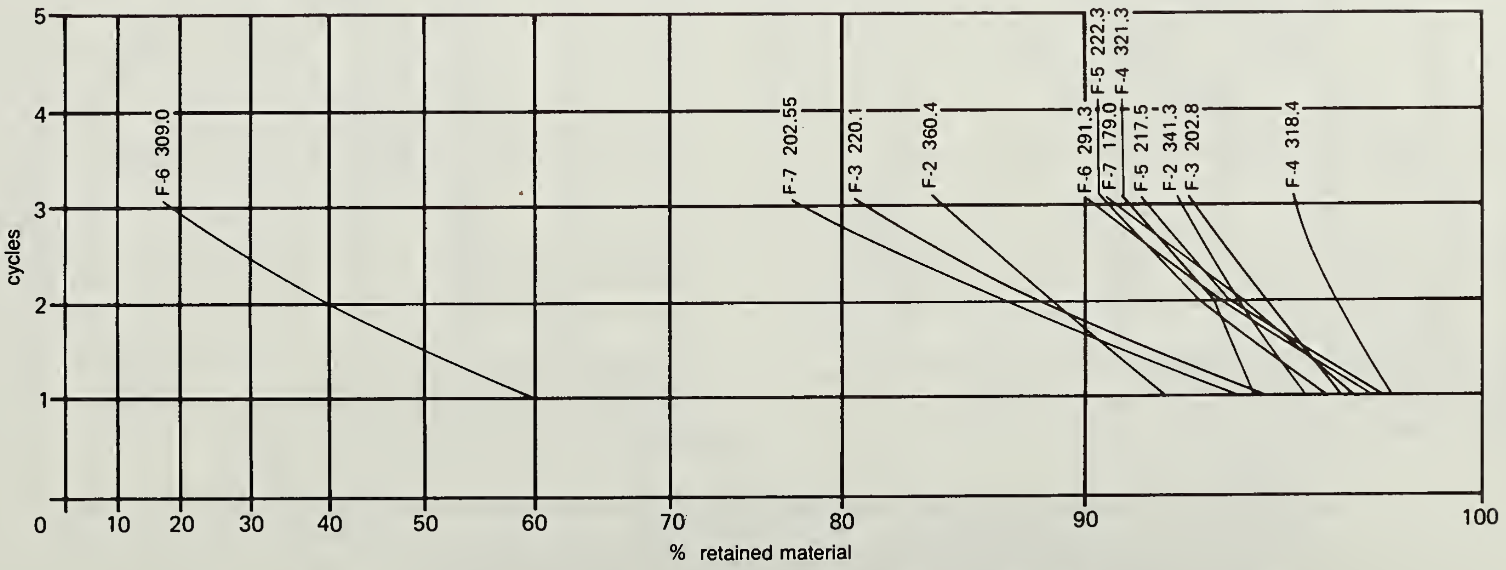


Figure 30 Slake durability values for Maquoketa shale samples, indicating medium to medium high resistance to slaking.

average to high. The average phi angle is 49°, average cohesion strength is 1,555 psi, and average unconfined compressive strength is 10,034 psi.

Dunleith Formation materials possess excellent average core recovery and RQD values of 99.4 and 97.6 percent, respectively. Compressive strength ranges from very low to low to medium, with most values in the medium range (fig. 29b; table 6). The modulus ratio is average to high. The average phi angle is 42°, average cohesion strength is 1,161 psi, and average unconfined compressive strength is 7,600 psi.

Platteville dolomite possesses excellent average core recovery of 93.4 percent. The average RQD is good at 89.6 percent. Compressive strength of the Platteville is medium and the modulus ratio is average to high (fig. 29b; table 6). The average phi angle is 53°, average cohesion strength is 1,884 psi, and average unconfined compressive strength is 12,169 psi.

In general, the analysis of engineering properties suggests that the bedrock--particularly the dolomites and limestones of the Galena-Platteville and Silurian Groups--is excellent tunneling material. The shales of the Maquoketa may be less desirable because of their lower strengths and moderate slaking, but even these shales make good tunneling material. The liquid limits of disintegrated Maquoketa shale are well below 30 percent, and according to criteria established by Brekke and Howard (1973) do not indicate a swelling problem.

Although these laboratory and field properties suggest excellent tunneling conditions, particularly for the Galena-Platteville, they can be only partly related to conditions at the actual tunnel site, because the overall strength of the rock mass is controlled by joints (fractures), joint spacing, joint shear strength, RQD, joint dips and direction, and water inflow.

Joint Characteristics

Joint sets (sets of parallel fractures or breaks in the rocks) in northeastern Illinois exhibit consistent directions with the primary joint set striking northwest (N50°W) and the secondary set striking northeast (N47°E) (fig. 31a) (Foote, 1982). Angle hole F-8 (fig. 31b) in the southwestern part of the SSC area, showed similar joint orientations, with a northwest orientation about N35°W; the direction of the northeast-trending set is N30-60°E.

Most of the joints noted in boreholes and rock quarries are near vertical; 84 percent in the Galena-Platteville have dips equal or greater than 70° (fig. 32a). Openings along these joints may range from hairline cracks to cracks less than one-fourth inch wide; those lying close to the bedrock surface that are opened by solution may be larger. These enlarged joints generally are found in the Silurian and Maquoketa dolomites, and Galena-Platteville, where they are at the bedrock surface, but not in the Maquoketa shales, which are not susceptible to solution. In the Galena-Platteville 80 percent of the joints in core from the first 17 boreholes contain no fill material, 10 percent contain some

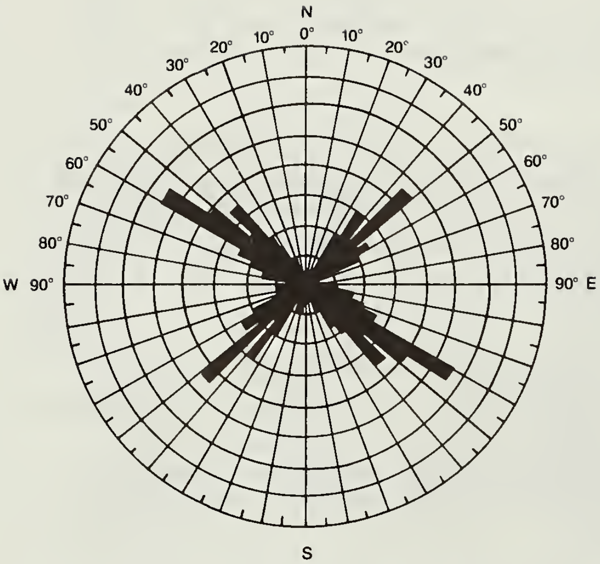


Figure 31a Joint set direction rosette diagram for Podschwit Quarry (Foote, 1982).

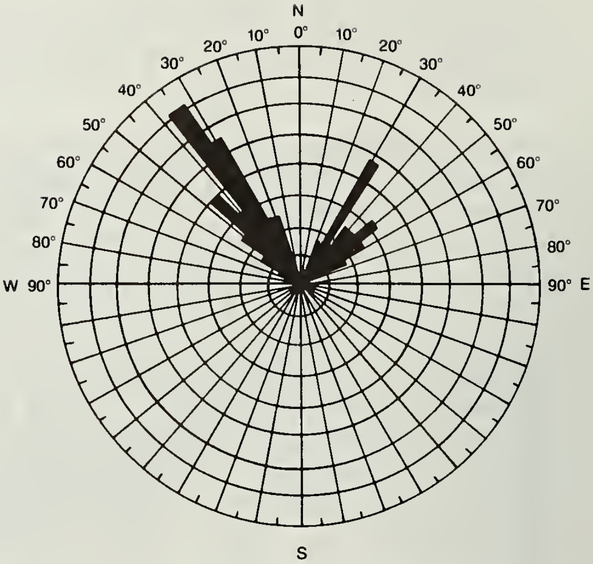


Figure 31b Joint set direction rosette diagram for SSC exploratory borehole F-8 (Foote, 1982).

clay or shale, and the remaining 10 percent are partly to completely mineralized with pyrite or calcite (fig. 32b). Ninety-seven percent of the joints are sound and show no weathering. Ninety-six percent of the joints are wavy and uneven (fig. 32c), and 93 percent of those wavy and uneven joints have rough asperities. The fact that most of the joints are wavy suggests that blocks of rock between joints would be less likely to fall into the tunnel than if the joints were smooth because the irregularities increase the shear strength of the joints and jointed blocks are likely to be held in place. Slickensided, planar joints (of which few have been encountered) would be more likely to present possible instability problems if not supported. Joint roughness (waviness or uneveness) is particularly important where joints are not filled with clay, shale, or other material, as these materials may affect the shear strength along joint faces; calcite, quartz, and pyrite fillings may increase shear strength, whereas shale and clay may decrease shear strength.

It is usually impossible to determine the actual joint frequency of near-vertical joints in vertical boreholes, so angle holes (such as F-8) and information from excavations such as underground quarries and previous tunneling projects are used to estimate joint frequency. Although joints are common in these rocks, the frequency of continuous joints (those that cut completely across the tunnel and therefore may present possible instability problems) are few and occur hundreds of feet apart.

Examination of joints in a nearby 500-foot-deep underground quarry excavated in the Galena revealed that most closely spaced joints are only 1.5 to 12 feet long, but continuous joints are spaced as much as 100 feet apart or more. On a large scale, the joints have wavelengths of about 13 to 20 feet and amplitudes of about 0.5 to 1.0 foot. Smaller scale wavelengths of about 1.5 to 3.5 feet have amplitudes of about 0.1

to 0.2 foot; these amplitudes correspond to inclination values ranging from 9° to 15°. These wavelengths and amplitudes should inhibit rock movement between joints.

Study of joints in seven TARP tunnels (Harza, 1984) totaling about 21 miles in length revealed that continuous joints in the northeast-trending set have an average frequency of 321 feet (standard deviation, 216 feet) and the northwest-trending set an average frequency of 143 feet (standard deviation 70 feet). The combined average joint frequency in these tunnels was 92 feet (standard deviation, 42 feet). In these tunnels, frequency of significant joints was found to be several tens to hundreds of feet. Joints that were weathered (requiring bolting) or contained water (requiring grouting) can be expected in any tunneling project, but did not cause major problems in the TARP tunnels, where they were encountered only infrequently.

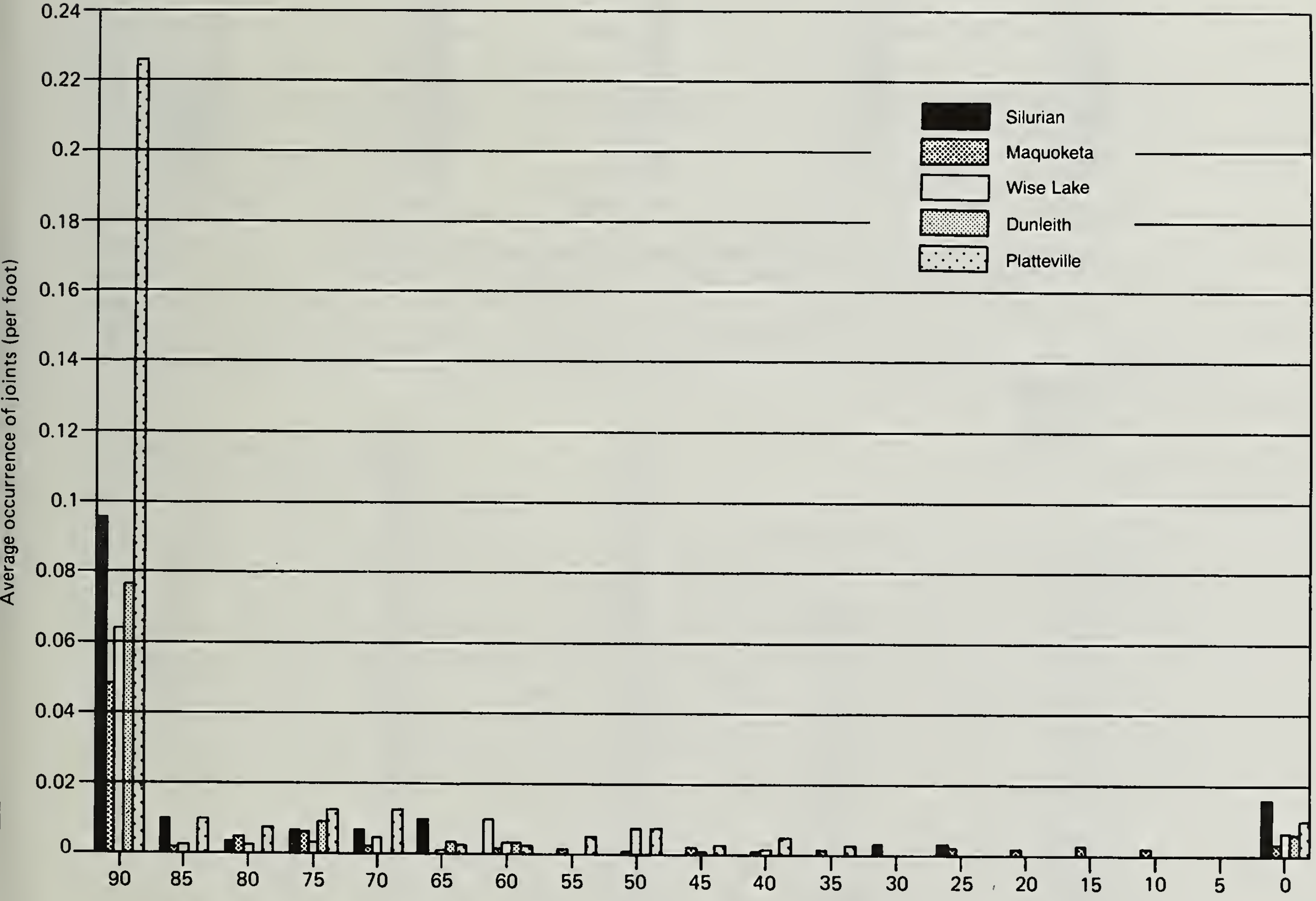


Figure 32a Joint dip (in degrees) per formation/group for boreholes F-1 through F-17.

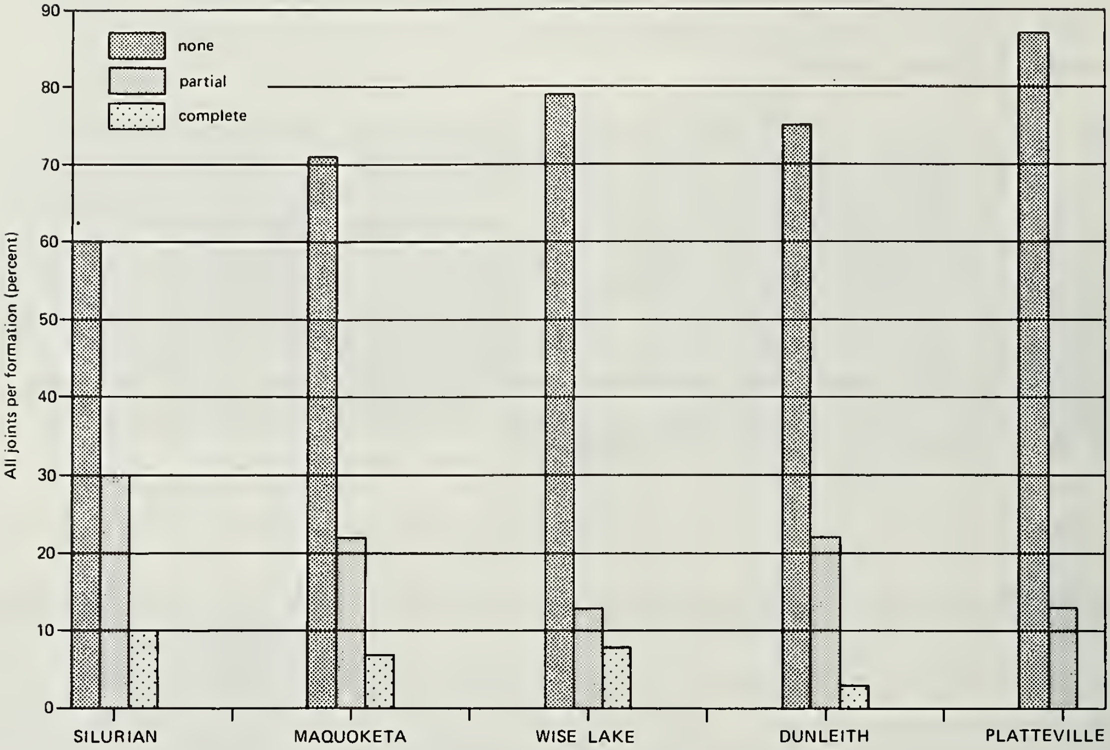


Figure 32b Filling in joints per formation/group for boreholes F1-through F-17.

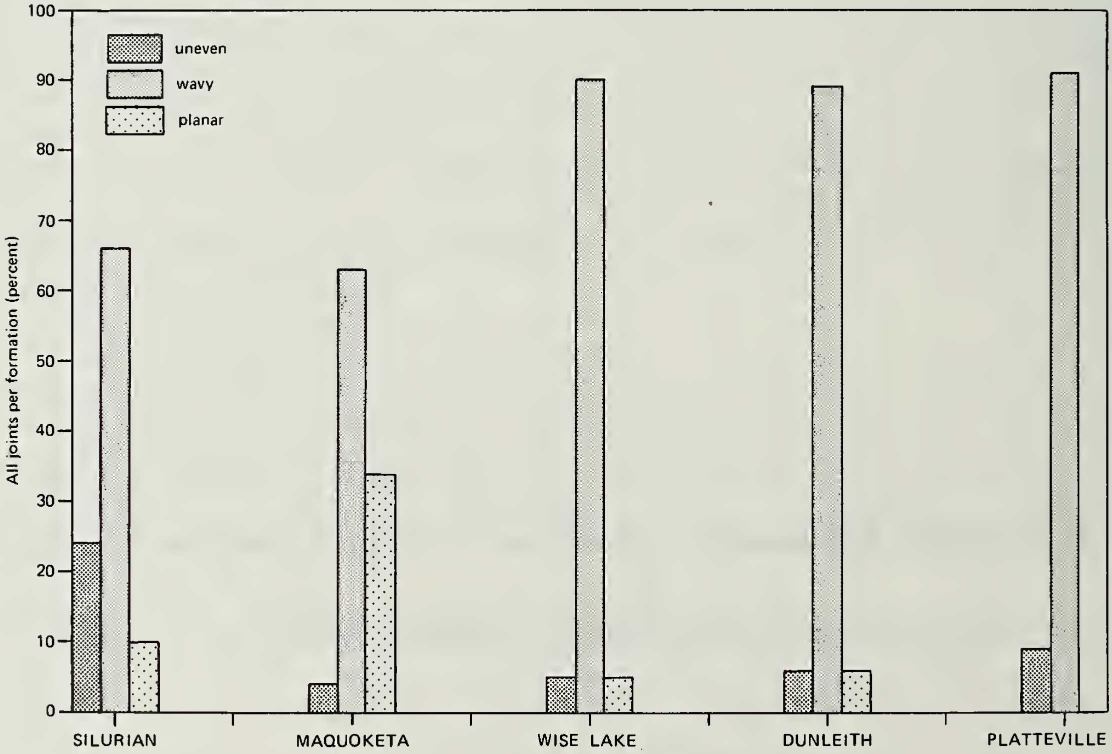


Figure 32c Joint roughness per formation/group for boreholes F-1 through F-17.

EVALUATION OF CONSTRUCTION CONDITIONS

R. A. Bauer, A. M. Graese, and W. G. Dixon Jr.

Studies on the geology, hydrogeology, and geotechnical aspects of the region indicate that construction of the SSC in bedrock is technically feasible. The uniform, high-quality, low-permeability materials in the study area provide favorable geological-geotechnical conditions. An extensive database of borehole information is available for the study area, and it is unlikely that any major unsuspected conditions will complicate construction. The low seismicity and lack of active faults in the area indicate no need for earthquake design. Construction of the tunnel, chambers, and shafts can be made with presently available technology and methods. Tunnel-boring machines were used successfully in the Chicago Tunnel and Reservoir Plan (TARP) and could be used to excavate the Galena-Platteville for the SSC. A letter report from Frank Dalton (1987), General Superintendent of the Metropolitan Sanitary District of Greater Chicago, states, in reference to the TARP construction, that "there were essentially no surprises and no overruns. Quantities and budget included for temporary support and groundwater control were underutilized and not necessary due to the soundness of the materials encountered."

This section includes general information on rock mass quality, support requirements, feasibility of tunnel-boring machine use, anticipated advance rates for tunnel construction, and water inflow estimates. This regional information can be compared with site-specific information available in Bauer, Hasek, and Su (in preparation), Kempton et al. (in preparation), and Harza with ISGS (1988).

TUNNEL CONSTRUCTION

Rock Mass Quality and Support

The good to very good quality of the rock mass is confirmed by the high rock quality designation (RQD) values, wide spacing between significant joints, low water inflow, and absence of significant faults or adverse geologic structures. Classification schemes assign values to rock mass properties and combine these ratings into an overall classification rating for the rock mass. These rating values are often compared with data from actual tunnel projects to determine how the ratings relate to observed rock mass behavior. Two classifications used in this study are the rock mass rating (RMR)(Bieniawski, 1979), and the Q-system (Barton, Lien, and Lunde, 1974). The RMR classification uses six parameters: uniaxial compressive strength, RQD, joint spacing, joint conditions, strike and dip of discontinuities, and groundwater conditions; the Q-System uses RQD, joint set number, joint roughness number, joint alteration number, joint water reduction factor, stress reduction factor, and excavation support ratio. Classification values based on the Q-system (Barton, Lien, and Lunde, 1974) (table 7; fig. 33) and Bieniawski's (1979) rock mass rating (RMR) (tables 6 and 8) are based on data from SSC regional studies to date and estimates of the most probable conditions that will be encountered in each rock unit. Q-values range between 14 and 98, and RMR values range from 52 to 92. On the basis of the RMR and Q values, respectively, tunneling conditions are expected to be fair to good in Maquoketa shale and good to very good in all of the dolomites. Both values predict good quality rock and favorable tunneling conditions. Moreover, the data indicate that the SSC tunnel in Illinois will require little or no support. These results, the expected ground behavior, and Muir-Wood (1972) strength-RQD classification values indicate that the bedrock is suitable for construction by tunnel boring machine (fig. 34).

Excavation Method

The feasibility of using a tunnel-boring machine to excavate a tunnel depends on rate of penetration, cutter costs, compatibility with the tunneling medium (type of rock), and utilization (Cording et al., 1975). Tunneling experience in northern Illinois with the successfully completed 72 miles of tunnels bored for the Tunnel and Reservoir Plan (TARP) and related sewers demonstrates that tunnel-boring machines could be used to excavate similar materials at the SSC site (Dalton, 1987; Harza with ISGS, 1988).

Advance Rates. Tunnel advance rates may be estimated in two ways: by comparison with excavation rates from similiar tunneling projects in rock in the area or by calculations based on rock properties. A

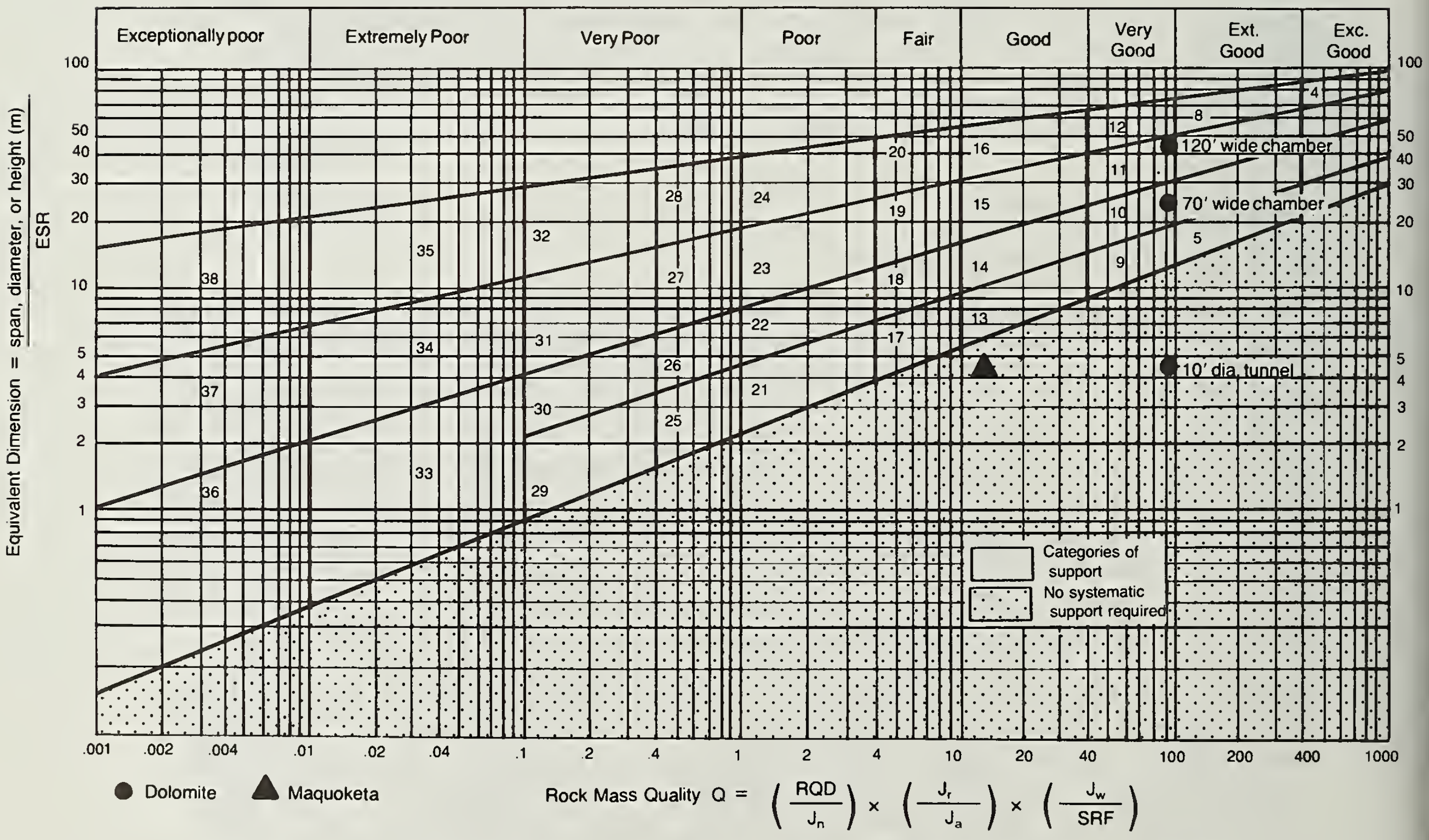


Figure 33 Evaluation of construction conditions in Galena-Platteville and Maquoketa bedrock, obtained by Barton's Q-classification System for estimating support requirements (Barton, Lien, and Lunde, 1974). See table 7 for explanation of abbreviations for equations.

Table 7. Barton's Q rock mass classification system

	Silurian	Maquoketa	Galena-Platteville
RQD = rock quality designation	95	95	95
J_n = joint set number	4	4	4
J_r = joint roughness number	3	3	3
J_a = joint alteration number	1	1	1
J_w = joint water reduction factor	0.66	1.00	0.66
SRF = stress reduction factor	0.5	5.00	0.5
ESR = excavation support ratio	0.8	0.8	0.8
Q =	94.1	14.2	94.1
Classification = (fig. 38)	very good	good	very good

Source: Barton, Lien, and Lunde, 1974.

Table 8. Bieniawski's rock mass rating (RMR) for most probable conditions

	Silurian	Maquoketa	Galena-Platteville
Rock strength	12	4	7
RQD	20	20	17 to 20
Groundwater	10	10	10
Spacing of discontinuities	20	20	20
Condition of discontinuities	30	10	30
Strike and dip of discontinuities	0 to -12	0 to -12	0 to -12
RMR =	80 to 92	52 to 64	72 to 87
Classification =	good to very good	fair to good	good to very good

Source: Bieniawski, 1979.

calculation based on conservative values for penetration rate (0.3 inches per revolution), machine revolutions per minute (15), machine utilization (40 percent), and shifts per day (two 10-hour shifts), indicates an average tunnel-boring machine advance rate of 180 feet per day. Estimates of instantaneous advance rates for the SSC tunnel can be made by using average rock property values summarized in appendix table C-6 and other laboratory test data (Nelson, O'Rourke, and Kulhawy, 1983; Tarkoy, 1975). Such estimates depend on the rotating speed of the cutterheads and thrust characteristics of the tunnel-boring machine. Overall penetration rates based on the relationship between data obtained with the Taber abrasion hardness test (table 6) and penetration rates found by Nelson, O'Rourke, and Kulhawy (1983), are 0.33-inch, 0.40-inch, and 0.37-inch per revolution of a tunnel-boring machine cutterhead for the Silurian, Maquoketa, and Galena-Platteville, respectively.

Results of testing by the Robbins Company (1987) on Galena-Platteville samples from the SSC study area corroborate these findings. The company's report states that "it is clear that tunnel-boring machine performance in the tested samples could range from 0.3-inch per revolution of the cutterhead in the hardest dolomite rock to more than 1 inch in the softest dolomite rock without exceeding the thrust and torque limits of today's 10- to 12-foot machines and 15 1/2-inch to 17-inch cutters." The report further states that "the limiting factor in machine performance will not be the capacity of the machine to bore the rock but will lie in the backup system and its capacity to handle muck."

Field penetration indices, defined as the ratio of the average thrust per cutter to the penetration rate (Nelson, O'Rourke, and Kulhawy, 1983) were determined for the Silurian (85 to 103 kips per inch), Maquoketa (50 kips per inch), and Galena-Platteville (65.5 to 72.2 kips per inch).

Cutter Costs. The Robbins Company's report further states that the nonabrasive characteristics of the dolomite rock should result in very little cutter usage. Estimated cutter costs in the hardest dolomite rocks should not exceed $1.50 per cubic yard; in most dolomite the cost will be below $1.00 per cubic yard. The cutter costs in the Maquoketa, should it be tunneled through, would be substantially lower; costs are estimated at about $0.30 to $0.75 per cubic yard.

Compatability with Tunneling Medium. The rock characteristics of the Galena make it suitable for tunnel boring (Muir-Wood, 1972) (fig. 34). The rock units that may be encountered by a tunnel-boring machine on this proposed project show no tendency for squeezing or swelling. The highest horizontal stresses measured in the area are oriented N60°E (Shuri and Kelsay, 1985). Tunnel alignments perpendicular to these high stress directions would be the most susceptible to any possible slabbing problems associated with this stress.

Utilization. The average utilization of tunnel-boring machines in 72 miles of bored tunnels for TARP was 44.1 percent (Dalton, 1987). Recent analysis of tunnel-boring machine performance on six projects (Nelson, O'Rourke, and Glaser, 1985) included projects in Buffalo and Rochester, New York, and Chicago, Illinois. The lowest downtime due to ground conditions reported in the study was for the TARP tunnel (1.3 percent); average downtime for the six projects was 12.6 percent.

SHAFT CONSTRUCTION

Relevant shaft construction experience in the region includes the excavation for TARP of 256 shafts with diameters ranging from 5.5 to 36.0 feet. These were constructed successfully through glacial drift and rock formations virtually identical to those found in the SSC region. Contractors used nine different methods of overburden support: various combinations of steel rings with timber lagging; soldier piles with timber lagging; sheet piles; steel casing; cement-bentonite wall; cast-in-place concrete rings; and liner plates. If additional exploration at specific shaft sites should reveal little or no water-bearing sand and gravel, methods similar to those used on TARP should be cost effective

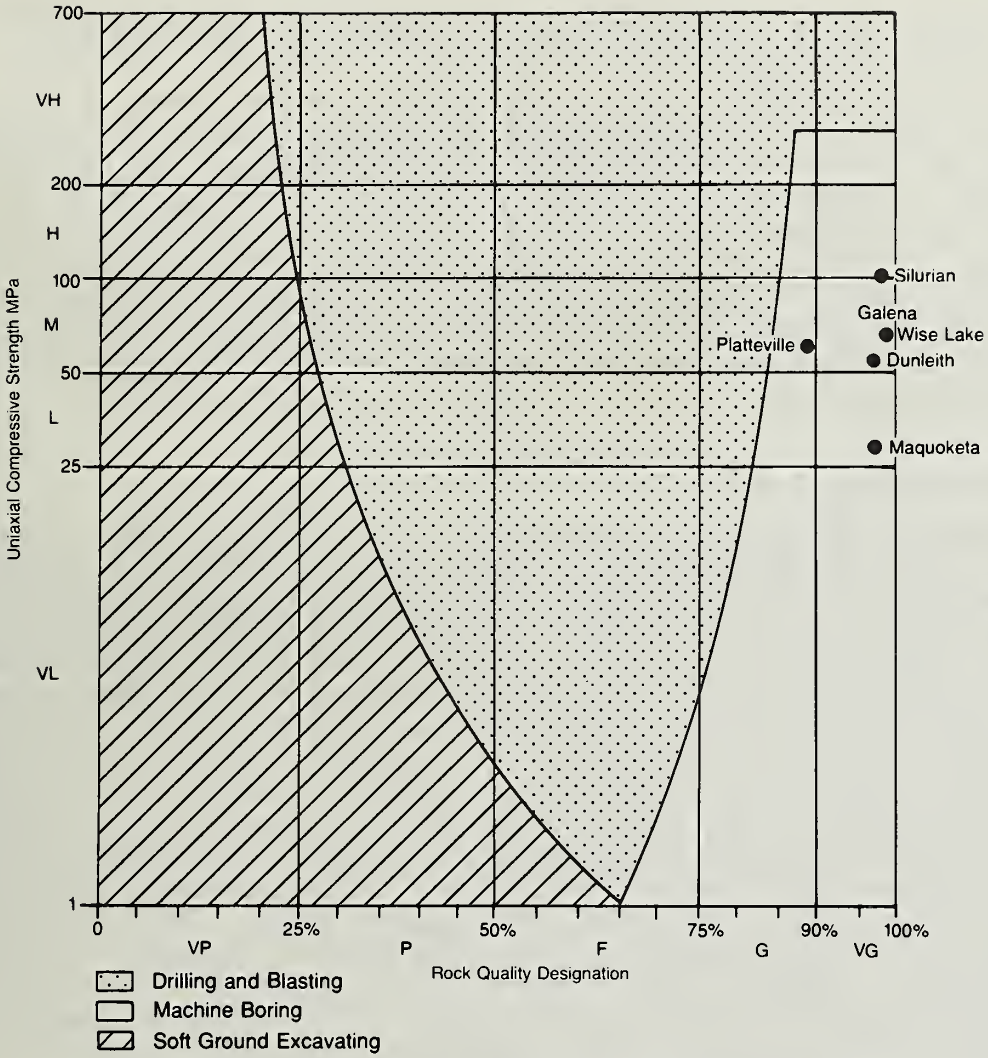


Figure 34 Muir-Wood diagram indicating tunneling conditions and appropriate tunneling methods in bedrock (Muir-Wood, 1972).

for the SSC project. If water-bearing sand and gravel is present to any great extent, the most effective method of supporting the excavation through the glacial overburden would be by means of a slurry-trench cutoff wall around the perimeter of each shaft prior to excavation; it would then be possible to drive the shaft from the top without disturbing the water table, thus permitting a dry excavation of the shaft. The base of the cutoff wall can be grouted to make the connection between the wall and the rock surface watertight. Other possible methods of support of the overburden during shaft construction include dewatering or freezing of the water-bearing strata (Harza with ISGS, 1988).

The sections of the shafts penetrating the rocks could be excavated in two stages. In the first stage a downdrill excavator similar to a Hughes CSD-820 could be used to drill a pilot hole approximately 13 feet in diameter. The second stage of excavation could consist of enlarging the shaft to its final size by using conventional drill-and-blast techniques. This procedure was used with high productivity and speed for similar shafts on the TARP project (Harza with ISGS, 1988).

Small amounts of methane gas originating from decomposition of organic material in the drift may be locally encountered (Meents, 1960; Coleman, 1976), but should not cause concern if conventional construction methods are used. Such drift gas occurrences are small, local accumulations, primarily of methane but also of small amounts of nitrogen and carbon dioxide. Drift gas is not an unusual phenomenon; it can be found in any glaciated area. No problems occurred with drift gas in TARP and no drift gas was encountered in the 33 boreholes drilled for the SSC study. However, drift gas has been noted in water wells at Lily Lake and in the surrounding vicinity.

CHAMBER CONSTRUCTION

The TARP mainstream system pumphouse caverns, the largest and deepest-mined caverns in northeastern Illinois, provide a useful and relevant comparison with the SSC chambers (Harza with ISGS, 1988). The caverns are 274 feet long, 96 feet high, 63 feet wide, and 358 feet below ground. Design studies called for crown support consisting of a pattern of 1.375-inch-diameter, 30 foot-long, tensioned, fully grouted rockbolts on 4-foot centers each way. Rockbolt lengths were reduced to 20 feet because of better-than-anticipated rock behavior observed in a 12-foot by 20-foot exploratory drift (a nearly horizontal underground opening) along the length of the cavern crown. During excavation of the crown the rock had a tendency to break along horizontal bedding planes and create slabs 6 to 12 inches thick. This slabbing generally occurred at the intersection of a wet joint and a bedding plane. The rock slabbing created local support needs but did not affect the overall stability of the opening. Further support was provided by a minimum 4-inch layer of shotcrete reinforced with welded wire fabric. A reinforced concrete roof arch 8 inches thick provided further assurance of long-term stability.

The proposed SSC chambers could be oriented nearly north-south. This orientation bisects the angle of the two dominant joint sets so that joints in the chamber walls are intercepted at the widest angle, providing the greatest possible sidewall stability.

SEISMICITY AND MAN-MADE VIBRATIONS

No apparent relationship exists between recorded earthquakes and the Sandwich Fault Zone (see section on geology); this confirms the zone's inactivity (fig. 35). Since 1804, only nine earthquakes with epicenters in northern Illinois have been recorded (fig. 35). In Kane County, none of these quakes has had a maximum intensity above VI on the Modified Mercalli Scale (table 9).

The modified Mercalli Scale uses the amount of shaking, damage to property, and earth deformation felt or observed to measure intensities of earthquakes. The observed intensity varies with the magnitude of the quake and the distance from the epicenter.

Table 9. Earthquakes with epicenters in and outside northern Illinois

Date	Epicenter intensity*	Intensity in Kane County
Epicenters in northern Illinois		
August 20, 1804	V-VI	---
May 26, 1909	VI	V-VI
January 2, 1912	V-VI	V-VI
January 23, 1928	IV-V	---
November 12, 1934	V-VI	<I
January 5, 1935	IV	<I
March 1, 1942	V	---
September 15, 1972	VI	V
September 9, 1985	III-IV	III-IV
Epicenters outside northern Illinois		
December 16, 1811	X	V-VI
November 9, 1968	VII	IV
June 10, 1987	VI**	III-IV**

* = Modified Mercalli Intensity Scale
** = Preliminary values
--- = No data
Source: Modified from Heigold, 1972

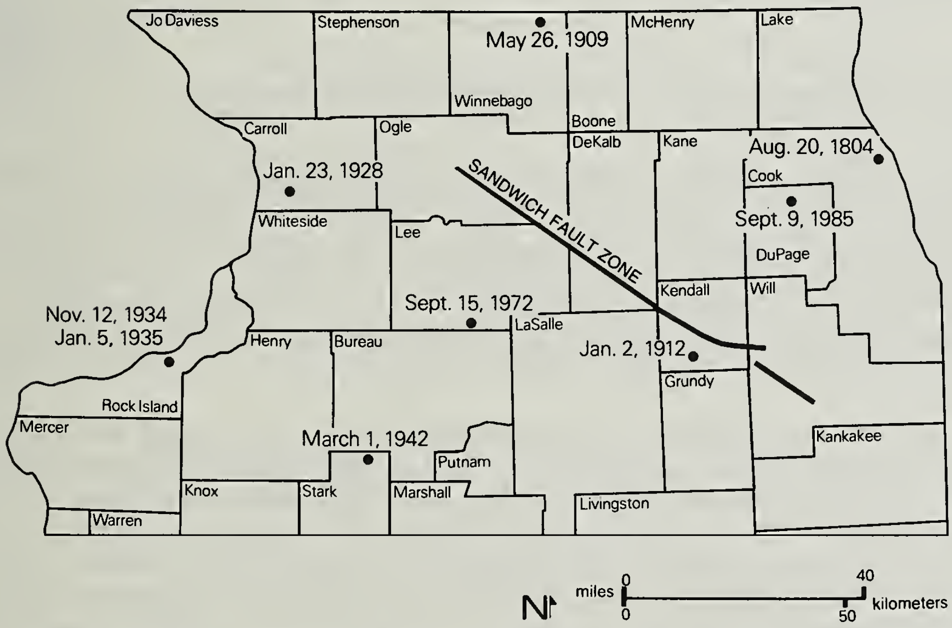


Figure 35 Epicenters and dates of earthquakes in northern Illinois, indicating no relationship of recorded earthquakes to the Sandwich Fault Zone (modified from Heigold, 1972).

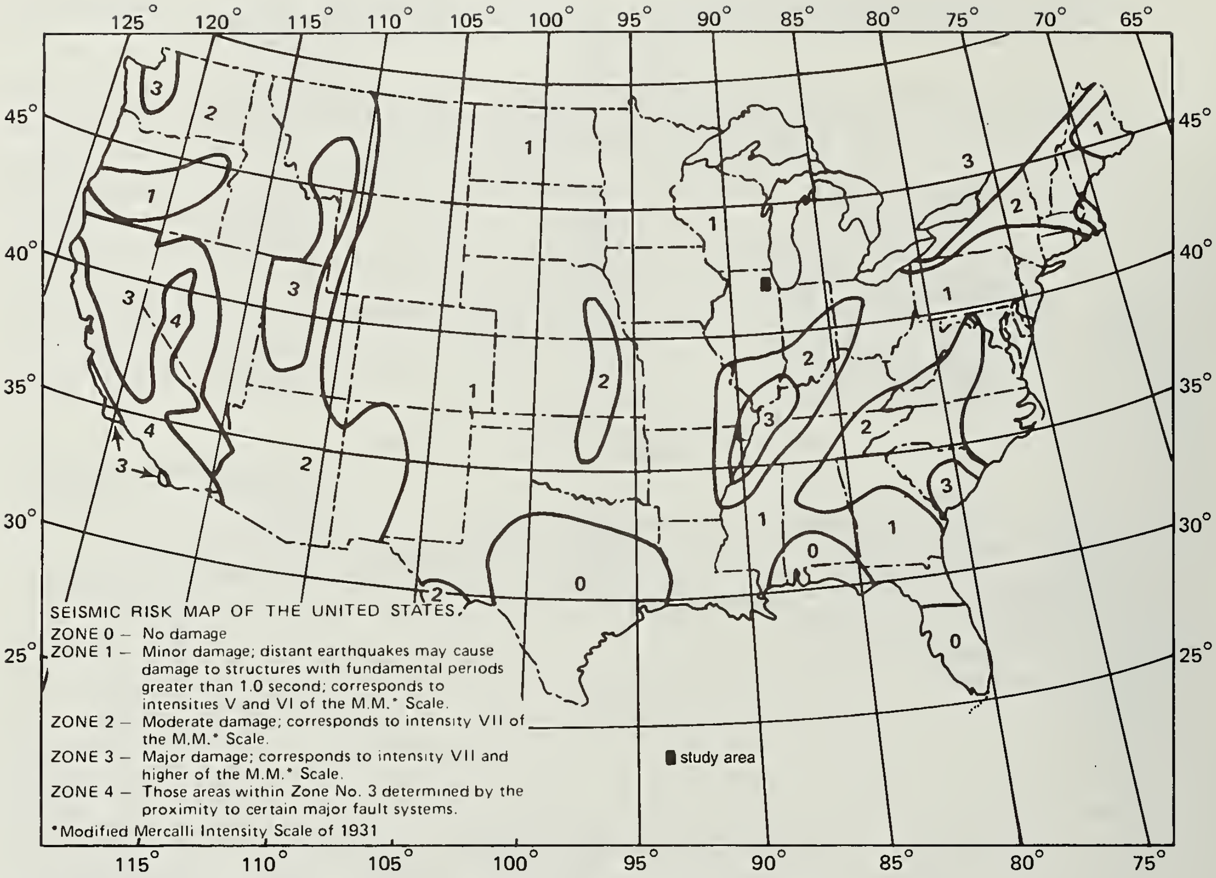


Figure 36 Seismic risk map of the United States (from Uniform Building Code, 1982).

The seismic risk map for the conterminous United States (fig. 36) shows that the study area is tectonically stable; no unusual design or construction will be required with respect to earthquake ground motion (International Conference of Building Officials, 1982). In northern Illinois there is a 90 percent probability that the peak horizontal acceleration caused by earthquakes should not exceed 4 percent gravity in 50 years (Algermissen et al., 1982) (fig. 37).

Although the seismic risk for the northern part of the state is low, repetition of the events that occurred in the New Madrid Seismic Zone during the winter of 1811-12 (table 9) could have some effect on northern Illinois. However, the intensity in northeastern Illinois of the December 16, 1811 quakes is estimated to have been no greater than VII MM in Kane County (Nuttli and Herman, 1978; see also Kempton et al., 1985, p. 49) and should have no impact on a tunnel in bedrock (Dowding, 1977). Dowding's analysis of the effects of earthquakes on 71 tunnels found no damage or falling rocks in unlined tunnels in which surface intensities were VII to VIII MM. Furthermore, on the basis of density of sand deposits in the area and the liquid limits of its clayey soils, liquefaction of the drift is not likely to cause a problem in the region.

The largest man-made vibrations expected in the SSC site would result from nearby blasting in rock quarries. The amount of ground motion at a specific point associated with blasting depends on the weight of the

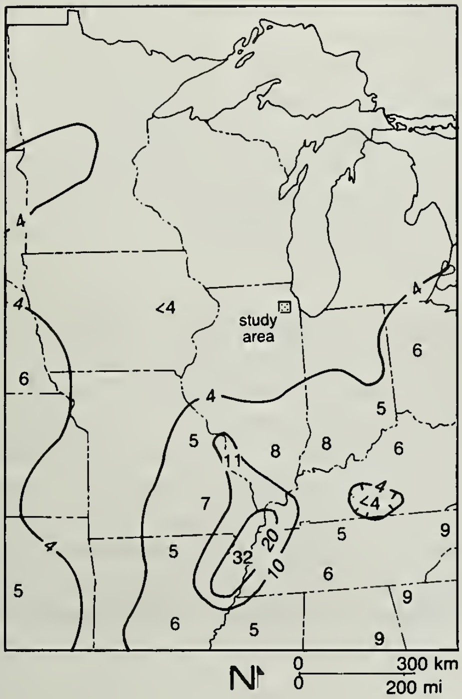


Figure 37 Map showing horizontal acceleration in bedrock (expressed as percentage of gravity) with a 95 percent probability of not being exceeded in 50 years (modified from Algermissen et al., 1982).

Table 10. Thresholds of damage from particle velocities

Particle velocity (inches/sec)	Damage criteria	Source
0.6	Damage to 36-hr-old concrete	LaLonde and James (1961)
2.0	No damage to normal house	Duvall and Fogelson (1962)
7.6	Fifty percent probability of major damage to house	Duvall and Fogelson (1962)
12.0	Fall of rock in unlined tunnels	Langefors and Kihlstrom (1963)
24.0	New cracks in rock in unlined tunnels	Langefors and Kihlstrom (1963)
12.0-24.0	Rare visible damage to unlined tunnels	Hendron and Oriard (1972)

explosives detonated, the distance between detonation and observation points, and the transmission characteristics of the rock and soil mass. Using the cube root scaling relationship for determining the impact on a point from the shock phenomena of an explosion produces a particle velocity of about 0.016 to 0.020 inches per second and maximum displacements of 0.00013 and 0.00016 inches, a distance of 1/2-mile for a charge of 125 to 200 pounds per delay. Table 10 summarizes some of the thresholds of damage from various particle velocities. The table clearly shows that stability of the tunnel will not be influenced by quarry operation. The threshold of possible movements (displacments) that the operating SSC can sustain is 0.002 and 0.0005 inches for the tunnel and interaction regions, respectively. Since no operating quarry is closer than 4,000 feet to any portion of the proposed tunnel and 21,000 feet to any chamber, the estimated displacements from quarry blasts are 30 times less than allowable limits for the tunnel and 100 times less than the limits for the chamber areas.

POTENTIAL USES OF EXCAVATED ROCK MATERIAL

An estimated 4.6 million tons of material would be excavated during construction of the proposed SSC tunnel, chambers, and shafts (Curran, Bhagwat, and Hindman, 1988). Fifty-nine percent of this material will be produced by tunnel boring machines, 38 percent by drill-and-blast and about 3 percent by clamshell excavation of the glacial till. This material must be disposed of in a manner that minimizes environmental damage and transportation costs.

Alternatives described in Curran, Bhagwat, and Hindman, (1988) include disposal in suitable sand and gravel pits and rock quarries. The total holding capacity of the 46 pits and quarries in the study area is estimated to be more than 79 million cubic yards--more than 19 times that needed to contain the estimated 4.1 million cubic yards of excavated material. Another alternative would be to use the excavated material for on-site landscaping. The material excavated, primarily dolomite, would be similiar to the gravel originally taken from quarries and sand and gravel pits within the area. Leachates from this material would have little or no impact on the surrounding surface or groundwater resources (Krapac, et al., 1988).

TUNNEL INFLOW ESTIMATES

Encountering very large uncontrollable inflows during construction is unlikely because of the low hydraulic conductivities of the upper Ordovician aquitard. There are no known major zones of faulted rocks other than the Sandwich Fault Zone to the southwest and no known severely sheared rock that could be water-bearing. Joints within the area are generally tight, and 10 percent of them have some amount of shale or clay filling. Solution-widened joints occur only in dolomite within the weathered upper bedrock. The vugginess of the Galena-Platteville does not appear to contribute to any sustained flow, as the vugs do not form an interconnected system.

An estimate of groundwater inflow (Q) into a unit tunnel length, of radius r, can be estimated by the equation (Goodman et al., 1965; Freeze and Cherry, 1979):

$$Q = \frac{2\pi K H_o}{2.3 \log\left(\frac{2 H_o}{r}\right)}$$

This equation assumes that the tunnel is a steady drain in a homogeneous, isotropic medium with hydraulic conductivity K. H_o is the height of the water column above the tunnel. The equation only approximates conditions in a tunnel in which flow occurs in a jointed medium. Upward migration of groundwater from the midwest sandstone aquifers has been considered in determining the inflow estimates and would most likely be of minor consideration in determining actual tunnel depth. The initial rates of inflow estimated for a tunnel with 350-foot elevation range from about 10 to 120 gallons per minute per mile (gpm/mile), with long-term rates of 5 to 100 gpm/mile before grouting (Dixon et al., 1985). These estimates will be modified by results obtained from a continuing exploration program (Curry et al., 1988; Kempton et al., in preparation). Actual inflows will most likely be similar to or less than those encountered by the Tunnel and Reservoir Plan (TARP), which averaged 112 gpm/mile prior to grouting (Harza, 1984). Grouting reduced this average inflow to less than 52 gpm/mile. The low to very low permeability of the rocks in the TARP mainstream system pump house caverns (as indicated by water pressure testing of boreholes) was substantiated by the very low to negligible amounts of flow encountered in the north (16 gpm) and south (30 gpm) pump houses. These low flows were encountered despite a head 200 to 300 feet above the base of the pump houses (Harza with ISGS, 1988; Harza, 1983). Inflows in TARP were found to decrease markedly over time as the tunnel proceeded to drain the adjacent jointed rock (Harza with ISGS, 1988). Inflow into the TARP tunnels has been mitigated by conventional construction methods (primarily grouting and pumping). The Fermilab Tevatron, situated in glacial drift, has a steady state flow of about 250 gpm/mile--sustained flow considerably higher than anticipated for the SSC (Treadwell, 1984).

SUMMARY AND CONCLUSIONS

This report presents regional information on the geology, hydrogeology, and engineering geology of a 36-township area in northeastern Illinois being considered as a location for the U.S. Department of Energy's proposed Superconducting Super Collider. Data obtained from water-well records and cuttings, test drilling, seismic refraction, in-situ hydraulic conductivity and water level measurements, and laboratory testing of rock properties were used to compile drift and bedrock maps and determine the general hydrogeologic and geotechnical characteristics of the SSC study area. This regional information will be used as baseline data for comparison with site-specific data obtained to select the final site for the proposed SSC (Kempton et al., in preparation; Harza with ISGS, 1988). The data could also be integrated into regional land-use planning studies (e.g., Berg, Kempton, and Stecyk, 1984) to screen potential areas suitable for landfills (Berg, Kempton, and Cartwright, 1984), and for suburban development and water (Gilkeson et al., 1987) and mineral resource studies (sand and gravel and dolomite).

Results of these investigations indicate that bedrock in the area is excellent rock in which to construct the SSC tunnel.

- A tunnel housed in bedrock rather than at or near the land surface will minimize impacts on homes, farms, and businesses, and on groundwater, surface water, natural areas, and archeological sites. Access and support buildings will be the only visible sign of the SSC on the land surface.

- The Galena and Platteville Groups together form a well-understood, thick, uniform, predictable, relatively undeformed, low-water-yielding rock unit with very good rock mass characteristics that make it suitable for tunnel-boring machines. Therefore, we recommend this unit as the medium to house the SSC tunnel and chambers. Other shallower tunnel configurations are also feasible, but it is possible that increased water inflows could cause construction and maintenance problems or adversely affect shallow groundwater resources.

- The location of a tunnel approximately tangent (at depth) to Fermilab's Tevatron can still be moved slightly. There appear to be no major constraints imposed by the subsurface geology other than depth--the tunnel should be located well below the bedrock valleys, preferably in the Galena-Platteville. The best orientation of the experimental chambers, which will be constructed along the long, straight segments of the tunnel, is north-south, with the eastern straight segment joined to the Tevatron by sloping tunnels. This orientation bisects the two regional joint sets, thereby maximizing sidewall stability of the chambers. There is some flexibility in this orientation; the ring could possibly be pivoted slightly around the Fermilab Tevatron to minimize impact on surface features such as homes, businesses, and water wells (Hines, 1986). This flexibility may be desirable in final site adjustment within the area.

- The low permeability of the Galena-Platteville suggests that construction and operation of the tunnel in the rock will have a minimal impact on groundwater resources; only minor amounts of groundwater are obtained from the Galena-Platteville. Wells within the area obtain water from the upper bedrock aquifer above the zone proposed for the tunnel and from deeper sandstone aquifers below the zone proposed for tunnel placement.

- Groundwater inflow or seepage should not pose any major difficulties during construction and operation of the SSC facility.

- Experiences of contractors who have used tunnel-boring machines in the region in rocks similiar to those at the proposed SSC site should help minimize risk and construction cost. The fact that construction of the 72 miles of tunnels and related sewers for the Tunnel and Reservoir Plan (TARP) under Chicago were, on the average, completed ahead of schedule and below cost estimates suggests that the proposed area is well suited for construction of the SSC tunnel. The LEP accelerator at CERN near Geneva, Switzerland, has also been constructed in bedrock at similiar depths.

Work completed from 1984 to 1986 and reported in this publication confirmed preliminary studies indicating the suitability of the Galena-Platteville bedrock in the 36-township region studied for construction of the SSC tunnel. Specific results of this work are summarized below.

GEOLOGY

Bedrock

The sequence of rocks considered for tunnel construction in the study region consists of carbonates and shales unconformably overlain by Quaternary glacial drift. The Galena-Platteville is a relatively homogeneous, massive carbonate unit 300 to 380 feet thick, which is overlain by Maquoketa shales and dolomites and Silurian dolomites. The Galena-Platteville provides an excellent medium for tunnel and chamber construction.

This area is seismically stable. No earthquakes with epicenters along the Sandwich Fault Zone (Heigold, 1972) have been recorded.

Detailed structure mapping on the top of the Galena Group (using a database of more than 850 wells and test holes) reveals that the bedrock units are nearly horizontal and relatively undeformed; there are no significant changes in elevation indicative of major offsets. Offsets with vertical displacements as much as 30 to 50 feet may be anticipated but cannot be substantiated on the basis of presently available well data control.

Bedrock Topography

The bedrock surface is characterized by uplands dissected by bedrock valleys. Maximum relief across the bedrock surface is 350 feet. The elevation of the bedrock uplands ranges between 700 and 800 feet above mean sea level in the central and northern parts of the study area and from 550 to 650 feet above mean sea level in the southern part. The two major bedrock valleys are the Troy Bedrock Valley along the west edge of the study region and the "Newark" Bedrock Valley. The lowermost valley bottom of the "Newark" is less than 450 feet above mean sea level. This elevation is an important consideration in determining tunnel depth, since the tunnel will be most economically constructed if placed well below the level of the drift-filled valleys.

Glacial Drift

The glacial drift deposits (0 to 400 feet thick) in the area consist of tills, outwash, lake and river sediments, windblown silts (loess), organic sediments, and colluvium. These units are interbedded and often discontinuous. Stratigraphically they can be subdivided (from base to top) into the Glasford Formation, modified or overlain by interglacial Sangamon Soil and Robein Silt, which in turn are overlain by the Wedron Formation or related deposits. Significant sand and gravel deposits within the drift are sources of groundwater. The thickness and characteristics of the drift may dictate the type of shaft construction methods used.

HYDROGEOLOGY

Regional Setting

Geologic materials can be classified into four informal hydrogeologic units on the basis of lithology and on water-yielding properties determined by their hydraulic conductivity: (1) glacial drift aquifers (water-yielding sand and gravel); (2) upper bedrock aquifer (fractured dolomite and shale directly beneath the drift; the water yield--depends on the extent and connections of fractures); (3) upper Ordovician aquitard (the relatively impermeable Maquoketa and Galena-Platteville Groups) that serves as the confining unit for the midwest sandstone aquifers (and would house the SSC tunnel); and (4) sandstone aquifers (Ancell Group and Ironton-Galesville Sandstones), water-yielding rocks lying below the Galena-Platteville Group within the midwest sandstone aquifer. The Galena-Platteville and Maquoketa Groups (the upper Ordovician aquitard) yield only small amounts of water, except in a zone that lies within the upper bedrock aquifer. This zone extends from the bedrock surface to a maximum depth of about 50 feet.

Hydraulic Conductivity

The average horizontal hydraulic conductivity of the Maquoketa and Galena-Platteville Groups (upper Ordovician aquitard) is low--generally less than 1×10^{-6} centimeters per second in both dolomite and shale; thus these rocks yield very little water. Hydraulic conductivities for the upper bedrock aquifer range from high (1×10^{-2}) to low (1×10^{-6} centimeters per second). Generally the permeability of the upper bedrock aquifer decreases with depth, with a gradual transition zone to the upper Ordovician aquitard.

Potentiometric Levels

The potentiometric surface (defined as the level to which water will rise in a well at one atmosphere pressure) of the midwest sandstone aquifers is depressed along and east of the Fox River because of the effects of pumping cones produced by heavy water use in urban centers along the Fox River and east of the study area in Chicago. Water flow gradients are generally from west to east in the upper bedrock aquifer and midwest sandstone aquifers. Water levels of the upper Ordovician aquitard are generally intermediate between those of the upper bedrock aquifer and those of the sandstones of the midwest sandstone aquifers.

Groundwater Resources

Water resources would not be affected if the tunnel is placed in the upper Ordovician aquitard. These rocks generally do not yield much water, so few water wells have been drilled in them. (Some wells producing from the upper bedrock aquifer have been finished in the upper Ordovician aquitard to provide additional storage capacity and, in some cases have minor additional yields.) Adequate water resources are available from surface water and groundwater for operation of the SSC facility. The principal aquifers in the region are the upper bedrock aquifer/drift aquifers and midwest sandstone aquifers.

GEOTECHNICAL PROPERTIES OF GEOLOGIC UNITS

Bedrock

Material properties compiled for the Galena-Platteville include core recovery (93.4 to 100 percent) average RQD (89.6 to 99.7 percent), compressive strength (medium), and modulus ratio (average to high), suggesting excellent tunneling material. Joint sets in northeastern Illinois exhibit consistent directions with a primary direction of N50°W and a secondary set at N47°E; orienting the chambers north-south so as to bisect these joint sets will maximize chamber sidewall stability.

Bedrock Surface

The top of the bedrock is generally more fractured than the underlying rock; the zone of most pronounced fractures is usually within 50 feet of the bedrock surface. Some of these fractures and bedding planes have been opened by solution of the rock due to groundwater movement in the upper bedrock aquifer. A tunnel bored beneath the pronounced fracture zone in the upper bedrock is desirable, as rock conditions and water inflow in this zone would increase tunneling costs and be less desirable.

Glacial Drift

Most of the materials overlying the bedrock consist of glacial till, glacial outwash, and lacustrine deposits. Tills are generally overconsolidated. Surficial lacustrine material is normally consolidated and may have low strength. When overlain by till, lacustrine sediment is overconsolidated. Outwash sands and gravels are dense to very dense.

EVALUATION OF CONSTRUCTION CONDITIONS

Tunnel Construction

Rock Mass Quality and Support. The good to very good quality of the dolomite rock mass is confirmed by high Rock Quality Designation, wide spacing between significant joints, low water inflow, and absence of faults or other adverse geologic conditions. Favorable rock-mass conditions, joint orientations, and dip and bed plane waviness indicate that no significant instability problems in the tunnel and chambers are anticipated. The SSC tunnel will require no systematic support--only spot bolting--if constructed in the Galena-Platteville.

Excavation Method

Rock mass quality, expected ground behavior, and Muir-Wood (1972) strength-RQD classification indicate that the bedrock is suitable for machine boring, a safer, faster, and less expensive method than blasting. The rock units that may be encountered by a tunnel-boring machine in the study area show no tendency for squeezing or swelling.

Advance Rates and Cutter Costs. Excavation rates should exceed excavation rates of other rock tunneling projects in the region--the Tunnel and Reservoir Plan (TARP) and the Milwaukee Water Pollution and Abatement Program (MWPAP)--considering recent advances in tunnel-boring machine technology and the excellent conditions expected. Advance rates of 180 feet per day (two 10-hour shifts) may be anticipated. Low cutter costs are expected because of the nonabrasive nature of the rock.

Shaft Construction

Several conventional shaft construction methods were successfully used to develop 256 shafts for TARP. These shafts encountered conditions nearly identical with those in the SSC region. The shafts can be excavated by drill-and-blast and machine boring. Water-bearing sands and gravels in shafts may require a slurry-trench cutoff wall or ground-freezing techniques (Harza with ISGS, 1988) which would permit shaft excavation without disturbing the water table.

Chamber Construction

Fracture orientations in the bedrock in the study area suggest that a north-south orientation of the six to eight chambers to be used as laboratories and utility halls will provide the greatest stability for underground construction. Conventional drill-and-blast methods would be used to excavate the chambers, the same methods used to construct underground pump-house chambers for TARP (Harza with ISGS, 1988).

Seismicity and Vibration Transmission

The SSC area is in a low seismic-risk zone (Zone I). Earthquakes having epicenters in northern Illinois have been infrequent and non-destructive. Therefore, no unusual design or construction requirements are necessary with respect to earthquake ground motion.

Neither stability of the bedrock tunnel nor the SSC operations will be affected by quarry blasting (the largest man-made vibrations expected in the area).

Potential Uses of Excavated Material

Material excavated during tunnel construction can be stored or disposed of in surface facilities such as dolomite quarries or gravel pits with no adverse effects on groundwater or surface water in the area (Curran, Bhagwat, and Hindman, 1988; Krapac et al., 1988).

Groundwater Inflow

A preliminary estimate of long-term average groundwater flow into a 10-foot-diameter, unlined, ungrouted tunnel is about 100 gallons per minute per mile or less, comparable with inflows encountered in TARP. Experience in the area shows that one-and-two pass grouting reduces the water inflow from 60 to 80 percent (Civil Engineering, 1988). Minimal water inflows encountered during construction of the TARP pumping stations were easily controlled by grouting despite chamber inverts 200 to 300 feet below the upper bedrock aquifer potentiometric surface (Harza with ISGS, 1988).

GLOSSARY

ablation till — till modified during and after deposition by ice, water, and mass wasting processes; ablation till may be more sandy and less densely compacted than unmodified till.

alluvium — the general term for all sediments deposited in land environments by streams.

argillaceous — clayey or containing clay.

aquifer — water-bearing layer of rock or sediment that will yield water in a usuable quantity to a well.

aquitard (or confining bed) — a rock unit or sediment layer — through which water travels very slowly — that restricts the movement of groundwater either into or out of adjacent aquifers.

basement — the crust of the earth below sedimentary rocks. In Illinois, these rocks consist primarily of red granite.

chert — hard, dense, cryptocrystalline, sedimentary rock, composed mostly of silica.

colluvium — a body of sediment, found at the bases of slopes, which has been deposited by any process of mass wasting or overland flow.

cross section — a diagram or drawing that shows geologic features transected by a given vertical plane though the earth.

dolomite — a mineral having the chemical composition calcium-magnesium carbonate; also, the sedimentary rock consisting mostly of crystals or particles of that mineral.

drift — a general term applied to all rock material (clay, sand, gravel, boulders) transported by a glacier and deposited directly by or from ice, or by water flowing from a glacier.

end moraine — a belt of low ridges and hills, composed of drift, that was deposited by a glacier along its front margin.

facies — part of a rock body differentiated from other parts of the same body by appearance, composition, fossil content, or some other characteristics.

fluvial — produced by the action of streams or rivers.

formation — in lithostratigraphy, the primary rock units that possess distinct lithologic features.

friable — easily broken, poorly cemented rock, particularly descriptive of some sandstones.

glauconite — dull green, earthy or granular minerals of the mica group, an iron-bearing clay indicative of deposition in a marine environment.

hydraulic conductivity — the capacity of a rock or sediment to transmit water.

invert — base of the tunnel

joint set — a group of more or less parallel fractures or breaks in the rock along which no movement has occurred.

kame — a body of ice-contact layered drift shaped as a short, steep-sided knoll or hummock.

kip — a unit of weight equal to 1000 pounds.

lacustrine — produced by or formed in a lake.

laminae — a rock layer or sediment less than one centimeter thick.

leachate — a solution obtained by leaching — for instance, water that has percolated through soil containing soluble substances and that contains amounts of these substances in solution.

limestone — a sedimentary rock composed largely of calcium carbonate.

lithology — the description of rocks, based on characteristics such as color, structures, mineralogic composition, and grain size.

loess — wind-deposited silt, usually containing some clay and some fine sand.

member — subdivision of a formation, generally of distinct lithologic character or of local extent.

muck — a dark soil with a high percentage of decomposed organic matter; also a term for debris produced by a tunnel-boring machine.

oolitic — composed of or containing oolites — sand-sized, round pellets formed of round concentric shells, generally of calcium carbonate.

outlier — an area or group of rocks surrounded by outcrops of older age.

outwash plain — sheet-like deposits of sand and gravel formed along the front of the ice margin of glaciers.

peat — a brownish, light weight mixture of partly decomposed plant tissues in which the parts of plants are easily recognized.

permeability — capacity of a material to transmit a fluid.

potentiometric surface — level to which water in a confined aquifer would rise above the aquifer by hydrostatic pressure of one atmosphere in a tightly cased well.

stratigraphy — that branch of geology that treats the formation, composition, sequence and correlation of the rock units that form the earth's crust.

tectonic — a term describing a feature or forces produced or associated with the earth's crustal movements.

till — a nonstratified glacial deposit containing a wide range of grain sizes.

till plain — a flat to undulating surface formed by glaciation and largely underlain by till commonly covered by ground moraine and subordinate end moraines.

topographic map — map showing the surface features of a land area, generally by means of contour lines.

valley train — a long narrow body of outwash sand and gravel confined within a valley.

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During the SSC drilling programs (Kempton et al., 1987a, 1987b; Curry et al., 1988; Vaiden et al., 1988) data were obtained on the geotechnical characteristics of the geologic units that would be encountered during tunnel construction. This information was used to estimate rock mass quality, ease of excavation, excavation rates and excavation equipment needed, and support requirements for underground construction.

At each drill hole the bedrock was continuously cored with a 10-foot-long barrel, and geologists described the distance between horizontal fractures, core recovery, Rock Quality Designation, and fracture frequency of the core. Core recovery, RQD and fracture frequency data are often used along with laboratory data to estimate tunneling conditions. Joint characteristics of the cores were also described.

The discussion of these geotechnical properties and their relevance to tunnel construction are taken from Curry et al., 1988.

Drilling rate indicates how resistant the rock will be to drilling at a particular site; it represents the average time taken to core each foot of rock, provided that a constant load is kept on the drill bit. Drilling through massive shaly units or cherty horizons is slower than drilling through massive carbonate rock.

Distance between horizontal separations is the length of core segments removed from the core barrel; measurements are affected by mechanically induced and handling-induced separations along bedding as well as natural fractures. These data help the engineer interpret rock character.

Core recovery is the total length of core collected from the core barrel divided by the length of the run, usually about 10 feet. Recovery of less than 100 percent may be the result of voids, soft rock that has been washed out by circulation of the drilling fluid or by fractured rock that has been pulverized during coring and lost through circulation during drilling.

Rock Quality Designation (RQD) is a standard engineering indicator for evaluating rock mass quality; it is equal to the sum of the length of all core segments longer than 4 inches between natural fractures divided by the length of the core run.

Fracture frequency is determined by counting the natural fractures in every 10-foot interval. As with RQD, breaks along bedding caused by handling of the core are not included in the count. There is generally good correlation between RQD and fracture frequency.

Joint characteristics affect the shear strength of the rock along the joints. Joints and fractures are discontinuities evaluated in core in the field. In the study area, the discontinuity planes (surfaces created by fractures or breaks) are high angle (near vertical), wavy, rough, nonweathered, sound, and tight; they infrequently contain clay filling. These characteristics, when coupled with adequate rock strength, indicate underground conditions ideal for construction because artificial means of supporting walls and roofs are less likely to be necessary. The orientation (strike) of the joints was also evaluated in ISGS hole F-8, drilled about 30 degrees from vertical. The core from this angled test hole may be oriented in the field to accurately determine the direction of discontinuities in the rock. Mapping joint characteristics is important for establishing the best way to orient the chambers. Vertical joints that parallel the tunnel and chambers provide a less stable configuration for construction than would joints cutting obliquely across the chamber.

Joint characteristics are described according to the degree of surface variation--planar, rough, or wavy. A planar joint is relatively flat, whereas a wavy joint has undulations that significantly affect the shear strength of the discontinuity. An uneven joint has a stepped surface. Irregularities on joint surfaces are called asperities, which may be rough or smooth. Slickensides are polished surfaces produced by shear movement along the plane. All these characteristics affect the strength along joints.

APPENDIX B. LABORATORY PROCEDURES

During the exploratory drilling program, drift and bedrock samples were sealed in jars, tins, or 6-mil-thick plastic sleeve bags immediately after samples were removed from the core barrel and described in the field. Samples were protected from sunlight and freezing and brought back to the ISGS Samples Library facility.

Drift Samples

Laboratory tests were performed on drift samples to characterize physical properties and clay mineralogy for stratigraphic purposes and to characterize engineering parameters.

Physical properties routinely determined for each split-spoon sample included particle-size distribution and moisture content. Particle-size data for silt and clay were obtained by hydrometer analysis and sand and gravel data by wet sieving. Dry and moist densities were determined for selected samples between 4.0 and 5.5 inches long by measuring their length and diameter in the field and sealing them in glass jars. In the laboratory the samples were weighed, dried, and then reweighed and remeasured.

Clay mineralogy was determined by X-ray diffraction of oriented, glycolated slides (Wickham, Johnson, and Glass, 1988).

BEDROCK SAMPLE TESTS

Axial Point Load Index. The point-load test was performed following procedures of D'Andrea, Fischer, and Fogelson (1965) for axial loading and of the International Society of Rock Mechanics (ISRM) (1973) for diametral loading. The point-load apparatus was designed with the standardized components presented in Broch and Franklin (1972) and ISRM (1973). The samples were loaded between two 60° cones with radius points of 5 millimeters. The cones were coaxially aligned and held rigidly in a specially designed jig. The load was increased until the sample failed along a fracture plane that intersected the two coaxial loading points. The exact solution of the imposed elastic stress was not derived, but the field was axially symmetrical about the points up to the onset of the defined fracture. The length-to-diameter ratios of the point-load samples were about 0.5 for axial loading and 1.4 for the diametral loading (Broch and Franklin, 1972 and ISRM, 1973).

Index of Anisotropy. An index of anisotropy is the ratio of point-load strength in the strongest direction divided by the strength in the weakest direction. The point-load test was strongest when applied in the axial direction and the weakest when applied diametrally along bedding.

Indirect Tensile Strength. Discs with thicknesses of about one-half the diameter of the core were compressed diametrically between high modulus steel platens.

The values of indirect tensile strength, σ_t, were calculated by the following equation:

$$\sigma_t = \frac{2F}{Dt\pi}$$

where F = axial load
D = diameter of the disc
t = thickness of the disc

Schmidt Hammer. The L-type hammer rebound test uses a spring loaded plunger which impacts a mass against a rock core sample mounted in a standard anvil. Ten readings are taken and only the five highest readings are averaged.

Shore Hardness. A model D schleroscope manufactured by Shore Instrument and Manufacturing Company, Jamaica, NY, was used for hardness determinations on compressive strength specimens. Each of the values in the summary tables is an average of the 10 highest values of 20 individual readings taken on the lapped end of the compressive strength test sample at natural moisture, following the procedures of ISRM (1978).

Slake Durability. The slake durability apparatus and testing procedure were developed at Imperial College by Franklin (1970) and Chandra (1970). A testing procedure was later suggested by the Commission on Standardization of Laboratory and Field Tests of the International Society for Rock Mechanics (1971). The test assesses the resistance offered by a rock sample to weakening and disintegration when it is subjected to a standard drying and wetting cycle and slight abrasion by tumbling.

The only deviation from the standard procedure by the ISGS Rock Mechanics Lab was that the samples used were discs of core, not spheres. The samples were handled as little as possible to ensure that their natural characteristics were being tested. All samples were run in distilled water.

Specific Gravity. The specific gravity of all samples was determined by a procedure in accordance with ASTM D-1188-71. Each sample was oven dried and coated with a plastic spray; its specific gravity was obtained by comparing its submerged weight in water to its weight in air.

Taber Abrasion (Modified). The taber abrasion test uses discs cut from the rock core that are mounted in a machine that rotates the disc and an abrasion wheel against each other for 400 revolutions on each side of the rock disc. The inverse of the weight loss in grams of the rock disc is the abrasion hardness. This test is sensitive to factors that influence small-scale strength, shearing, crushing and abrasion. The procedures followed are presented in Tarkoy (1975).

Tangent Modulus. The tangent modulus is the slope of a line that is tangent to the stress-strain curve developed by unconfined compressive strength testing of a core sample. The tangent modulus data presented in this report are calculated at 50 percent of the ultimate compressive strength of the sample.

Triaxial Strength. A triaxial compression test is performed on samples machined to the dimensions and tolerances of the unconfined compressive strength test. In the triaxial test the samples are placed in a container where pressures are exerted all around the sides of the core. This confining pressure (σ_3) is supplied by oil under pressure. The core samples are then loaded axially (σ_1) until they fail. This is performed on multiple samples at different confining pressures. Most rocks show an increase in strength with an increase in confining pressure.

The phi angle (angle of internal friction) and cohesive strength are the dip and intercept of a line which defines the failure envelope of the rock. The envelope is constructed by running multiple triaxial strength tests at different confining pressures (σ_3) and plotting the Mohr circle of σ_1 and σ_3 for each test (fig. B-1).

Unconfined Compressive Strength. Immediately prior to testing, a section of core was removed from the protective plastic bags. Samples were cut to a right cylinder with a saw and the ends were then lapped to obtain a length-to-width ratio of about 2 with a 0.0025-inch tolerance for nonparallelism. The compressive strength values of the samples were in the raw state and were not normalized to any specific length-to-width ratios. Loading was under constant strain conditions. No caps of any type were used.

Water Content. Samples were unwrapped, prepared, and tested the same day to minimize moisture loss. Parts of the strength-tested samples were used for water content determinations. Moisture content was calculated as a percentage of the dry weight of the sample.

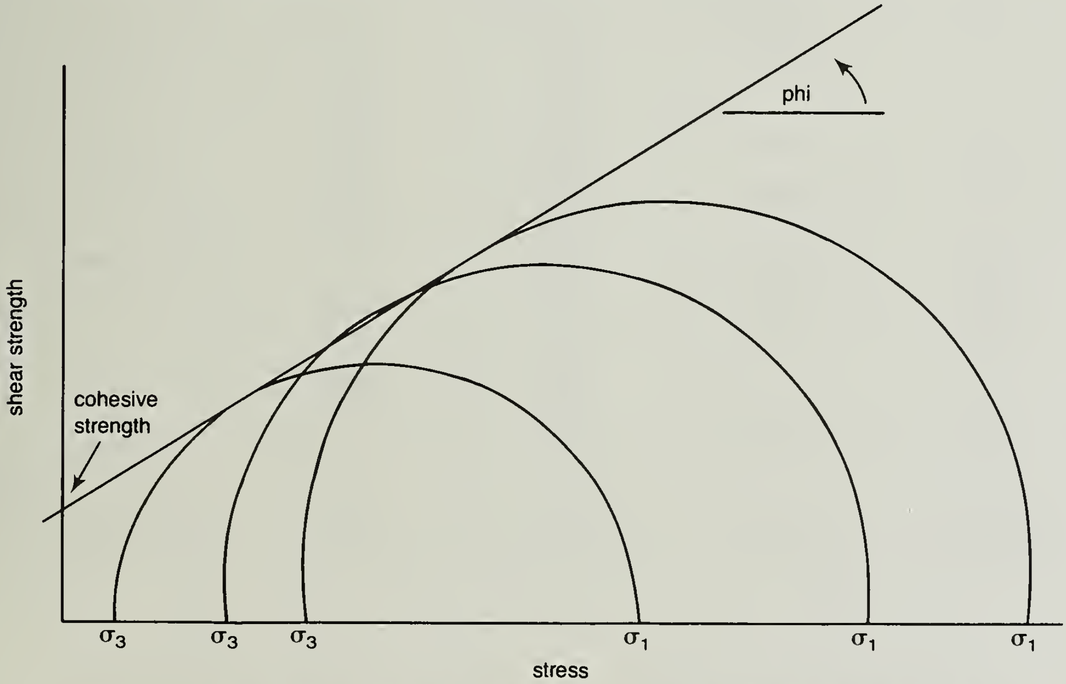

Figure B-1 Mohr-Coulomb failure envelope defined by three triaxial strength tests showing cohesive strength and phi angle (angle of internal friction).

APPENDIX C. GEOTECHNICAL DATA FOR ISGS TEST HOLES F-1 THROUGH F-17

Table C-1. Drilling rates (minutes per foot)

Borehole no.	No. of core runs	Silurian	No. of core runs	Maquoketa	No. of core runs	(Galena) Wise Lake	No. of core runs	(Galena) Dunleith	No. of core runs	Platteville	No. of core runs	(Ancell) St. Peter
F-1	11	1.68	8	2.07	12	1.75	1	3.00				
F-2	3	1.80	16	1.58	3	1.82						
F-3			7	2.31	9	1.52						
F-4	2	1.52	21	1.86	2	1.64						
F-5			5	2.04	12	1.80	4	1.86	2	2.61		
F-6	6	1.80	16	2.04	3	2.33						
F-7	2	2.29	11	2.21	12	1.64	3	1.56				
F-9			6	2.97	13	2.25	4	1.95	5	2.44		
F-10	3	1.69	15	2.26	13	2.13						
F-11					13	1.69	4	1.58	16	1.87		
F-12			14	2.42	14	1.75	5	2.08	2	1.95		
F-13			5	2.10								
F-14			1	2.22	16	1.41	5	1.69	9	1.88		
F-15			16	2.60	12	2.07						
F-16			12	2.40	12	2.06						
F-17					9	1.98	5	2.12	16	2.45	21	1.93
Total no.of core runs	27		153		155		31		50		21	
Average drill rates		1.75		2.18		1.84		1.89		2.15		1.93

Table C-2. Average core recovery values (percent)

Borehole no.	No. of core runs	Silurian	No. of core runs	Maquoketa	No. of core runs	(Galena) Wise Lake	No. of core runs	(Galena) Dunleith	No. of core runs	Platteville	No. of core runs	(Ancell) St. Peter
F-1	14	99.66	16	99.26	14	99.93	1	99.00				
F-2	2	99.90	23	99.80	6	99.90						
F-3			12	99.40	9	99.80						
F-4	2	100.00	21	99.40	2	100.00						
F-5			6	99.91	14	100.00	6	100.00	2	98.00		
F-6	7	99.60	15	98.60	3	100.00						
F-7	2	100.00	13	99.65	14	100.00	3	99.33				
F-8			18	97.10	14	99.90						
F-9			8	98.91	15	100.00	5	99.60	5	99.80		
F-10	3	100.00	16	99.50	13	99.64						
F-11					13	100.00	4	96.87	16	100.00		
F-12			16	97.39	15	100.00	5	100.00	2	100.00		
F-13			7	83.71								
F-14			1	100.00	16	99.84	5	100.00	9	100.00		
F-15			16	99.50	12	100.00						
F-16			12	99.58	12	99.83						
F-17					10	99.60	5	100.00	18	81.27	22	94.54
Average recovery per stratigraphic unit		99.74		98.50		99.90		99.48		93.42		94.54

Table C-3. Lowest core recovery values (percent)

Borehole no.	Silurian	Maquoketa	(Galena) Wise Lake	(Galena) Dunleith	Platteville	St. Peter
F-1	97	96	99	99		
F-2	99	98	99			
F-3		96	99			
F-4	100	95	100			
F-5		99	100	100	98	
F-6	97	84	100			
F-7	100	98	100	98		
F-8		91	99			
F-9		97	100	98	99	
F-10	100	96	98			
F-11			100	90	100	
F-12		70	100	100	100	
F-13		41				
F-14		100	97	100	100	
F-15		96	100			
F-16		97	98			
F-17			96	100	18	60

Table C-4. Average RQD values (percent)

Borehole no.	No. of core runs	Silurian	No. of core runs	Maquoketa	No. of core runs	(Galena) Wise Lake	No. of core runs	(Galena) Dunleith	No. of core runs	Platteville	No. of core runs	(Ancell) St. Peter
F-1	14	97.96	16	97.33	14	99.57	1	99.00				
F-2	6	99.90	21	96.50	5	99.90						
F-3			10	99.30	9	99.80						
F-4	2	100.00	21	98.70	2	100.00						
F-5			6	97.25	14	99.85	6	99.00	2	98.00		
F-6	7	98.70	16	97.90	3	99.30						
F-7	2	100.00	13	99.65	14	99.42	3	97.00				
F-8			19	98.00	14	98.80						
F-9			8	97.40	15	99.60	5	94.60	5	99.80		
F-10	3	100.00	16	98.84	13	99.64						
F-11					13	96.57	4	93.55	16	98.56		
F-12			14	97.39	15	99.53	5	99.20	2	100.00		
F-13			7	70.14								
F-14			1	100.00	16	99.34	5	98.20	9	98.44		
F-15			16	99.50	12	98.58						
F-16			12	99.58	12	99.83						
F-17					10	96.70	5	100.00	19	73.36	22	73.36
Average RQD per stratigraphic unit		98.87		97.24		99.10		97.59		89.66		73.36

Table C-5. Lowest RQD values (percent)

Borehole no.	Silurian	Maquoketa	(Galena) Wise Lake	(Galena) Dunleith	Platteville	St. Peter
F-1	70	65	95	99		
F-2	99	64	99			
F-3		88	99			
F-4	100	91	100			
F-5		84	98	96	98	
F-6	95	84	98			
F-7	100	98	92	93		
F-8		91	75			
F-9		90	94	75	99	
F-10	100	92	99			
F-11			80	84	88	
F-12		70	97	98	100	
F-13		0				
F-14		100	98	97	93	
F-15		96	94			
F-16		97	98			
F-17			88	100	0	60

Table C-6. Summary of rock mechanics data (per hole and rock unit)

Borehole no.	Rock type	Unconfined compressive strength (psi)	Tangent modulus (psi x 10^6)	Indirect tensile strength (psi)	Axial point load index (psi)	Moisture content W(%)	Specific gravity	Shore hardness	Diameter point load index (psi)	Index of anisotropy
					SILURIAN					
F-1	Dolostone	14,259	4.55	1,050	2,098	1.83	2.67	54	598	3.8
F-2	Dolostone	15,529	9.30	1,248	2,600	0.25	2.74	65	747	3.5
F-4	Dolostone	18,194	6.91	1,578	2,612	0.92	2.61	63	756	3.4
F-6	Dolostone	18,825	6.68	1,130	2,185	1.40	2.70	54	613	3.7
F-7	Dolostone	20,918	11.56	1,016	2,023	1.41	2.68	52	569	3.6
F-10	Limestone	13,859	6.61	1,002	1,488	2.06	2.68	50	530	2.8
AVERAGE		16,065	7.13	1,159	2,252	1.31	2.69	57	649	3.6
					MAQUOKETA					
F-1	Dol-Shale	4,457	0.98	537	724	3.80	2.53	26	218	3.7
F-2	Dol-Shale	3,662	0.59	401	479	4.87	2.43	28	145	3.7
F-3	Dol-Shale	3,996	0.56	519	827	4.61	2.43	24	295	3.5
F-4	Dol-Shale	3,608	0.82	458	664	4.50	2.54	26	165	4.3
F-5	Dol-Shale	4,277	0.52	669	768	4.97	2.38	25	94	8.7
F-6	Dol-Shale	5,133	1.10	554	679	2.92	2.48	25	150	5.5
F-7	Dol-Shale	5,299	0.65	637	1,258	3.10	2.59	32	564	2.7
F-9	Dol-Shale	6,654	1.12	684	898	2.58	2.62	41	344	2.8
F-10	Shale	3,480	0.49	438	417	6.40	2.36	15	86	5.2
F-15	Dol-Shale	6,737	1.02	727	727	3.22	2.47	32	170	5.7
F-16	Lim-Shale	4,199	0.57	585	765	4.10	2.51	28	245	4.1
AVERAGE		4,405	0.77	523	686	4.22	2.48	27	201	4.3
F-1	Dolostone	10,024	3.34	953	1,551	1.74	2.69	47	524	3.1
F-2	Dolostone	6,955	3.17	579	2,591	2.15	2.68	47	611	2.1
F-4	Dolostone	8,755	2.72	860	1,427	1.92	2.45	55	477	3.3
F-6	Dolostone	8,655	4.19	780	1,262	1.24	2.62	63	335	3.6
F-7	Dolostone	10,083	2.65	757	814	0.96	2.61	45	199	4.3
AVERAGE		8,998	3.13	817	1,456	1.62	2.59	52	430	3.3
F-12	Limestone	21,061	4.30	1,245	1,853	0.67	2.72	67	889	2.3
F-15	Limestone	19,417	3.94	1,518	1,322	0.11	2.71	56	648	2.0
F-16	Limestone	9,344	1.39	798	1,292	2.23	2.59	38	335	4.0
AVERAGE		15,805	3.00	1,092	1,537	1.26	2.66	53	617	3.0
					GALENA (Wise Lake)					
F-1	Dolostone	8,696	5.02	806	1,856	0.64	2.68	64	624	2.3
F-2	Dolostone	11,342	5.58	958	1,423	1.36	2.69	65	525	3.3
F-3	Dolostone	9,482	5.99	884	1.960	1.08	2.66	60	572	3.5
F-4	Dolostone	9,538	6.27	861	1,446	1.97	2.67	59	467	3.3
F-5	Dolostone	9,754	5.40	801	1,296	1.64	2.65	51	485	2.9
F-6	Dolostone	10,168	4.59	973	1,748	1.06	2.65	58	582	3.2
F-7	Dolostone	9,414	7.73	677	1,324	1.69	2.69	59	591	2.3
F-9	Dolostone	11,330	6.47	719	983	1.43	2.54	50	410	2.5
F-11	Dolostone	6,800	4.73	852	1,364	2.36	2.62	55	384	3.7
F-12	Dolostone	7,136	3.37	614	917	3.63	2.54	41	397	2.5
F-14	Dolostone	9,963	4.07	700	1,100	2.61	2.56	50	483	2.4
F-15	Dolostone	11,763	5.86	830	1,306	1.35	2.70	62	634	2.1
F-16	Dolostone	12,237	6.08	1,023	1.807	1.05	2.66	58	628	3.0
F-17	Dolostone	10,179	7.65	847	1,666	0.70	2.65	59	657	2.7
AVERAGE		10,034	5.62	841	1,428	1.58	2.65	57	536	2.9
F-10	Limestone	16,148	11.72	1,089	1,974	0.79	2.66	49	609	3.4
					GALENA (Dunleith)					
F-5	Dolostone	7,193	4.54	768	1,256	2.65	2.57	42	445	2.9
F-7	Dolostone	9,659	4.14	639	1,144	1.35	2.64	59	529	2.3
F-9	Dolostone	9,163	6.01	626	1,015	1.97	2.55	52	441	2.6
F-11	Dolostone	1,666	1.56	207	663	7.62	2.43	36	155	2.5
F-12	Dolostone	6,688	4.69	530	718	4.67	2.47	46	281	2.5
F-14	Dolostone	6,406	2.72	527	863	2.34	2.56	46	337	2.6
F-16	Dolostone	7,326	3.30	1,111	1,146	2.42	2.62	68		0.0
F-17	Dolostone	11,267	8.08	1,125	1,524	0.65	2.70	60	574	3.4
AVERAGE		7,600	4.63	635	999	2.89	2.56	49	398	2.6
					PLATTEVILLE					
F-5	Dolostone	10,262	6.56	835	1,452	2.53	2.56	49	498	3.2
F-11	Dolostone	10,874	8.02	1,025	1,625	1.40	2.68	64	786	2.2
F-12	Dolostone	10,045	3.76	843	1,338	2.95	2.51	40	488	2.7
F-14	Dolostone	14,506	4.52	1,205	1,520	1.76	2.66	54	687	1.9
F-17	Dolostone	14,798	8.49	1,171	2.003	0.15	2.73	67	986	2.1
AVERAGE		12,169	6.56	1,034	1,601	1.62	2.64	57	747	2.4
F-11	Limestone	22,775	6.30	1,411	2,460	0.24	2.69	58	715	3.4
					ST. PETER					
F-17	Sandstone	1,795	0.69	120	260	6.62	2.23	12	58	4.5

Table C-7. Triaxial test results (total stress path)

Borehole No.	Maquoketa		Wise Lake		Dunleith		Platteville		St. Peter	
	Ø	C	Ø	C	Ø	C	Ø	C	Ø	C
F-1	44	1,179	46	2,008						
F-2	25	1,502	45	2,223						
	35	704	48	1,780						
F-3	30	822	52	2,214						
			42	1,069						
F-4	33	916	48	1,404						
F-5	29	962	53	1,623	47	1,163				
					49	2,073				
F-6	31	890	50	1,897						
F-7			49	1,337	51	1,408				
F-9			52	1,215	40	1,102	56	1,637		
F-10			53	2,842						
F-11			58	552	19	489	53	3,054		
F-12			44	742	46	732	54	1,901		
							46	1,513		
F-14							46	2,457		
F-15			47	1,451						
F-16			55	2,126						
F-17			54	1,684			62	1,910	61	24

Ø = degrees

C = cohesion (psi)