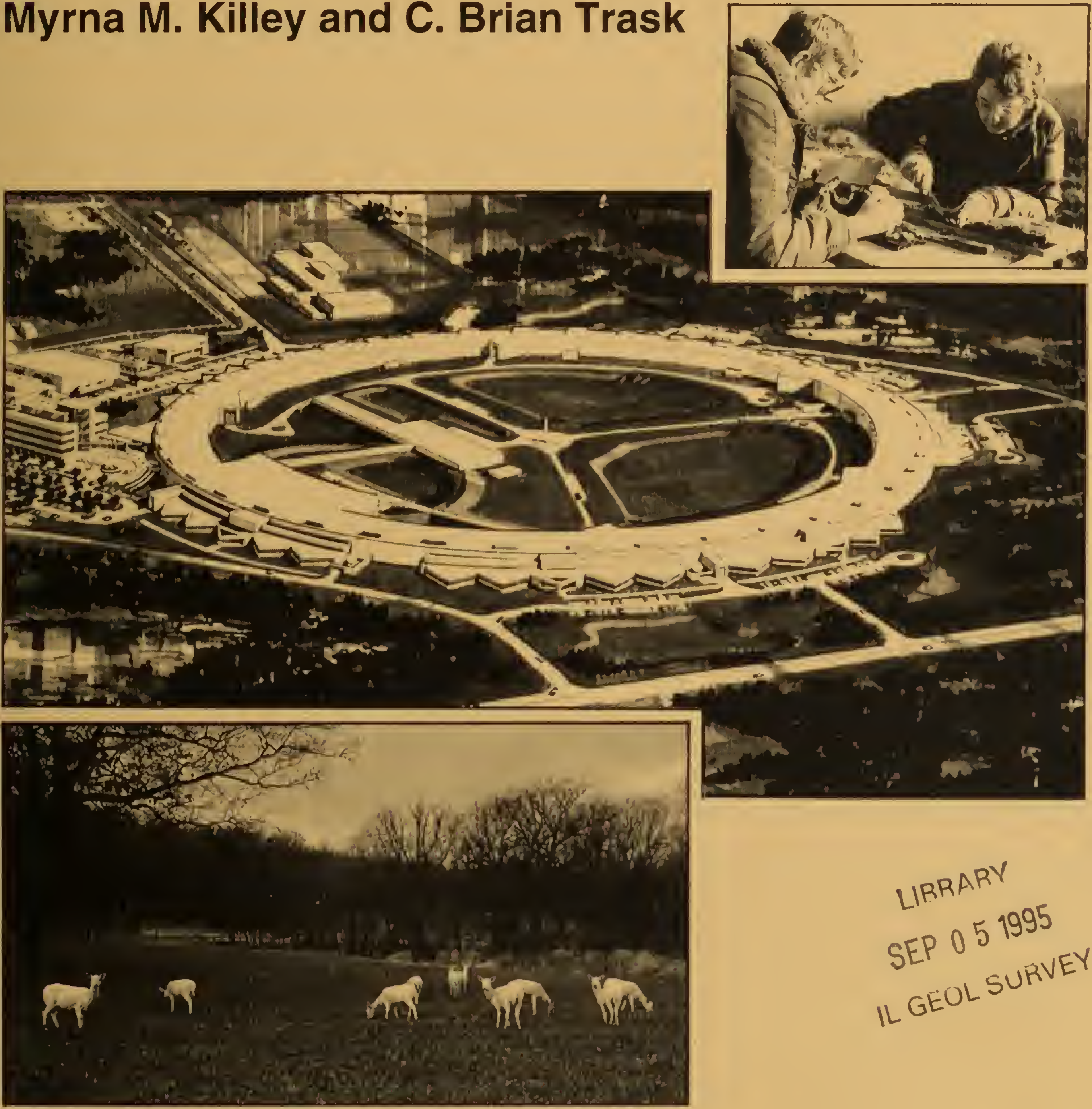
Geol Survey

Geotechnical Site Investigation for an Advanced Photon Source at Argonne National Laboratory, Illinois

Myrna M. Killey and C. Brian Trask



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Geotechnical Site Investigation for an Advanced Photon Source at Argonne National Laboratory, Illinois

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Cover photos: (upper right) Principal investigators describe core at drilling site, photo courtesy of Argonne National Laboratory. (center) Proposed APS facility at Argonne National Laboratory, artist's rendering courtesy of Argonne National Laboratory. (lower left) White fallow deer on Argonne National Laboratory grounds, photo taken by Myrna Killey.

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ABSTRACT

In 1987 Argonne National Laboratory near Chicago was designated as the site for construction of a 7 billion electron volt (7 GeV) Advanced Photon Source (APS). This national research facility will use the newest technology to produce the brightest beam of X-rays ever available for research. To ensure that no unexpected geological conditions would be encountered during construction, the Illinois State Geological Survey (ISGS) participated in a preliminary geotechnical site investigation.

Studies of the regional geologic setting provided a framework for interpreting the geologic units underlying the site. Silurian dolomite at the bedrock surface is overlain by the Lemont drift and the Wadsworth Till Member of the Wedron Formation, two Woodfordian-age glacigenic deposits. These materials were characterized during a program that included geophysical surveying, drilling, and sampling on site, as well as testing at ISGS laboratories. We studied 44 logs from previous drilling programs. Vertical electrical soundings (92) and reversed seismic refraction profiles (46) were run across the entire site. A total of 28 boreholes were drilled on or near the proposed APS site.

The geology of the APS site is predictable and consistent with the regional geologic framework. The attitude and nature of the bedrock surface indicate a gently undulating surface with no major paleovalleys. The lithologic variability of the Lemont drift is consistent with regional observations, and the relative uniformity of the Wadsworth Till Member is broken only by a possibly continuous overpressured sand. Design and construction of the facility should take into account the geologic conditions represented by this sand unit. Statistical analysis of seismic refraction profiles revealed no significant difference in bedrock velocities but did indicate that vibration attenuation characteristics of the drift may be greater in certain directions. Water level data yielded an overall picture of groundwater movement in the bedrock and glacial materials. The results of this investigation indicate that the geologic materials at the site are suitable for the construction and operation of the APS facility.

ACKNOWLEDGMENTS

We thank the following ISGS staff for their contributions: Ross D. Brower, Stephen K. Danner, Terrie Adams, and Edward Smith for field assistance; Herbert D. Glass and Rebecca J. Roeper for various laboratory analyses; and Jacquelyn L. Hannah for drafting the illustrations. In addition, discussions with Ardith K. Hansel and Donald G. Mikulic provided clarification of regional drift and bedrock stratigraphy, respectively.

Pieter H.M. Braam, independent consultant, coordinated the preliminary geotechnical site investigation for Argonne. Russell H. Huebner of Argonne provided guidance and liaison. Joseph A. Jendrzejczyk and Roger Smith, also of Argonne, solved several problems of design and retrieval of downhole equipment.

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INTRODUCTION

Argonne National Laboratory, referred to as Argonne in this report, was designated in 1987 by the U.S. Department of Energy (U.S. DOE) as the site for construction of a 7 billion electron volt (7 GeV) Advanced Photon Source (APS). Argonne is located approximately 25 miles southwest of Chicago in southeastern Du Page County, Illinois (fig. 1). The Illinois State Geological Survey (ISGS) was invited to participate in a three-way cooperative project with Argonne and STS Consultants Ltd. The project was designed to (1) provide an early start to overall site characterization prior to retaining an architectural-engineering firm for a final design study and (2) ensure that no unexpected geological conditions would be encountered as construction proceeded. This report summarizes the studies undertaken by the ISGS on behalf of Argonne in evaluating the character of the surficial geologic materials upon which the facility is to be built.

Advanced Photon Source

The 7 GeV APS is designed to use recently developed technology to produce an X-ray beam 10,000 times brighter than is currently available. This high energy X-ray will open up new avenues of research in science and technology, including the areas of physics, chemistry, biology, medicine, materials sciences, biotechnology, and geosciences. The APS facility will have a linear accelerator, synchrotron, and positron storage ring, and related experiment-support buildings, offices, and meeting rooms (fig. 2). The focal point of this facility is the storage ring, which has a circumference of 3,622 feet (1,104 m) at the center of the ring. It will be housed in an annular building. Reliable operation of the positron beam within the storage ring requires that the structure be built according to stringent vibration and settlement standards. The design of the foundation and the resulting impact of vibration and settlement are directly related to areal distribution, lithological and engineering properties, and hydrogeologic conditions of the geologic materials on which the foundation will rest.

Nature and Purpose of ISGS Involvement

The Illinois State Geological Survey's involvement grew out of a request from Argonne to the Governor's Commission on Science and Technology. Argonne sought advice on the nature and extent of interest by the State of Illinois in participating in and providing support for a geotechnical investigation for the APS project. An understanding was reached whereby the ISGS was to

- provide the regional geologic framework and resistivity, seismic refraction, and downhole geophysical surveys;
- share the tasks of field and laboratory testing with the contractor;
- cooperate with Argonne on project overview.

The primary purpose of these studies was to characterize the bedrock and glacial drift at the site to ensure that no unexpected geological or hydrogeological conditions would be encountered as construction of the APS proceeded. Because vibration transmission could have a significant impact on the effective operation of the facility, the ISGS studies would also draw attention to any geological characteristics that might have a bearing on vibration transmission through earth materials and thus be applicable to Argonne's analysis of vibrations at the site.

It should be noted that since the ISGS investigation was completed, a site was selected for construction of the storage ring approximately 200 feet south and 100 feet west of the site originally chosen (Rick Fenner, Argonne National Laboratory, personal communication 1991). Figures in this report reflect the location of the original site.

GEOLOGIC SETTING

Sources of Data

Many geological studies of bedrock and overlying glacial deposits of northeastern Illinois have been conducted by the ISGS over the years. Bedrock studies include Horberg (1950), Buschbach and Heim (1972), Willman (1973), and Kolata et al. (1978). Glacial drift studies include Horberg and Potter (1955),

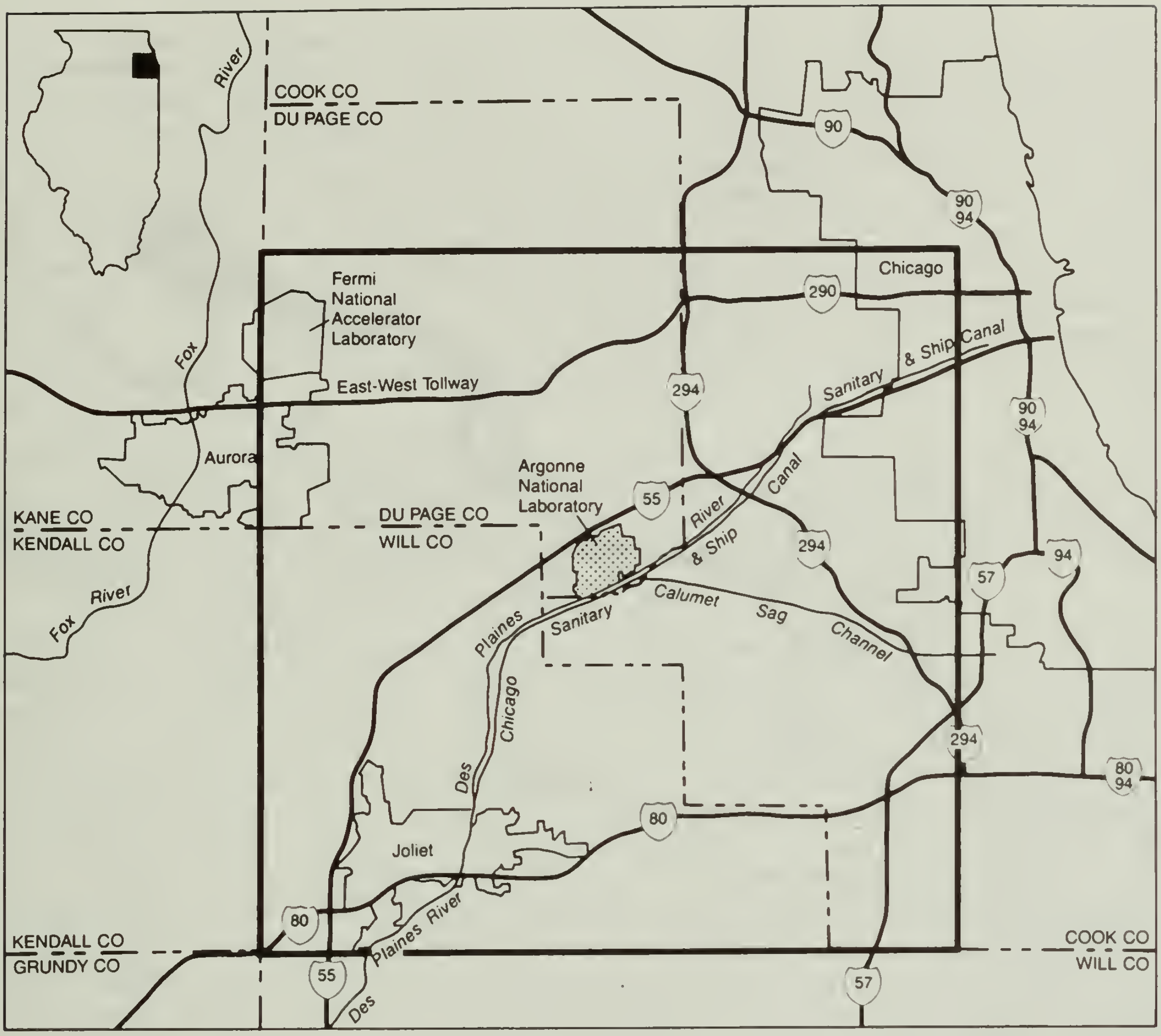


Figure 1 Location of Argonne National Laboratory in northeastern Illinois. The regional study area is outlined.

Kempton and Hackett (1968), Landon and Kempton (1971), and Piskin and Bergstrom (1975). Other discussions of bedrock and drift units appear in Willman (1971), Kempton et al. (1977) and, more recently, a series of reports on investigations conducted adjacent to the APS regional study area that resulted from geological-geotechnical studies for siting the Superconducting Super Collider in Illinois (Kempton et al. 1985, Kempton et al. 1987a, b, Curry et al. 1988, Graese et al. 1988, Vaiden et al. 1988). Recent investigations into the glacial deposits of northeastern Illinois relevant to this study are Johnson et al. (1985), Hansel and Johnson (1986), Wickham et al. (1988), and Johnson and Hansel (1989). Several graduate theses present detailed studies of various drift units in nearby areas (Bogner 1973, Kemmis 1978, Wickham 1979, Brossman 1982). In addition, sources of unpublished data, all on open file at the ISGS, include logs and records of subsurface drilling and sampling programs for various studies, as well as engineering and highway borings.

Regional Geologic Framework

An evaluation of the regional setting provided ISGS researchers with insight into the geologic units that were expected to be present at the APS site, thus improving our confidence in the reliability of the results of the site investigation. The ISGS selected an area of approximately 900 square miles surrounding Argonne for its study of the regional geologic framework. This region consisted of the southern two-thirds of Du Page County, the northern half of Will County, and southwestern Cook County (fig. 1).

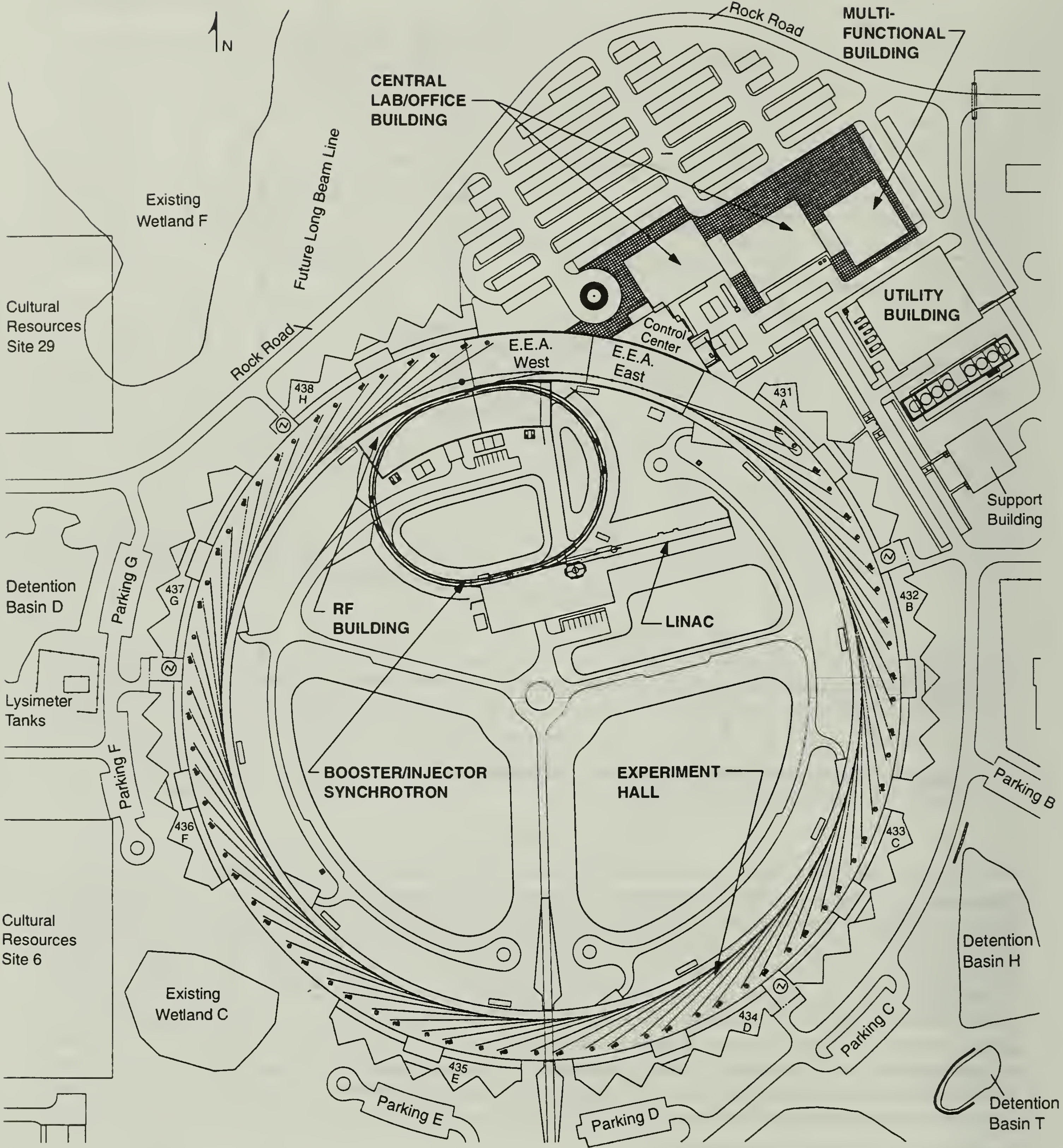


Figure 2 Plan view of proposed APS facility (illustration provided courtesy of Argonne, 1991). The positron storage ring is contained in the experiment hall.

Bedrock Silurian-age dolomite approximately 200 feet thick forms the bedrock surface in the regional study area. The Silurian System is underlain by older sedimentary rocks (shale, dolomite, and sandstone) of the Ordovician and Cambrian Systems (fig. 3). Silurian strata, described in detail by Willman (1973), range from the shaly Wilhelmi Formation at the base, through dolomites of varying purity, to the Racine Formation at the bedrock surface. The Racine averages about 50 feet in thickness and consists of alternating beds of shaly dolomite, cherty dolomite, and purer dense dolomite. Dolomite at and near the bedrock surface appears to be fractured but relatively unweathered (D.G. Mikulic, ISGS, personal communication 1987); it is overlain by broken bedrock rubble. Regionally, two joint sets have been observed in the bedrock (Graese et al. 1988, Bauer et al. 1991), and horizontal separations commonly exist in the upper parts. Higher bedrock elevations, 600 to 650 feet or more above mean sea level (msl), occur in a general northwest–southeast trend and are transected by lows that trend northeast–southwest (fig. 4).

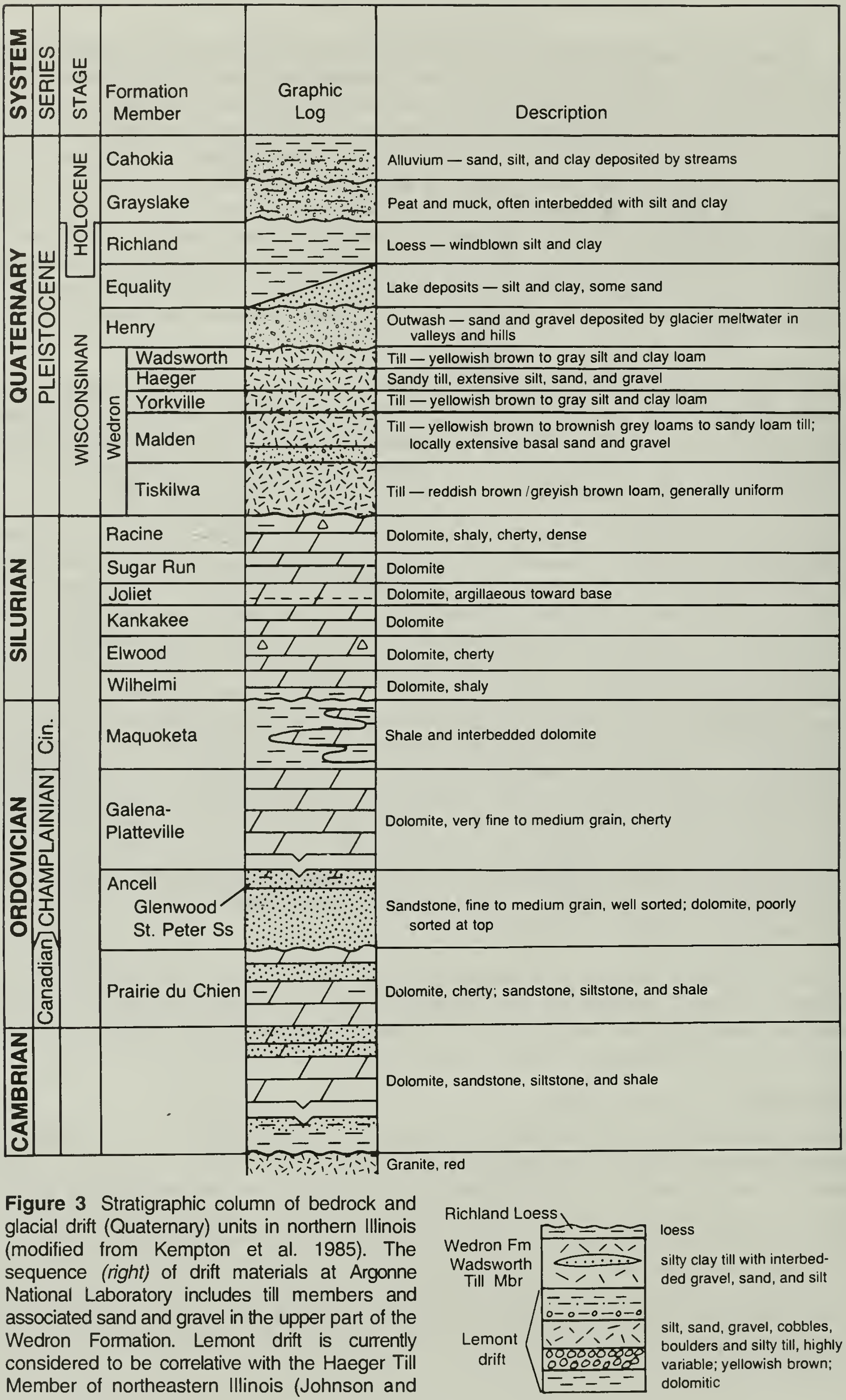
Glacial drift Glacial drift overlies the bedrock. Although the drift is absent in places, it is as much as 200 feet thick in parts of the study area (Piskin and Bergstrom 1975). The thickest drift occurs along a northwest–southeast trend, which generally coincides with the closely grouped sequence of end moraines formed where the terminus of glacial ice remained relatively stationary. The Argonne grounds are located on the Keeneyville Moraine in the central part of the Valparaiso Morainic System (fig. 5).

The generalized succession of glacial drift above bedrock in the regional study area consists of (1) a lithologically variable unit (the Lemont drift, currently considered to be correlative with the Haeger Till Member in this area, see fig. 3) composed of silty diamicton, silt, sand, gravel, cobbles, and boulders, overlain by (2) a silty clay diamicton, the Wadsworth Till Member of the Wedron Formation, with interbedded sand and silt lenses. The Wadsworth till is fairly uniform in comparison with the Lemont drift and is the major surficial geologic unit across the region (fig. 6). Till, lacustrine deposits, and outwash predominate in the geologic materials forming the land surface in the region (fig. 6), although a thin (<5 ft) cover of loess blankets most of the upland area. Alluvium, slopewash, and peat also occur in the region. A cross section (fig. 7) reveals both the general sequence of glacial deposits that can be expected to occur in the region and the complexity and variability of these deposits both locally and regionally. The complete sequence of Lemont drift consists of a thick basal sand and gravel overlain by silty diamicton interbedded with sorted sediment and a thin sorted and stratified sediment at the top. This complete sequence commonly appears in borings and quarry exposures near the West Chicago and Wheaton Moraines (fig. 5). The sequence is less complete and more variable toward the east and south (A.K. Hansel, ISGS, personal communication 1987). Bogner (1973) and Johnson et al. (1985) have described the type section of the Lemont drift in an exposure south of Argonne near Lemont.

The complexity and variability of this generalized vertical sequence of glacial deposits, due primarily to local variations in glacial depositional and erosional processes, can result in considerable variation in engineering properties of these materials. An understanding of the degree of this variability, as it might affect construction and efficient operation of the APS facility, was one of the goals of this study.

Site Description

General site description Argonne National Laboratory occupies 1,700 acres on the bluffs and uplands approximately 1/2 mile north of the Des Plaines River floodplain (fig. 8). The APS facility is being constructed on the undeveloped southwestern part of the Argonne campus (figs. 8 and 9). Figure 8 outlines an area of the Argonne campus referred to in this report as "the general APS site" or "the general site." This area is used as a base map for many subsequent figures, starting with figure 9. This base map uses Argonne's coordinate system, which also provides a useful scale on subsequent illustrations. The Argonne coordinates of the southwest corner of this rectangle are given in figure 8; the coordinates of the general site are 50,000 to 53,000 feet north and 30,000 to 32,000 feet east (fig. 9). The southwest corner of the general site (Argonne coordinates 50,000 N, 30,000 E, fig. 8) coincides with the southwest corner of Section 9, T37N, R11E.



SYSTEM	SERIES	STAGE	Formation	Member	Description
QUATERNARY	PLEISTOCENE	HOLOCENE	Cahokia		Alluvium — sand, silt, and clay deposited by streams
			Grayslake		Peat and muck, often interbedded with silt and clay
			Richland		Loess — windblown silt and clay
		WISCONSINAN	Equality		Lake deposits — silt and clay, some sand
			Henry		Outwash — sand and gravel deposited by glacier meltwater in valleys and hills
			Wedron	Wadsworth	Till — yellowish brown to gray silt and clay loam
				Haeger	Sandy till, extensive silt, sand, and gravel
				Yorkville	Till — yellowish brown to gray silt and clay loam
				Malden	Till — yellowish brown to brownish grey loams to sandy loam till; locally extensive basal sand and gravel
				Tiskilwa	Till — reddish brown /greyish brown loam, generally uniform
SILURIAN			Racine		Dolomite, shaly, cherty, dense
			Sugar Run		Dolomite
			Joliet		Dolomite, argillaeous toward base
			Kankakee		Dolomite
			Elwood		Dolomite, cherty
			Wilhelmi		Dolomite, shaly
ORDOVICIAN	Cin.		Maquoketa		Shale and interbedded dolomite
	CHAMPLAINIAN		Galena-Platteville		Dolomite, very fine to medium grain, cherty
			Ancell	Glenwood St. Peter Ss	Sandstone, fine to medium grain, well sorted; dolomite, poorly sorted at top
	Canadian		Prairie du Chien		Dolomite, cherty; sandstone, siltstone, and shale
CAMBRIAN					Dolomite, sandstone, siltstone, and shale
					Granite, red

Figure 3 Stratigraphic column of bedrock and glacial drift (Quaternary) units in northern Illinois (modified from Kempton et al. 1985). The sequence *(right)* of drift materials at Argonne National Laboratory includes till members and associated sand and gravel in the upper part of the Wedron Formation. Lemont drift is currently considered to be correlative with the Haeger Till Member of northeastern Illinois (Johnson and Hansel 1989).

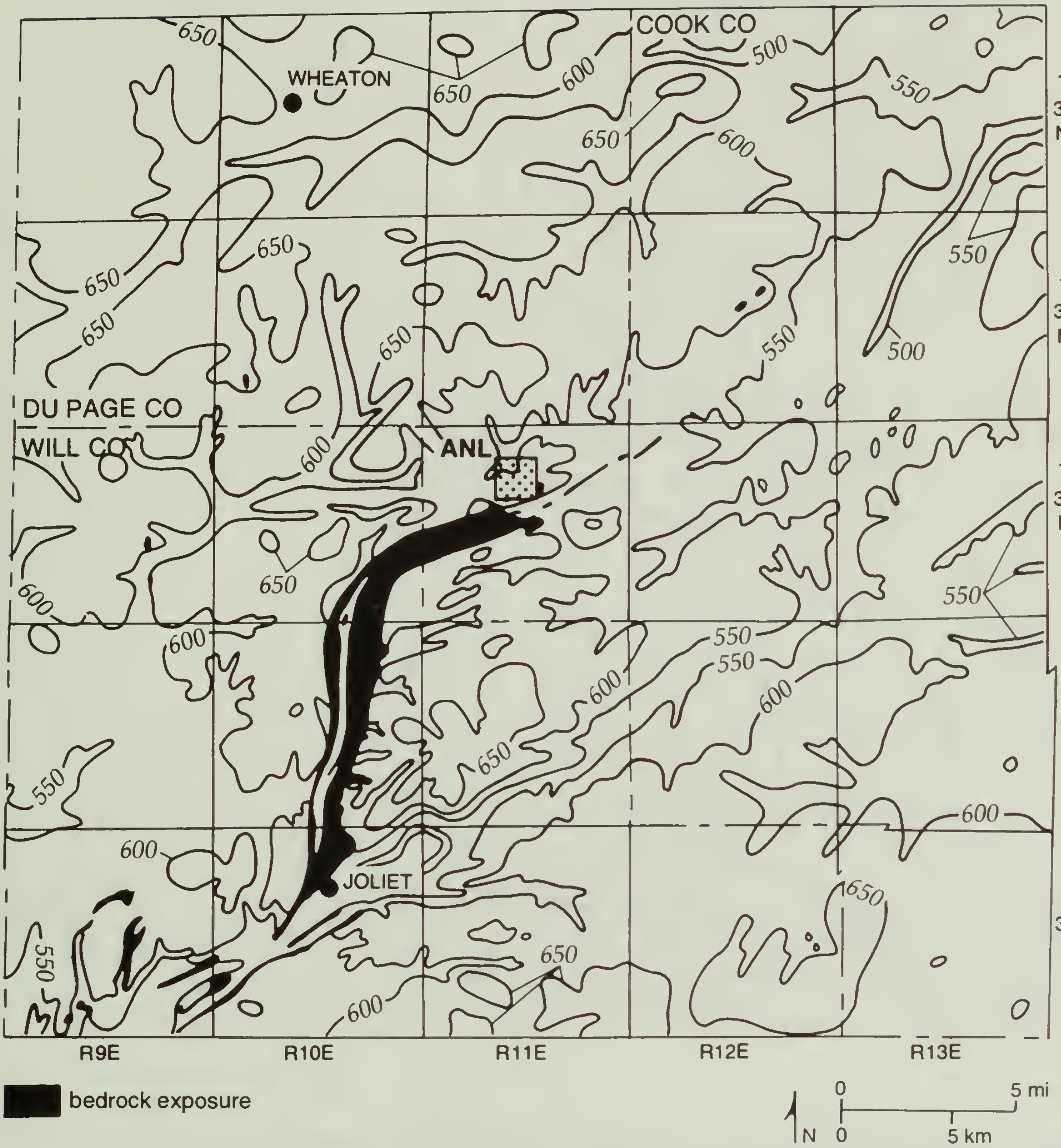


Figure 4 Generalized bedrock topography of the regional study area (after Horberg 1950). In this and subsequent figures, Argonne National Lab is listed as ANL.

Geomorphic characteristics The APS facility will be built on a drainage divide (fig. 10) that runs northeast–southwest across the general site. From this divide, southward-flowing drainage flows directly to the Des Plaines River through a series of subparallel, sharply incised valleys cut into the northern valley wall of the Des Plaines. Northward-flowing drainage flows indirectly to the Des Plaines by way of Freunds Creek (on the southern part of the Argonne campus), which flows into Sawmill Creek, a tributary to the Des Plaines.

Elevation of the general site ranges from about 725 to more than 760 feet msl, a relief of about 35 feet (fig. 11). Among the topographic features of interest on the general site are several enclosed depressions including natural topographic lows, a beaver impoundment, and excavations for the never-built Argonne Advanced Research Reactor (A^2R^2). During the abnormally dry summer of 1988,

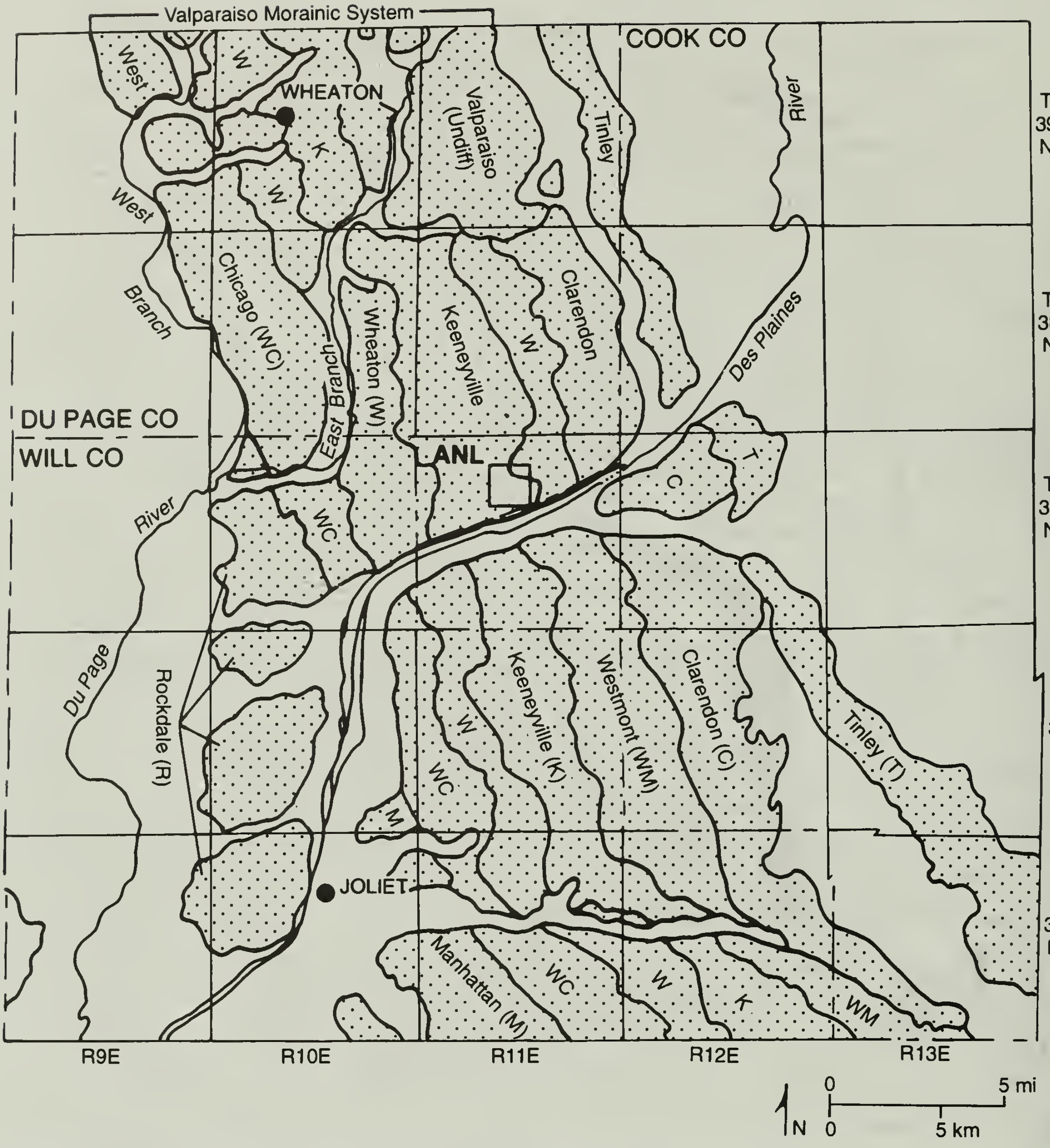


Figure 5 End moraines in the regional study area (after Willman and Frye 1970).

these areas were dry or nearly so except for the A^2R^2 excavation. The presence and level of water in the depressions depended on the elevation of the water table, which varies seasonally and according to distribution and intensity of rainfall events. Since completion of this study, the A^2R^2 excavation has been backfilled.

METHODS OF STUDY

We used two types of data for this study. First, information contained in reports of previous drilling programs were used to provide a general geological framework on which to build the investigation. Second, initial geophysical field work, consisting of vertical electrical soundings (VES) and seismic refraction profiling, was used to confirm the shallow geological framework of the APS site, provide information on the continuity of geologic materials at the site, and define the nature of the bedrock surface.

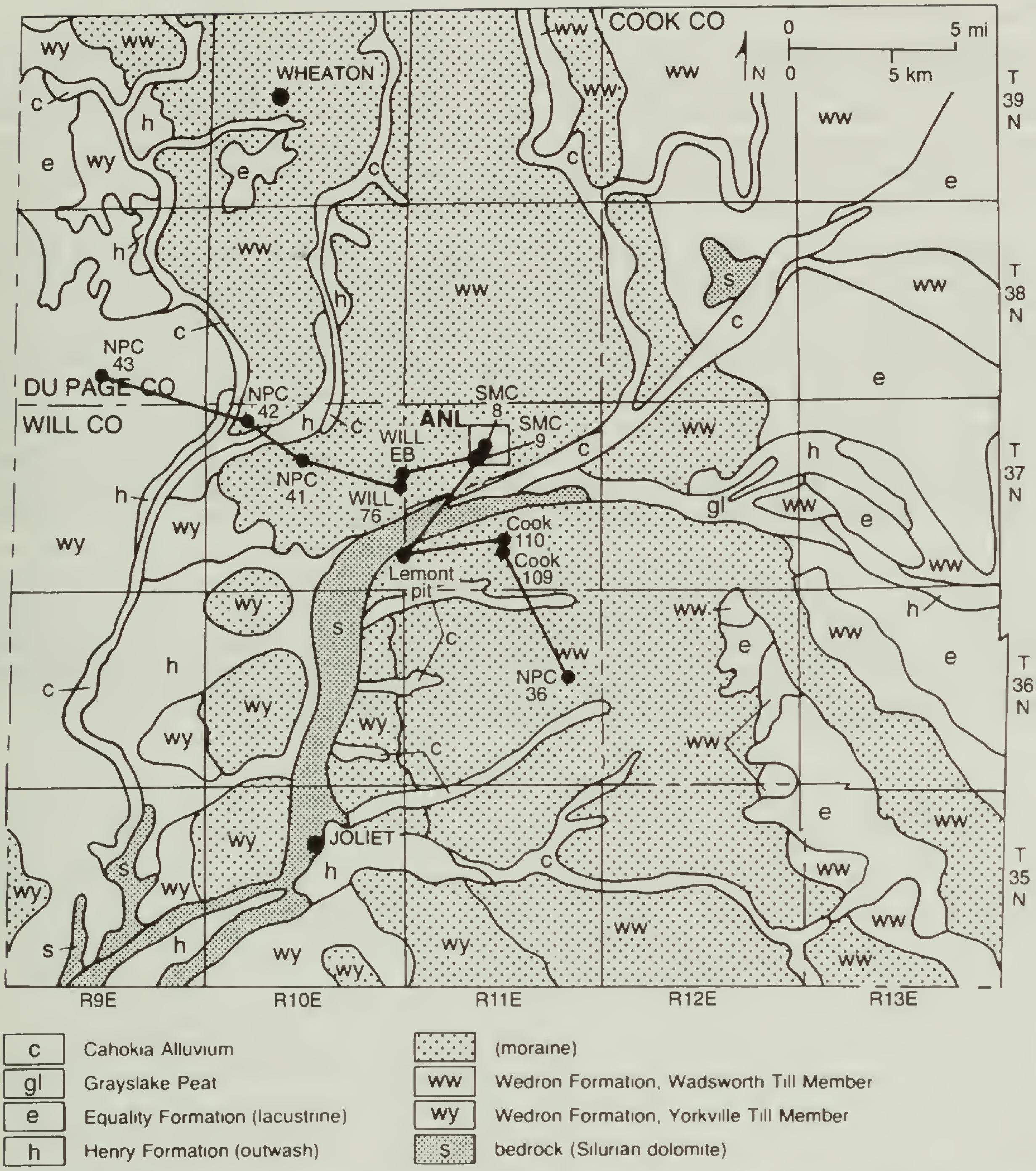


Figure 6 Surficial Quaternary deposits of the regional study area (after Lineback 1979). The line of the cross section depicted in figure 7 is shown.

Direct information on lithologies and engineering properties was obtained from our drilling and field-testing program.

Previous Drilling Programs at Argonne

We studied 44 drilling logs from three previous subsurface investigations (fig. 12, tables 1 and 2). Eleven of the test holes had been drilled into bedrock, and 13 reached total depths just above the bedrock surface. Reports from these drilling programs contained information on lithologies as well as results of field and laboratory engineering testing, including the standard penetration test, moisture content analyses, and unconfined compressive strength.

Field Data Collection

Surficial geophysical surveying Surficial geophysical surveying performed prior to drilling allowed for preliminary estimates of depth to the bedrock surface. The geophysical work also included evaluation of VES data to detect any potential lithologic variabilities that might affect the placement of exploration boreholes. Vertical electrical soundings and reversed seismic refraction profiles were run across the entire general site. The resistivity and compressional wave velocity data obtained from these surveys formed the basis for inferences about the nature of the near-surface deposits and the bedrock surface.

Vertical electrical soundings A direct current resistivity meter was used to make 92 vertical electrical soundings across the general site. Soundings were made using a Wenner electrode configuration with the a-spacing expanded in 10-foot increments, usually to a maximum of 170 feet. For each VES, a corresponding curve (apparent resistivity vs. a-spacing) was plotted, examined for qualitative information, and then inverted according to a procedure described by Zohdy and Bisdorf (1975). This inversion technique yielded a layering-parameters solution, that is, thicknesses and "true" resistivities of assumed horizontal layers below the center of the Wenner electrode configuration. (The expression "true" resistivity is used to indicate that this resistivity value was obtained through the inversion procedure.) An inversion procedure such as the one used in this study analytically provides only one layering-parameters solution. Care was taken to ensure that each solution was reasonable in light of the geology of the study area as understood at the time.

Data giving the coordinates of the center of the Wenner electrode configuration, the orientation of the configuration, the maximum a-spacing, and the layering-parameters solution for each VES are on open file at the ISGS. "True" resistivity cross sections based on VES data are composites of layering-parameters solutions of VES curves obtained from VES profiles located along these lines. Horizontal planar ("slice") sections of resistivities in the study area are also based on layering-parameters solutions of all the VES curves.

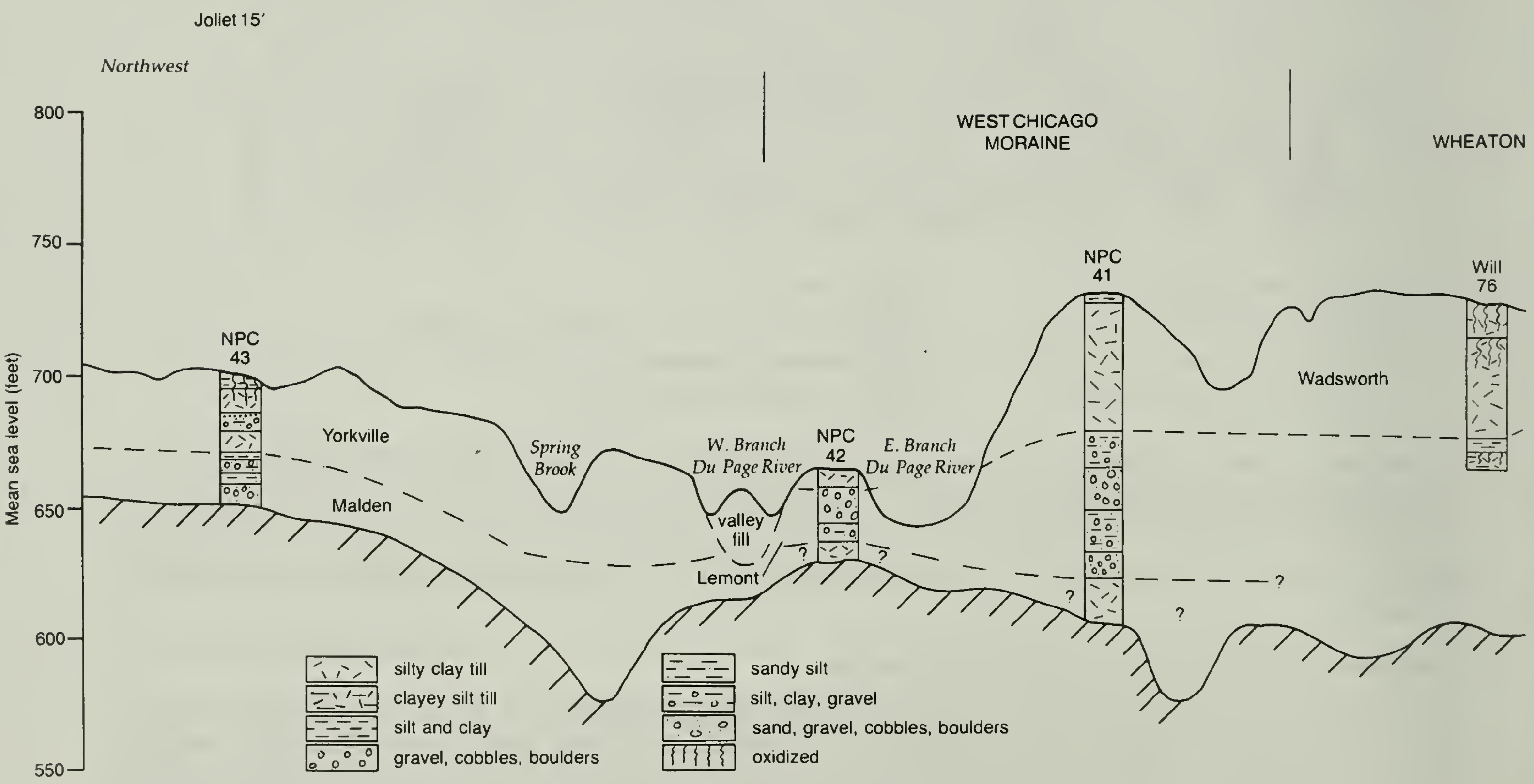
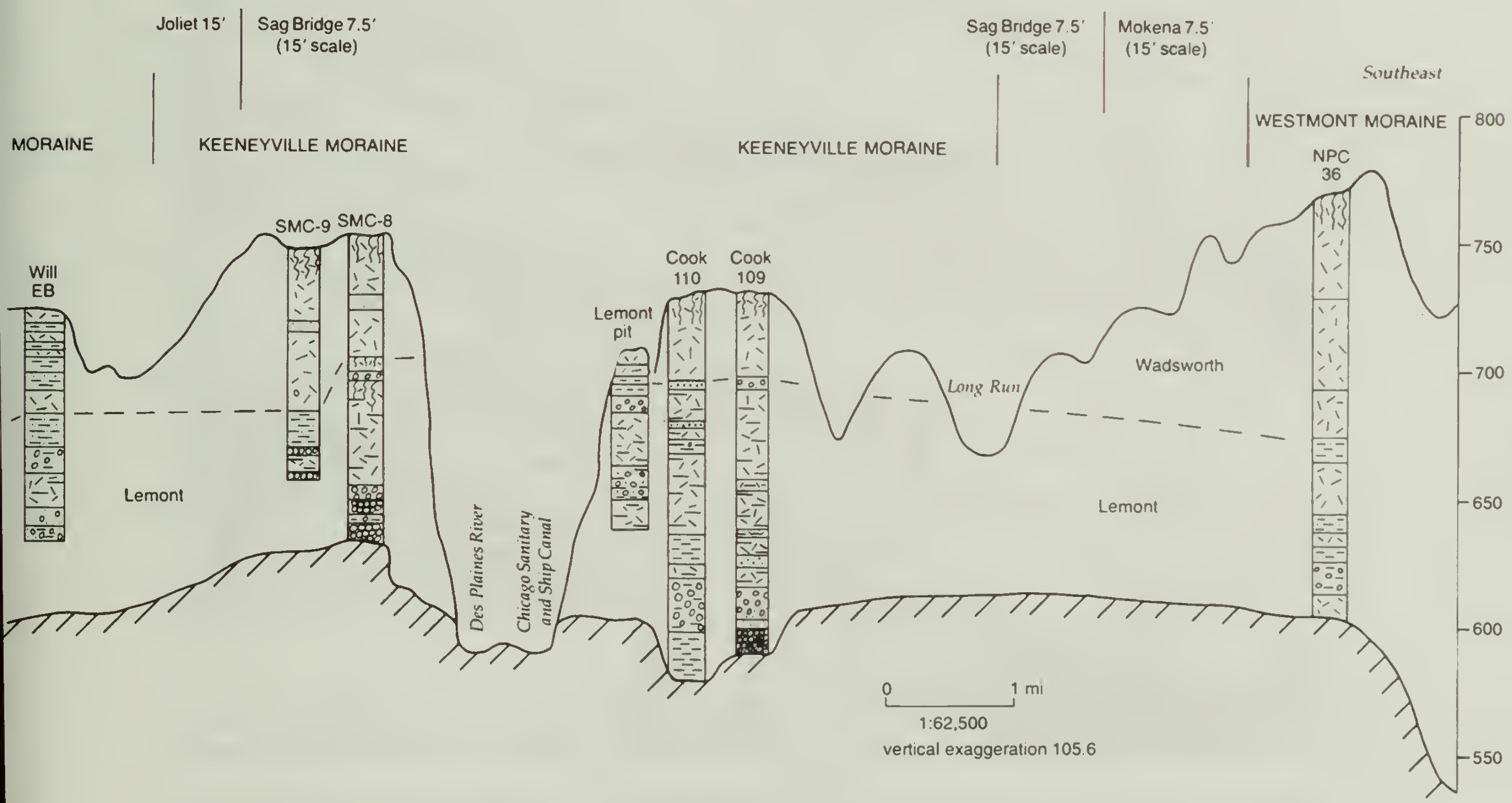


Figure 7 Northwest–southeast cross section of the regional study area (see fig. 6) illustrates the relationship of Lemont drift and Yorkville and Wadsworth Till Members of the Wedron Formation (modified from Killey et al. 1987).

Seismic refraction profiling Forty-six reversed seismic refraction profiles were run with a 12-channel seismograph in east–west or north–south directions across the study area. Profile lengths were usually 600 feet with 50-foot geophone spacings. The energy source was 1/3 pound of dynamite detonated in a hand-augered hole 4 feet deep. Field data are available on open file at the ISGS.

First-arrival time-distance plots were interpreted according to a procedure described by Heiland (1968). Interpretation of the first-arrival time-distance plots generally involved three layers: (1) a thin weathering layer at the earth's surface, (2) a layer of unlithified deposits, and (3) solid or fractured bedrock. The thin weathering layer, composed of loess, topsoil, and fill, was found to have a consistent velocity of approximately 1,250 ft/s. The unlithified deposits, usually composed of glacial till, sand, and gravel, had velocities ranging from 4,228 to 6,476 ft/s. The lower values correspond to loose, coarser grained deposits, whereas the higher velocities correspond to more rigid and argillaceous deposits. Bedrock surface velocities ranged from 11,351 to 19,826 ft/s. Because the bedrock surface in the study area is composed of Silurian carbonates (Willman et al. 1967), the lower values probably correspond to the fractured bedrock surface.

One difficulty encountered in the interpretation of the seismic refraction data was caused by lateral velocity variations within the glacial deposits and the upper part of bedrock. In these rare cases, the Heiland procedure was replaced with a more subjective ray-tracing procedure. Another difficulty concerning the interpretation of the seismic refraction data was the so-called hidden-layer problem, which occurs when a slow-velocity layer (e.g., basal gravel) of considerable thickness occurs between a compact till and solid bedrock (which both have higher velocities). The slow-velocity layer will not be apparent on the first-arrival time-distance plot. An error will occur in the calculated depth to bedrock, and the error will be directly proportional to the thickness of the neglected slow-velocity layer (Banerjee and Gupta 1975). Nevertheless, the seismic data were combined with the borehole data to give the most reasonable bedrock-surface map (see Results and Interpretations).



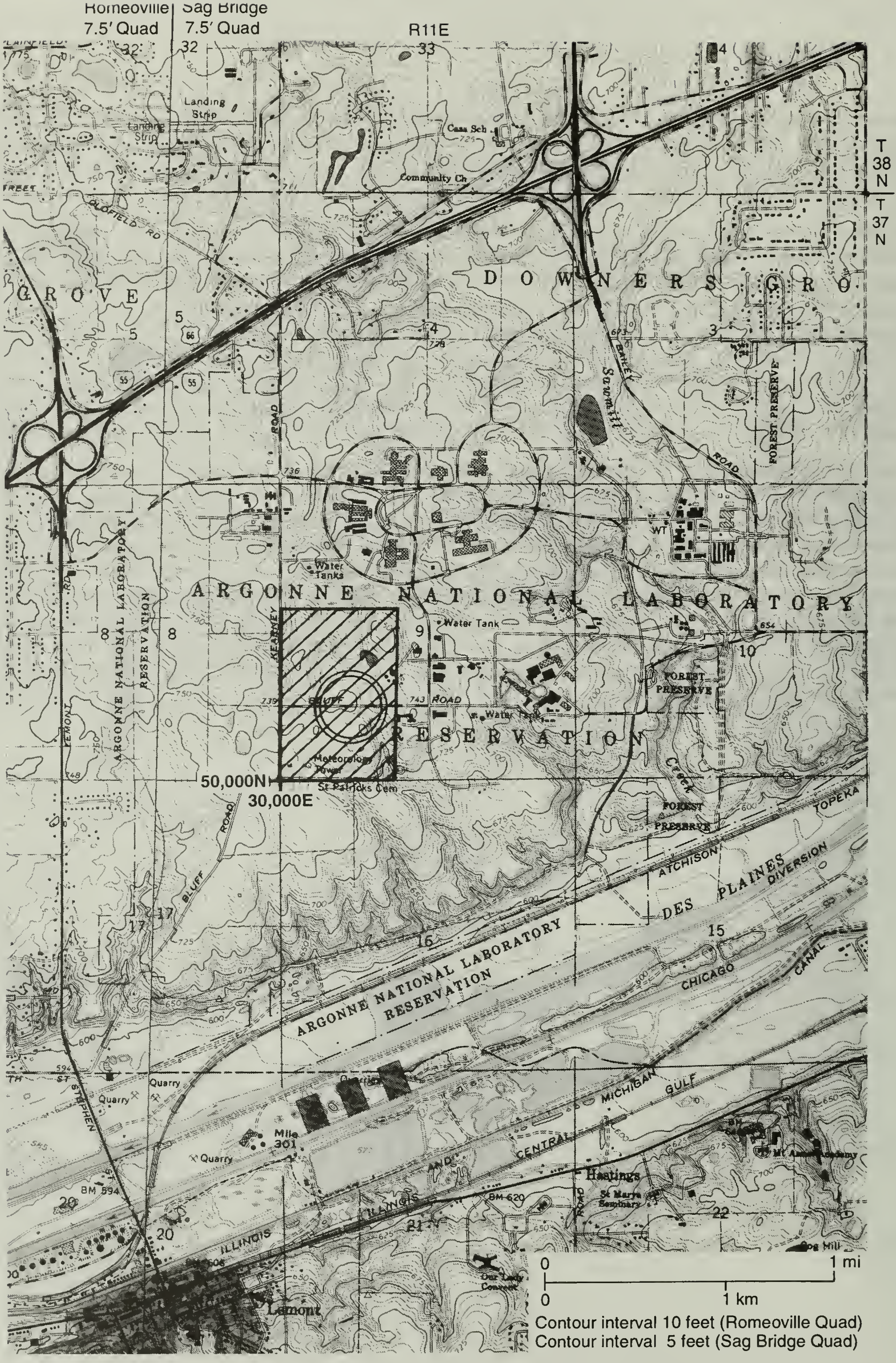


Figure 8 Topographic map of Argonne National Laboratory and the surrounding area. The hachured rectangle indicates the general APS site shown on subsequent maps; coordinates of the southwest corner of the site are marked and are coincident with the southwest corner of section 9, T37N, R11E. Subsequent figures use Argonne's coordinate base.

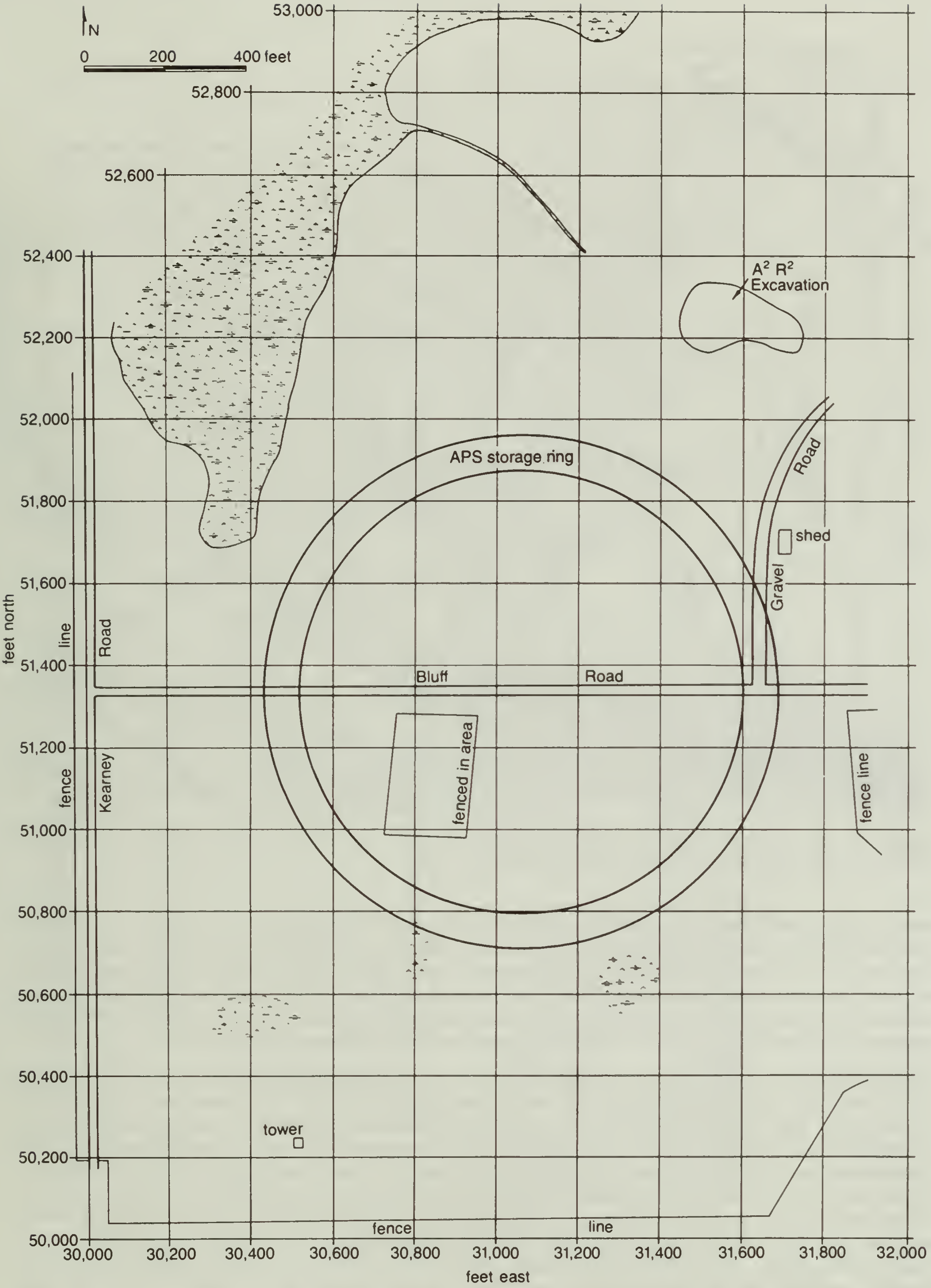


Figure 9 Map of the general APS site showing locations of the experiment hall/storage ring and selected other features as of 1989. Swamp symbols denote low areas that intermittently contained standing water during the first 6 months of this investigation. The coordinate grid is used as the basis for locating boreholes.

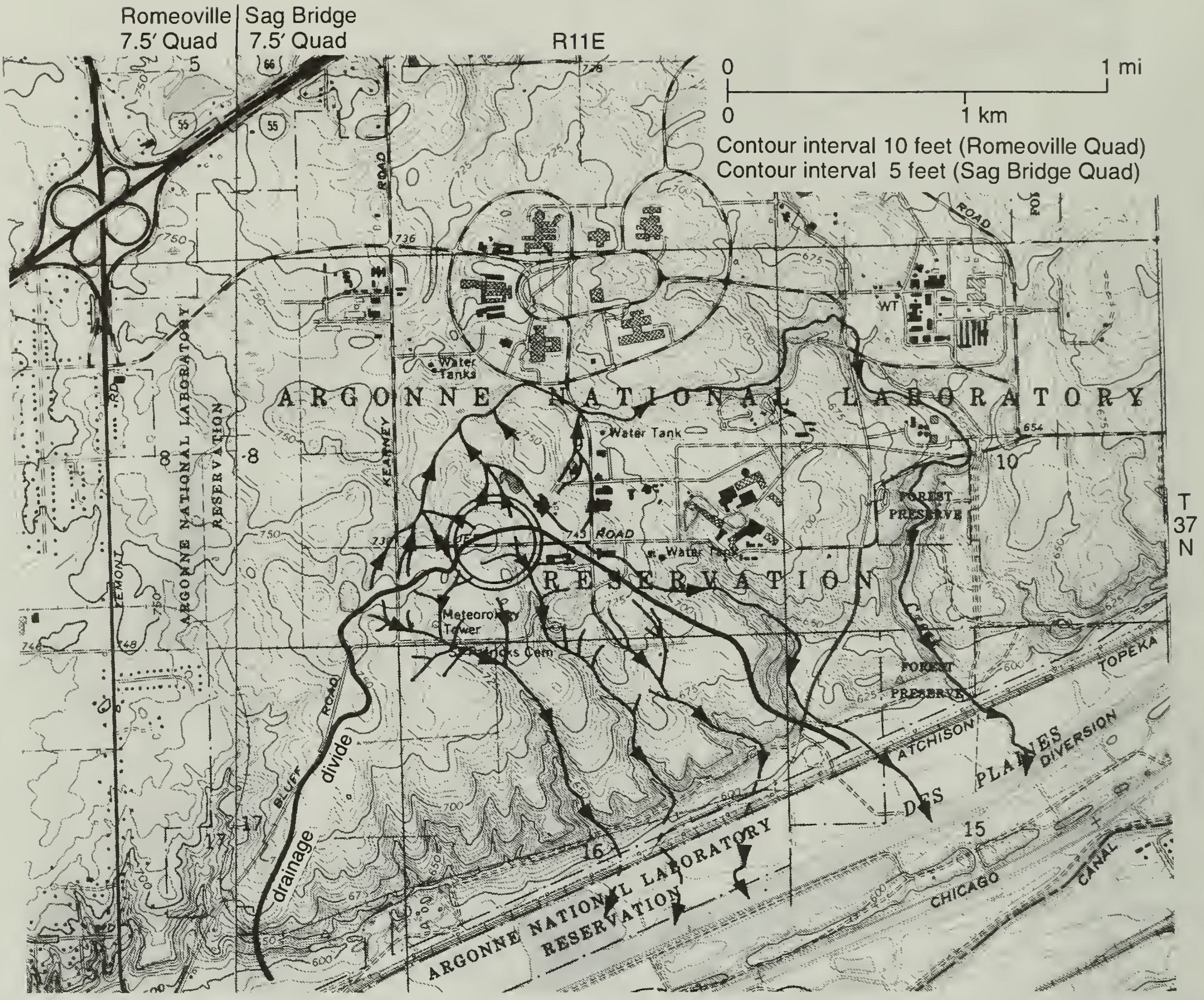


Figure 10 Topographic map of Argonne National Laboratory and the surrounding area showing lines of drainage north and south from drainage divide crossing the general APS site.

Field drilling and testing After the surficial geophysical surveying was completed, a detailed examination of the geology of the general APS site was carried out through drilling, sampling, and testing. This allowed for the identification and characterization of the geologic units on which the APS facility would lie, a process that added site predictability to engineering analyses performed at specific locations. Soil materials were described and samples submitted for laboratory analyses. In addition, piezometers were installed in the Wadsworth till, Lemont drift, and bedrock to characterize groundwater flow.

Drilling program A total of 28 boreholes (APS-1 through APS-28) was drilled on or near the footprint of the APS ring (fig. 12). APS-1 through APS-12 were drilled for the contractor's cross-hole seismic investigations. Four boreholes (APS-21 through APS-24) penetrated the entire drift sequence into bedrock for stratigraphic control. All others were shallow drift holes planned for near-surface exploration and for consolidation and compaction test sampling (consolidation tests were performed at STS laboratories; the results are discussed in STS Consultants 1988). Three of the bedrock holes (APS-21, 23, and 24) were located about 200 to more than 350 feet outside the ring site (fig. 12). The single bedrock borehole on the ring site (APS-22) is shown on cross section A–A′ (pl. 1). A 10-foot core of bedrock was obtained from each of APS-22, 23, and 24; a 7-foot core was obtained for APS-21. Intermittent samples (at variable intervals, see borehole logs in Killey and Trask 1989) of the drift were taken from four of the cross-hole seismic boreholes and from all remaining APS boreholes except for APS-25.

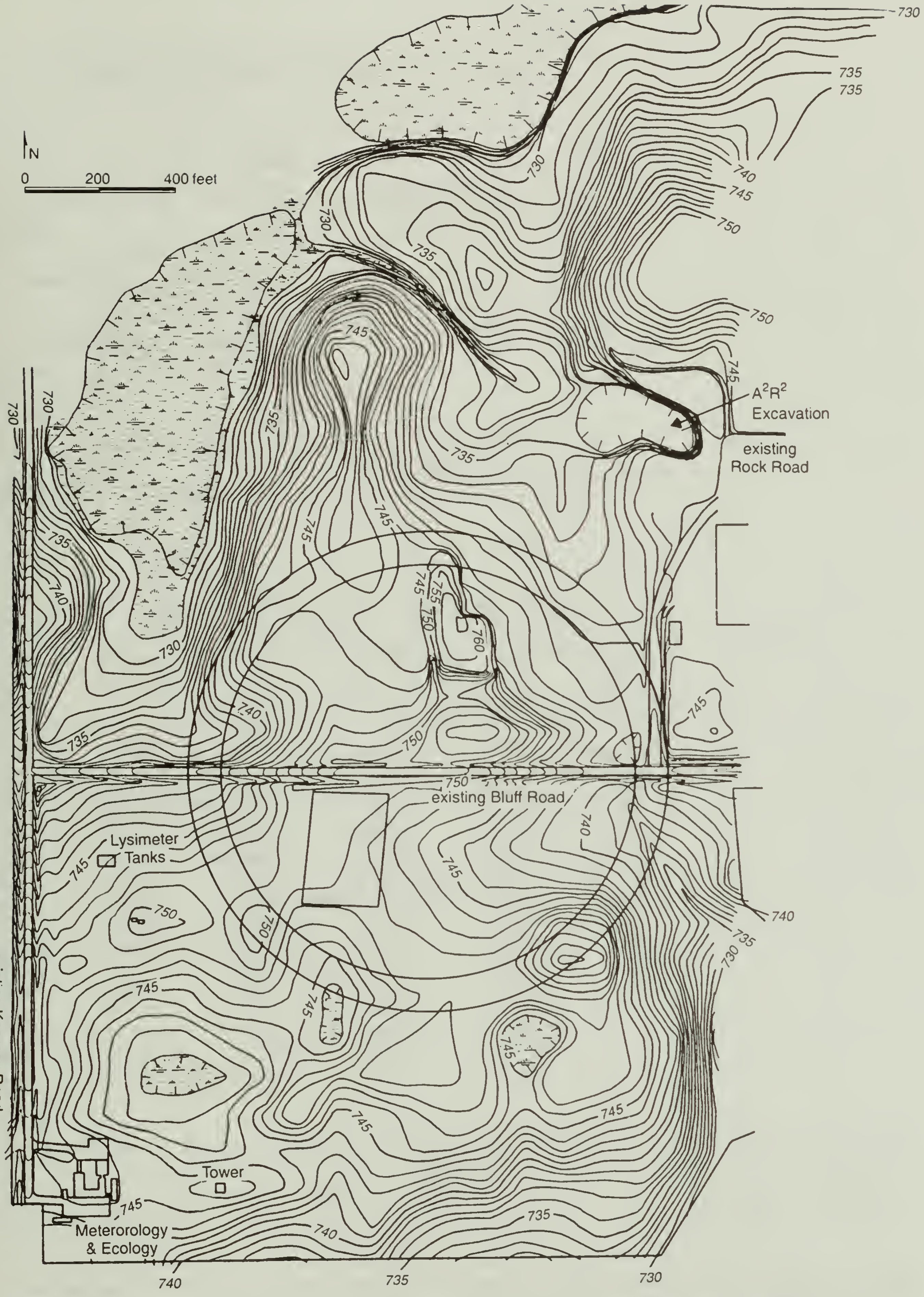


Figure 11 General APS site map showing the topography and original location of the APS storage ring. Map provided courtesy of Argonne.

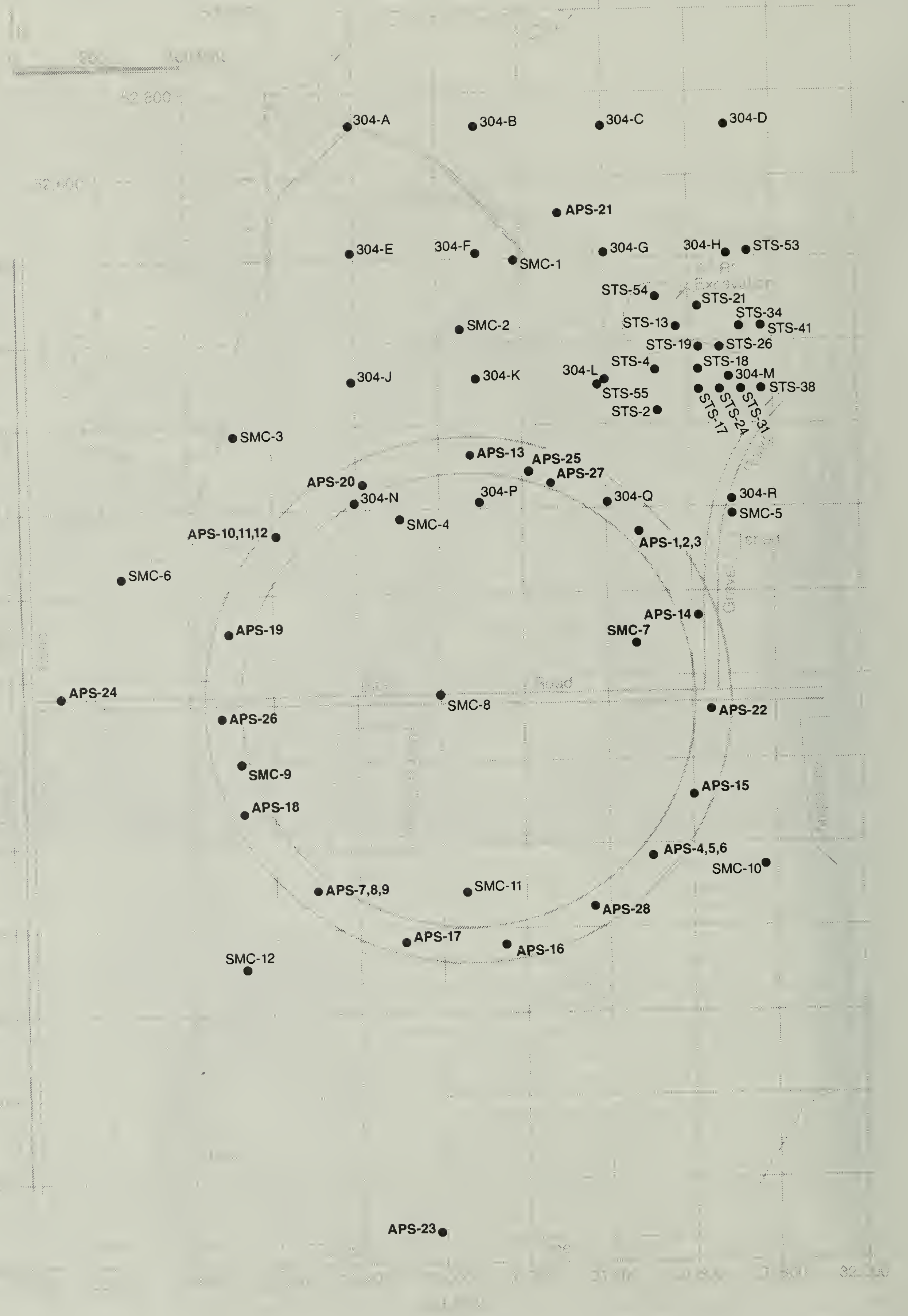


Figure 12 Location of all boreholes used to characterize the geology of the general APS site. Boreholes with APS prefixes were drilled specifically for this project.

Table 1 Database used for the ISGS investigation.

Previous subsurface investigations

Boring type	Number	Year	Location	Prefix
Soil	16	1948	Argonne site	304
Soil and rock	16	1966	A^2R^2 site	STS
Soil and rock	12	1986	APS site	SMC

1987-1988 APS subsurface investigations

Type	Number	Remarks
Soil borings	24	
Soil and rock borings	4	
VES stations	92	
Seismic refraction profiles	46	22 E-W, 22 N-S, 2 NW-SE
Downhole geophysical logs	18	11 APS holes, 7 SMC holes

Table 2 Boreholes studied from previous subsurface investigations (see table 1).

1948		1966		1986	
Borehole	Total depth (ft)	Borehole	Total depth (ft)	Borehole	Total depth (ft)
304-A	90.00	STS-2	82.0	SMC-1	55
304-B	97.25	STS-4	82.0	SMC-2	65
304-C	108.00	STS-13	139.1	SMC-3	162
304-D	100.75	STS-17	132.7	SMC-4	163
304-E	115.00	STS-18	132.3	SMC-5	145
304-F	88.50	STS-19	140.0	SMC-6	65
304-G	128.33	STS-21	143.5	SMC-7	65
304-H	133.33	STS-24	81.6	SMC-8	160
304-J	78.50	STS-26	63.0	SMC-9	90
304-K	93.25	STS-31	81.0	SMC-10	162
304-L	103.25	STS-34	81.5	SMC-11	65
304-M	87.25	STS-38	80.1	SMC-12	153
304-N	101.00	STS-41	80.1		
304-P	87.00	STS-53	81.6		
304-Q	100.75	STS-54	130.0		
304-R	96.75	STS-55	122.00		

Geophysical borehole logging Interpreted lithologies from downhole geophysical logging, which was carried out in 11 APS boreholes and 7 boreholes from the 1986 drilling, supplemented intermittent sampling from the drilling program. Because the intensity of gamma radiation is higher in more finely grained deposits, natural gamma ray logs were found to be useful for stratigraphic correlation, identification of lithology in fine grained sediments, and characterization of various attributes of earth materials across the general site. Most earth radiation in Illinois is generated by isotopes of potassium-40, uranium-238, and thorium-232. Because these elements are most common in clay minerals (found abundantly in diamictons and fine grained lacustrine sediments), the amount of natural gamma radiation is directly related to the amount of clay in the sample. This correlation between natural gamma radiation and amount of clay minerals has been observed in bottom sediments of the Mississippi River (Reed et al. 1983a), in the vadose (unsaturated) zone (Reed et al. 1983b), and in borings through unlithified glacial sediments (Reed 1985). Geophysical logging was accomplished using 1.75-inch-diameter sondes ranging from 4.0 to 9.35 feet in length. Fluid or air-filled boreholes cased with plastic or steel have little effect on levels of radiation required for meaningful log configurations. All of the APS boreholes were cased with steel; the 1986 boreholes were uncased and open from depths ranging from 26.7 to 59.5 feet. Natural gamma radiation was measured in API (American Petroleum Institute) units (Owen et al. 1974) and correlated with actual clay content determined from grain-size analyses. Linear correlation coefficients relating clay particle size (<4 µm) and natural gamma radiation of earth materials sampled with Shelby tubes and split spoons are given in table 3.

Table 3 Linear correlation coefficients between natural gamma radiation and amount of clay.

APS hole no.	Coefficients	No. of analyses
21	0.92	7
22	0.82	12
23	0.91	8
24	0.85	9

Laboratory Testing

Grain size and clay mineral composition Grain size of the glacial drift samples was determined using ASTM standard methods for hydrometer, sieve, and pipette analyses at the ISGS Geotechnical Laboratory. X-ray diffraction analyses were made by the oriented-aggregate methods described in Hughes and Warren (1989).

Engineering properties Testing of unconfined compressive strength of bedrock was planned but, because of the highly fractured and broken nature of the bedrock cores, no section of unbroken core was long enough to test for unconfined strength. Tests run on glacial drift samples included Atterberg limits, specific gravity, compaction, and moisture content; ASTM standard methods were used for all tests. Samples from boreholes at sites likely to be used for borrow were of particular interest. Compaction tests were run to determine the optimum moisture–density relationship for materials potentially available for borrow. Data on all the above testing are available on open file at the ISGS.

RESULTS AND INTERPRETATIONS

Geological materials across the general site were correlated on the basis of APS drilling and sampling, as illustrated in a cross section (pl. 1). This cross section illustrates the relationships of the geologic units discussed in this section.

Bedrock

Because the APS is to be constructed as a surface facility, the storage ring will lie at least 120 feet above bedrock. The main reasons for investigating the elevation and attitude of the bedrock surface related to reflection and focusing of vibrations as well as to groundwater considerations.

The bedrock surface was eroded before and during glaciation. The dolomite-rich composition of the Lemont drift overlying the bedrock supports the supposition of glacial entrainment of local bedrock. Because the bedrock surface is buried, its character and configuration must be estimated from the various sets of subsurface data.

Regional mapping by Horberg (1950), Suter et al. (1959), and Zeizel et al. (1962) indicates that a well developed drainage pattern exists on the bedrock surface. The bedrock valleys are oriented in a general southwest–northeast configuration east of the site and northeast–southwest pattern to the west of it. The APS site is situated on the east edge of a bedrock divide that trends north–south and has elevations ranging from slightly more than to slightly less than 600 feet. Late glacial meltwater erosion that formed the Des Plaines River Valley cut down to bedrock along the valley, locally exposing bedrock south of the APS site (fig. 4) (Bretz 1951, Hansel 1986, Hansel and Johnson 1986).

Lithologic characteristics Cores retrieved from APS-21, 22, 23, and 24 consisted of highly fractured, light gray, cherty dolomite characterized by fine vuggy, sucrosic texture as well as some clay partings and fossiliferous zones. Dolomite from APS-23, however, was noticeably iron-stained to a distinct yellow that faded downward to the more typical light gray.

On the basis of our examination of core retrieved from APS-21, 22, 23, and 24 and of core available from 1986 drilling, we concluded that the bedrock surface is generally unoxidized. It is, however, regionally fractured to depths of up to several tens of feet (Soil and Material Consultants 1986, Graese et al. 1988, Bauer et al. 1991) and may have undergone dissolution. Above this surface are larger bedrock slabs broken along bedding planes or exfoliation joints, overlain by a zone of cobbles and pebbles of bedrock. This debris is contained in a matrix of silt. Iron-stained bedrock occurs in places where dissolution was unable to remove all oxidized material.

Bedrock surface It was important to know whether there were any paleovalleys in the bedrock because they would probably be areas where unlithified glacial sediments are thick and older units are present. These thick deposits could enhance seismic waves emerging from the bedrock. Because of discrepancies between the bedrock surface elevations indicated by the seismic refraction and borehole data, we discuss and compare the results of these data separately.

Borehole data Elevation of the top of bedrock, as determined from borehole data (fig. 13), shows a bedrock surface that is highest (646 ft) near the Des Plaines River Valley to the south and decreases in elevation to the north, east, and west. The lowest elevations occur at the north edge of the general APS site. From the borehole data, we estimated a minimum relief on the bedrock surface of 43 feet.

Seismic refraction data Elevation of the top of bedrock, as determined by seismic refraction, ranges from 565 to 670 feet msl, a relief of 105 feet. The seismic map (fig. 14) shows a series of topographic highs and lows trending predominantly northeast–southwest and, to a lesser degree, northwest–southeast. Isolated hills and closed lows are also evident. This character of the bedrock surface is similar to that determined by Horberg (1950), Suter et al. (1959), and Zeizel et al. (1962) for a preglacial drainage system that shaped the bedrock surface. These trends parallel joints in the region as mapped by Foote (1982), Graese et al. (1988), and Bauer et al. (1991).

Comparison of borehole and seismic data Seismic refraction data give a measure of depth to the interface that marks a change from the lower velocities characteristic of glacial drift to the higher velocities characteristic of dolomite bedrock. This interface may be the top of unfractured bedrock below a fractured zone, the erosional bedrock surface, the top of dolomite debris on the erosional surface, or any combination of these. Comparison of the two maps shows that the elevations obtained from the seismic data are generally lower than those from the borehole data. This comparison of the two maps also shows parallels and similarities; for example, trends and locations of bedrock highs and lows are shown in approximately the same locations on both maps. Because the borehole data give actual values of elevation of the bedrock surface and the seismic data give a more detailed picture of the character of the surface, the two types of data can be integrated into one map (fig. 15). The borehole data were used for reference elevations and the seismic data to show the overall appearance of the bedrock surface.

We used all available data from the exploration program to determine the attitude and nature of the bedrock surface. We interpreted the surface to be gently undulating, with isolated depressions and minor troughs and ridges oriented east–west to northeast–southwest. Bedrock is higher to the south (consistent with the regional analysis, see fig. 4), reaching elevations of more than 640 feet. Elevation of the bedrock surface decreases to less than 580 feet in the north in lows that trend east–west to northeast–southwest in the central and northern parts of the general site. We detected no major bedrock paleovalleys that might focus vibrations on the APS facility.

Glacial Drift

As a surface facility, the APS will lie entirely upon the Wadsworth Till Member of the Wedron Formation. The underlying Lemont drift was of secondary interest to this study, except for estimating its depth in the event caissons were used. Secondarily, it was of interest to ascertain whether the lithologic characteristics of the unit on site differed substantially from those described elsewhere in the region and, if so, what would be the implications of such differences for the construction and operation of the APS.

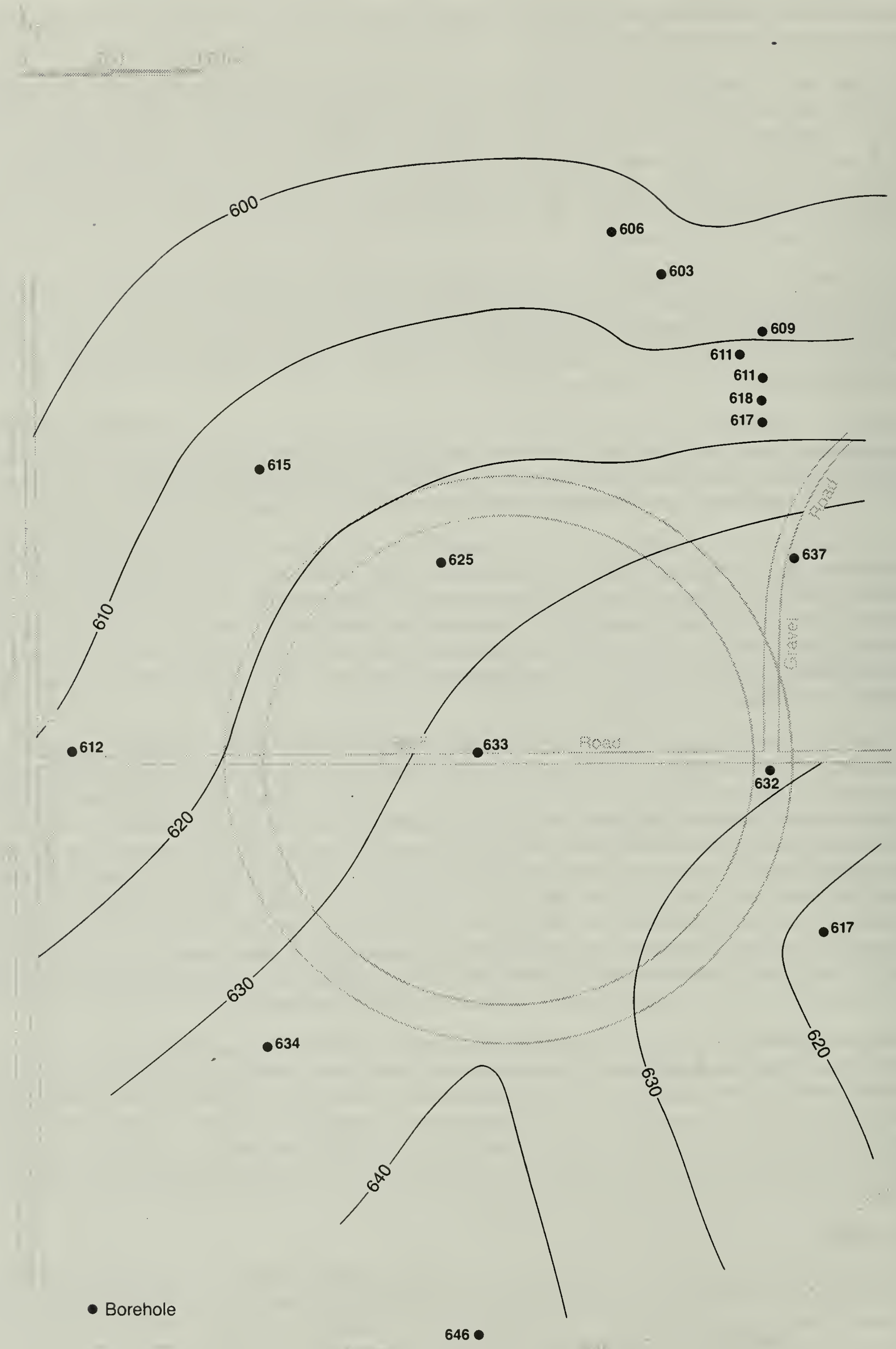


Figure 13 Elevation of the bedrock surface, as determined from borehole data.

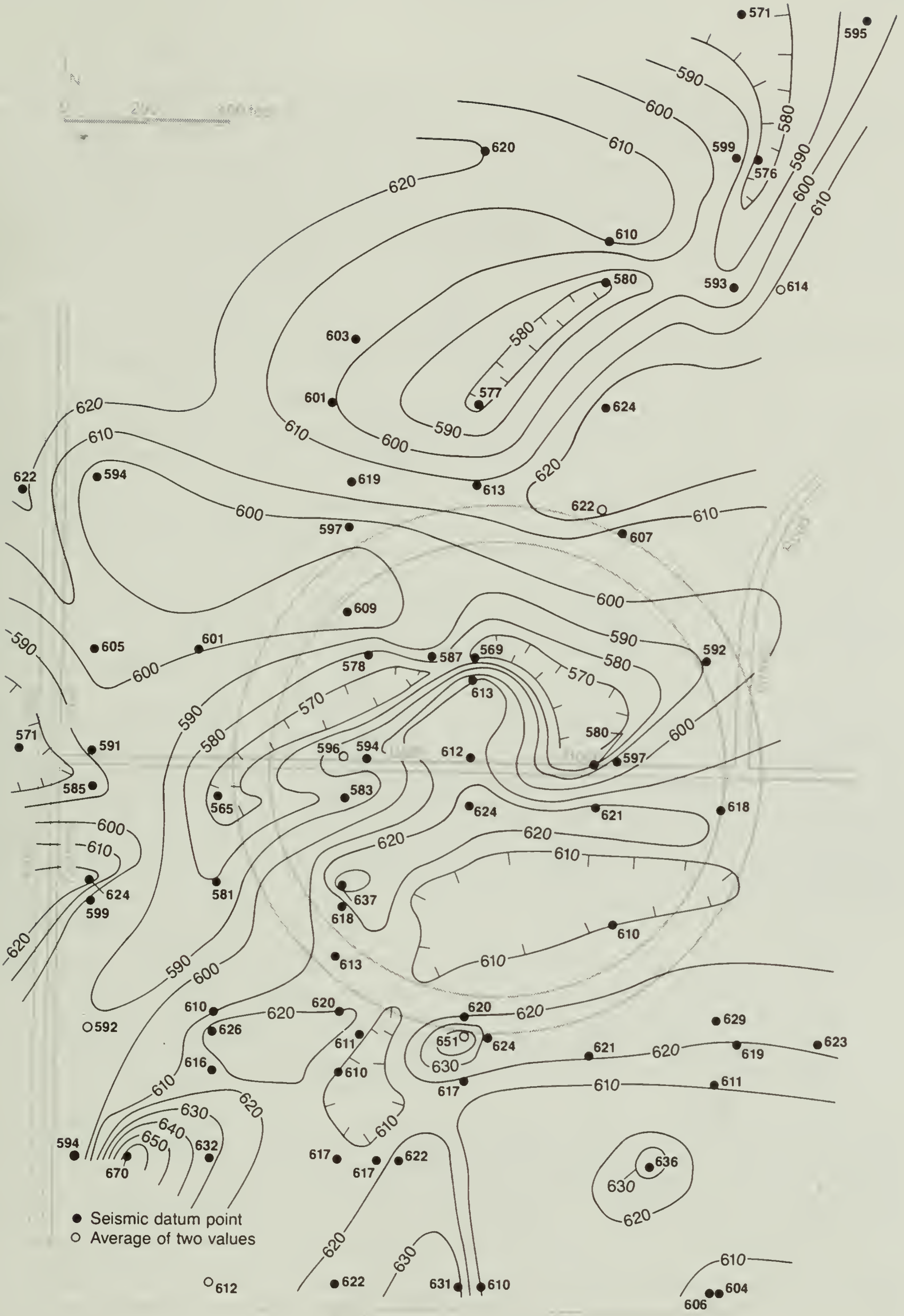


Figure 14 Elevation of the bedrock surface, as determined from seismic refraction data. Data points are locations of shot points.

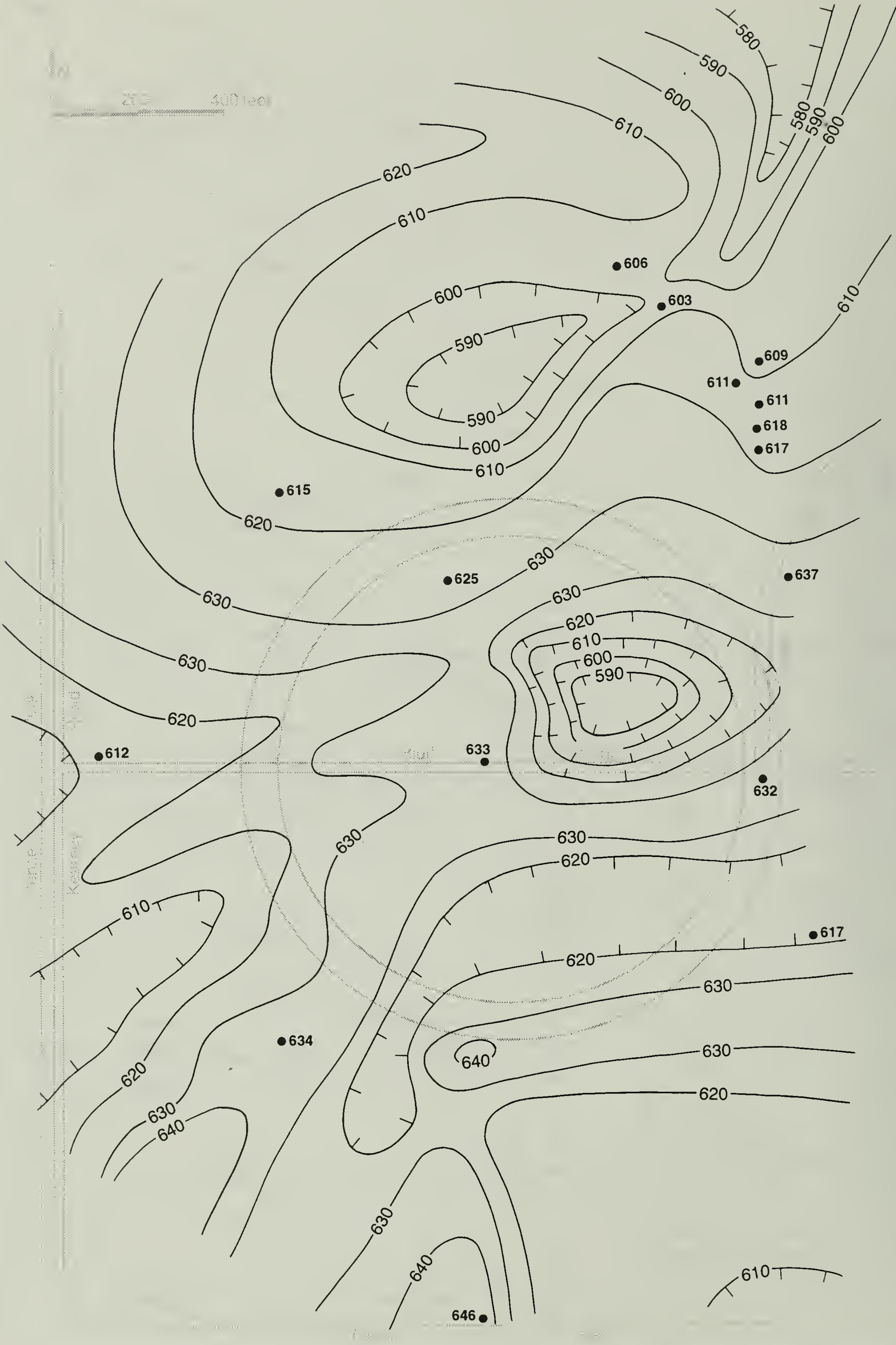


Figure 15 Bedrock topography, determined using borehole data for reference elevations and seismic data for overall appearance and interpretation.

Lemont drift Thickness of Lemont sediments ranges from about 35 to 75 feet (average 58 ft). The top of the Lemont was estimated by using both the drilling and sampling on site and the information available from the 1986 and 1966 drilling on the general site. In many cases, the estimates of the top of the Lemont were determined using limited information. These estimates were made on the basis of combinations of lithologic descriptions and engineering data and were generally confirmed with the APS drilling. The top of the Lemont drift across the general APS site ranges from approximately 662 to 709 feet in elevation (fig. 16). The top of the Lemont is highest north of the ring; it is also high in the center of the ring and decreases in elevation radially away from the middle. The elevation of the top of the Lemont around the ring site, as inferred from figure 16, is shown on plate 1.

Data on the northeast side of the storage ring indicate a more complicated upper surface of the Lemont drift. Relief shown on figure 16 was estimated using a larger number of data points in this area than elsewhere on site, and the elevation of the top of Lemont may be as variable in other areas.

Lithologic character APS borings in the Lemont were sampled at 5-foot intervals; therefore, description of continuous sediment sequences was not possible. Available information indicated, however, that the dominant on-site Lemont lithology is pebbly dolomitic diamicton having matrix textures of silty clay loam, silt loam, and loam. Sixteen samples of Lemont diamicton from the APS borings (ASTM standard D 422) averaged 16% sand, 64% silt, and 20% clay, compared with the average of 16% sand, 45% silt, and 39% clay in the Wadsworth Till Member (fig. 17, table 4). This indicates that the Lemont diamictons on site are characterized by considerably more silt and less clay than the overlying Wadsworth. These matrix textures compare with an average of 27% sand, 50% silt, and 23% clay reported for Lemont diamictons by Johnson and Hansel (1989). The Lemont also contains numerous beds of silt, sand, and dolomite-rich gravel. Coarser zones are generally oxidized olive to olive brown and brown. Although siltier, softer zones within the Lemont sediments could be sampled by Shelby tube, most of the lithologies required split-spoon sampling with high blow counts.

Locally across the general site, as well as on regional cross sections such as that shown in figure 7, there appears to be little lateral or vertical consistency in the lithologic sequence of Lemont sediments. Numerous beds of clayey silt to silty clay and silt diamictons are interspersed with beds of silt and sand, silt and gravel, silt, and clayey silt, as interpreted from the 1966 borehole logs made for the A^2R^2 site, the 1986 borehole logs, and our field descriptions of APS-21 through APS-24. Sediments in the basal Lemont appear to be highly variable. They range from very coarse materials (boulders, gravel, and broken rock), composed chiefly of dolomite, to silt and fine sand. The sediments at the top of the Lemont drift are mostly fine grained silty diamictons, silt, clay, and sand. Coarser grained sediments, including gravel and boulders, are found at the top of the Lemont in two boreholes on site, but these layers are relatively thin and overlie clayey silt diamicton or sandy silt.

These on-site lithologies generally support the regional observations of Johnson and Hansel (1989):

> The Lemont commonly contains a thick coarsening-upward sand and gravel sequence at or near the base, an overlying diamicton complex with interbedded sorted sediment that varies vertically and laterally, and a relatively thin sequence of sorted and stratified sediment at the top. . . Locally, diamicton and/or fine-grained sorted sediment occurs as the basal unit above bedrock.

Vertical electrical soundings Maps of vertical electrical soundings at certain elevations (horizontal planar maps) were constructed early in the study as a check on the distribution of coarse grained versus fine grained lithologies across the site and between boreholes at selected elevations. The 640-foot elevation was chosen because we estimated this to be at or near the bedrock surface; the 680-foot elevation was chosen as an approximation of the top of the Lemont drift. The 640-foot elevation is discussed here because this elevation is mostly above the bedrock surface (as shown in figs. 13, 14, and 15).

The 640-foot resistivity map (fig. 18) is dominated by "true" resistivity values greater than 200 ohm-feet (an arbitrary value separating fine from coarse grained deposits); four small areas, on a north–south trend through the center of the study area, have values in excess of 600 ohm-feet, values comparable to those expected from carbonate bedrock. Maximum resistivity of more than 900 ohm-feet occurs approximately

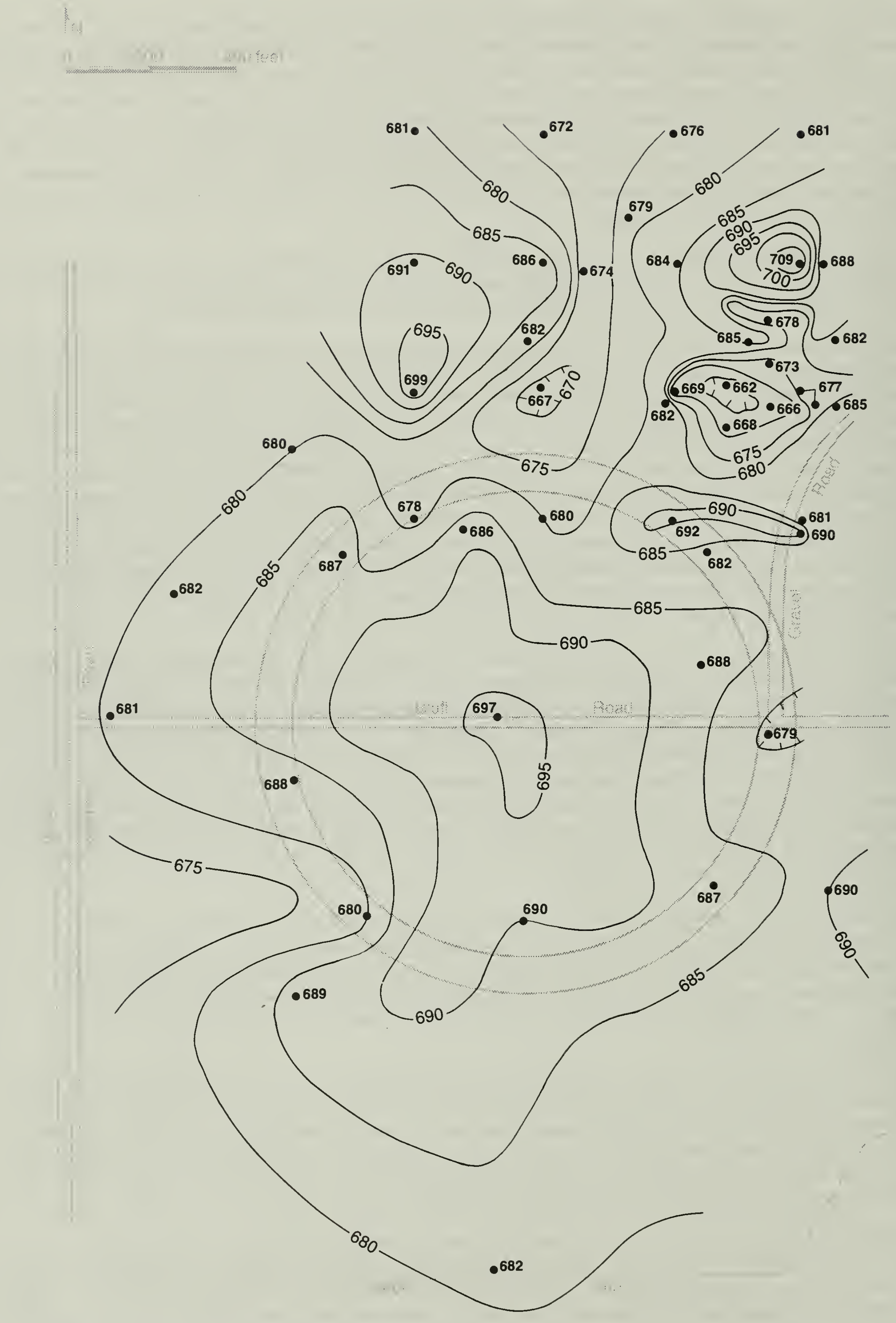


Figure 16 Estimated elevation (msl) of the top of Lemont drift.

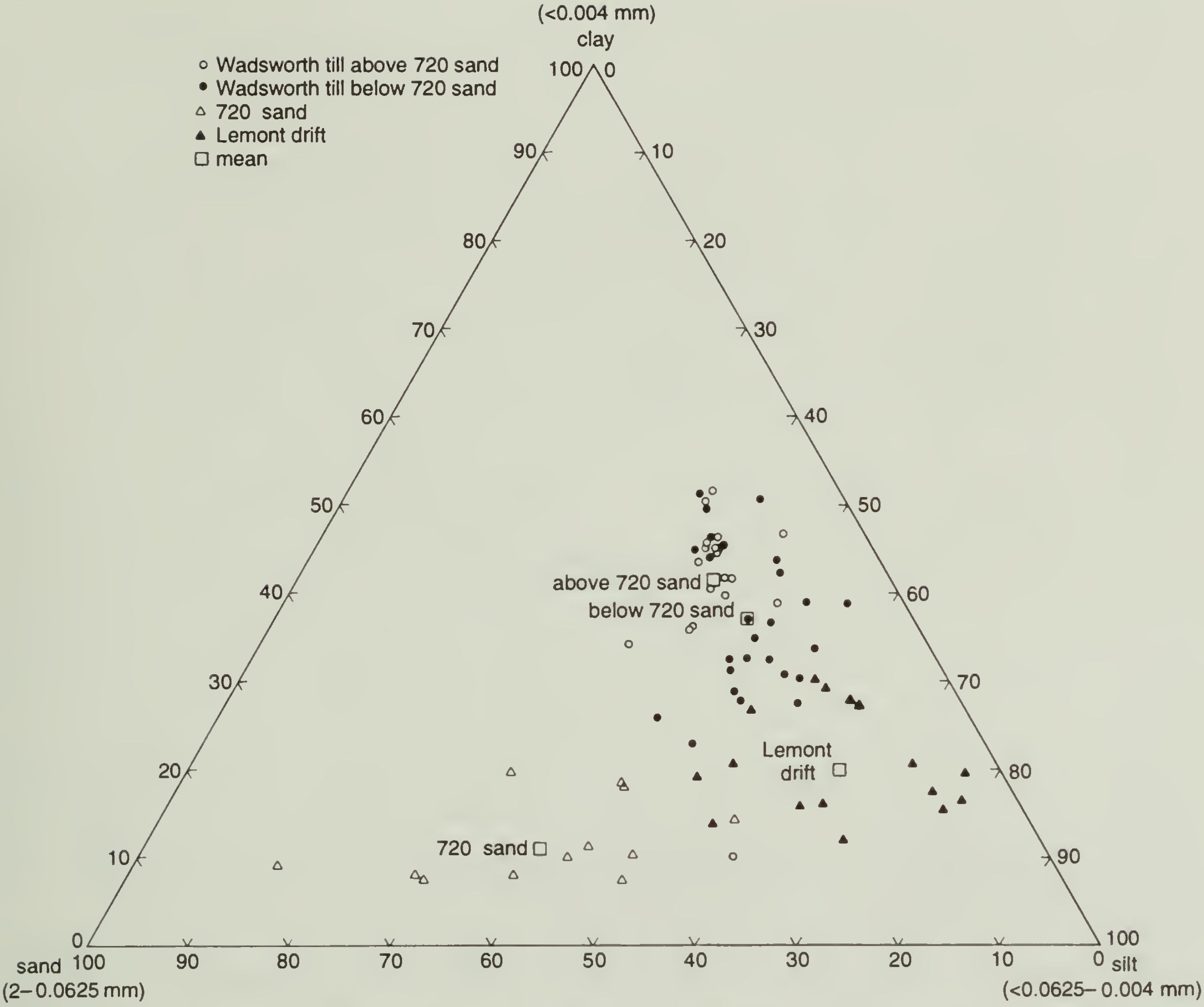


Figure 17 Ternary diagram illustrating grain-size distribution of the fine grained (<2 mm) matrix of the 720 sand, the Wadsworth till above and below the 720 sand, and diamicton in the Lemont drift.

300 feet east of the center of the proposed ring. An addition to the "640 slice map" of 640-foot contours from the bedrock elevation map (fig. 15) shows that the bedrock surface appears to intersect the 640-foot elevation in only three areas south and southwest of the ring (where the bedrock is high). The high resistivity values found elsewhere at this elevation must, therefore, reflect coarse grained material in the basal Lemont.

Table 4 Summary of grain-size data for matrix of diamictons in 16 Lemont drift samples.

	sand	silt	clay
Mean %	16	64	20
Minimum %	4	51	12
Maximum %	32	78	30
Standard deviation	8.8	9.3	5.8

In the 680-foot horizontal planar map (fig. 19), there are four small areas with values in excess of 400 ohm-feet, which is indicative of very coarse grained deposits. Maximum "true" resistivity values of more than 600 ohm-feet occur near the center of the proposed ring. An addition to the "680 slice map" of 680-foot contours from the map showing the top of the Lemont (fig. 16) is somewhat difficult to interpret because of the lithologic and areal variability of Lemont sediments. The maximum value corresponds, however, with the highest elevation of the upper Lemont surface.

Figure 18 "True" resistivity map for an elevation of 640 feet msl. Contour interval is 100 ohm-feet. Hachured contours show the location of the top of the bedrock (see fig. 15) at this elevation.

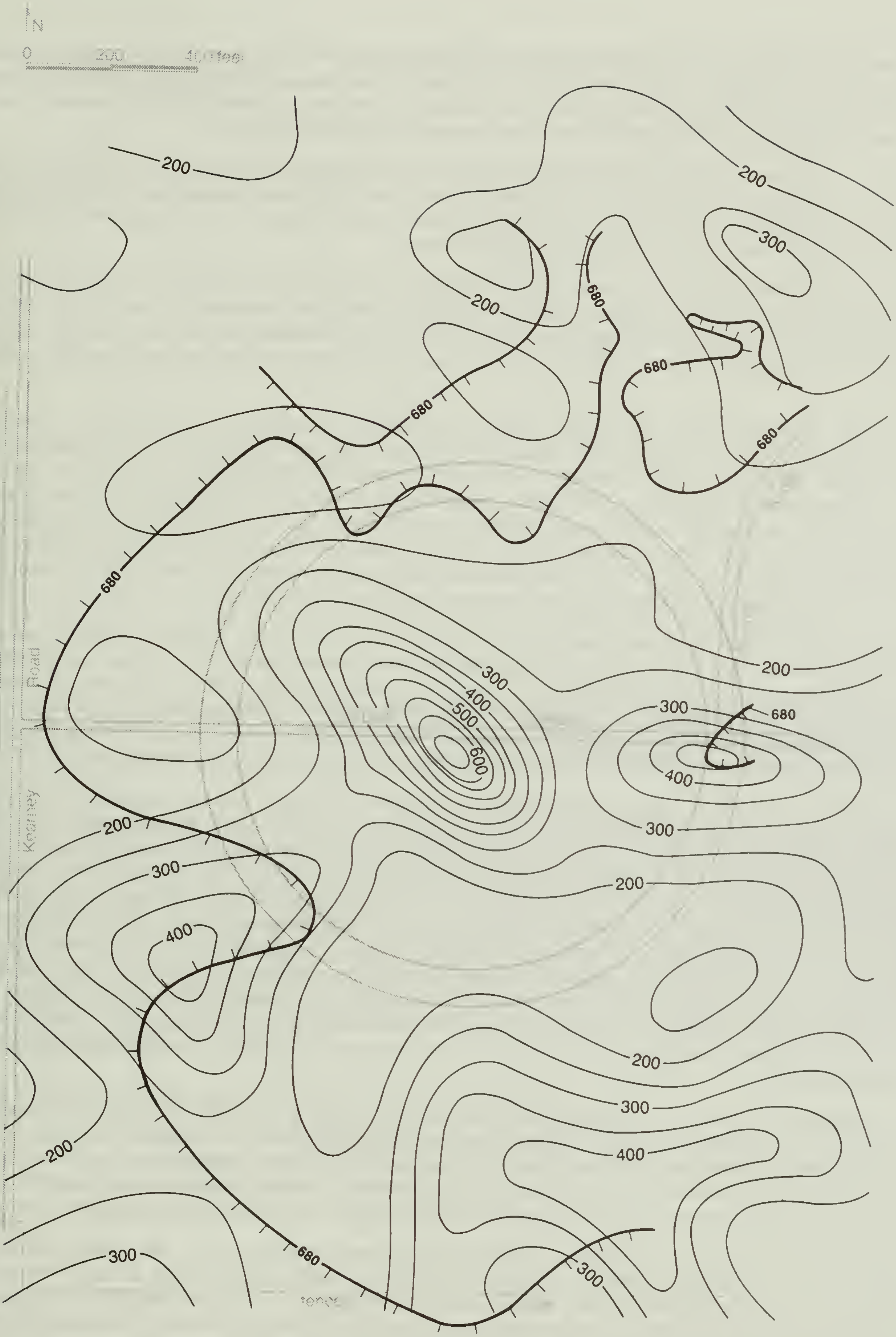


Figure 19 "True" resistivity map for an elevation of 680 feet msl. Contour interval is 50 ohm-feet. Hachured contours show the location of the top of the Lemont drift at this elevation.

Engineering properties Five Atterberg-limits tests (ASTM standard D 4318) were run on Lemont diamicton samples taken at depths ranging from 62.5 to 81.5 feet. These deeper samples were more commonly classified as low plasticity clay-silt (CL-ML in Unified Soil Classification System, ASTM standard D 2487) than were the shallow (<10 ft) samples from the Wadsworth Till Member (fig. 20).

Summary The Lemont drift is a lithologically variable unit, dominated by silty diamictons, especially in the upper part. It is interspersed with beds of silt, sand, gravel, and clay. Basal Lemont sediments range from very coarse materials to silt and fine sand. The top of the Lemont averages approximately 682 feet msl in elevation. Lemont diamictons test in the low plasticity range.

Wadsworth Till Member The Wadsworth Till Member is the uppermost glacial till across the entire area and was the main unit of interest in this investigation, both as the foundation for the APS facility and as a source of borrow for fill. The Wadsworth ranges from approximately 50 feet to as much as 80 feet thick and averages about 60 feet thick. It contains lenses of sand, silt, and clay, as well as minor oxidized zones.

Grain size Compared with the Lemont drift, the Wadsworth is uniform across the site, consisting primarily of silty clay, clay loam, and silty clay loam diamicton. Laboratory analyses of 46 samples resulted in an average for the fine grained matrix (<2 mm) of 17% sand, 44% silt, and 39% clay (fig. 17, table 5). This compares with an average of 14% sand, 45% silt, and 41% clay reported by Johnson and Hansel (1989) and with an average of 13% sand, 38% silt, and 49% clay reported by Willman and Frye (1970) for drift associated with the Keeneyville Moraine in Du Page County. Pebble content, as estimated from field descriptions, ranges from 1% to 7%; higher concentrations were observed in zones scattered throughout the till. Most of the pebbles are composed of dolomite and shale, but dolomite predominates.

One of the sands in the Wadsworth diamicton (referred to as the 720 sand, discussed below) appears to be fairly continuous and to subdivide the Wadsworth into two units as indicated by a small but consistent textural difference in the grain size data (fig. 17, table 5). Overall, the lower unit of the Wadsworth is siltier and less clayey than the upper; the fine grained matrix of the upper till averages 18% sand, 41% silt, and 41% clay, whereas that below averages 16% sand, 47% silt, and 37% clay. Using a t-test comparison of the mean silt content, we can be 99% certain that the means come from two different populations.

Clay mineral composition The <2 µm fraction of samples from every interval recovered in the four boreholes drilled to bedrock (APS-21, 22, 23, and 24) was analyzed using X-ray diffraction methods (Hughes and Warren 1989). The analysis was for expandable clay minerals, illite, kaolinite plus chlorite, and relative abundances of calcite and dolomite; the data are on open file at the ISGS. The unaltered Wadsworth diamicton can generally be subdivided into two compositional units: an upper unit averaging about 76% illite and a lower unit averaging approximately 71% illite (Killey and Trask 1989). The upper unit ranges from 5 feet (APS-22) to 17 feet thick (APS-23); some of it exhibits a color change from gray to brown, which we interpreted to be a result of weathering. These compositional zones, as observed in all four bedrock holes, provided another line of evidence supporting the stratigraphic continuity of units; they also help to identify alteration of these units across the entire general site. The boundary between these zones, however, does not generally correspond with the textural subdivisions of the Wadsworth diamicton as discussed above.

The generally low amounts of expandable clay minerals, ranging from 3% to 7% in the unaltered Wadsworth till, indicate that there is little shrink-swell problem with the material. Low shrink-swell characteristics are desirable for fill materials. The Wadsworth till, however, generally ranges from 20% to more than 50% clay, and it was overconsolidated by overriding glaciers. Slight expansion was observed when samples were extruded; therefore, when confining pressure is removed, slight expansion may occur.

Altered till Till altered by weathering and soil-forming processes occurs in the upper part of the Wadsworth in all boreholes. Alteration generally ranges from 8 feet to approximately 23 feet in depth; the primary indicators of alteration to these depths is color (from gray to brown) and leaching of carbonates. X-ray diffraction data also indicate alteration by loss of chlorite in the upper samples. Pocket-penetrometer readings indicate that bearing strength of in-place till does not appear to be affected by alteration.

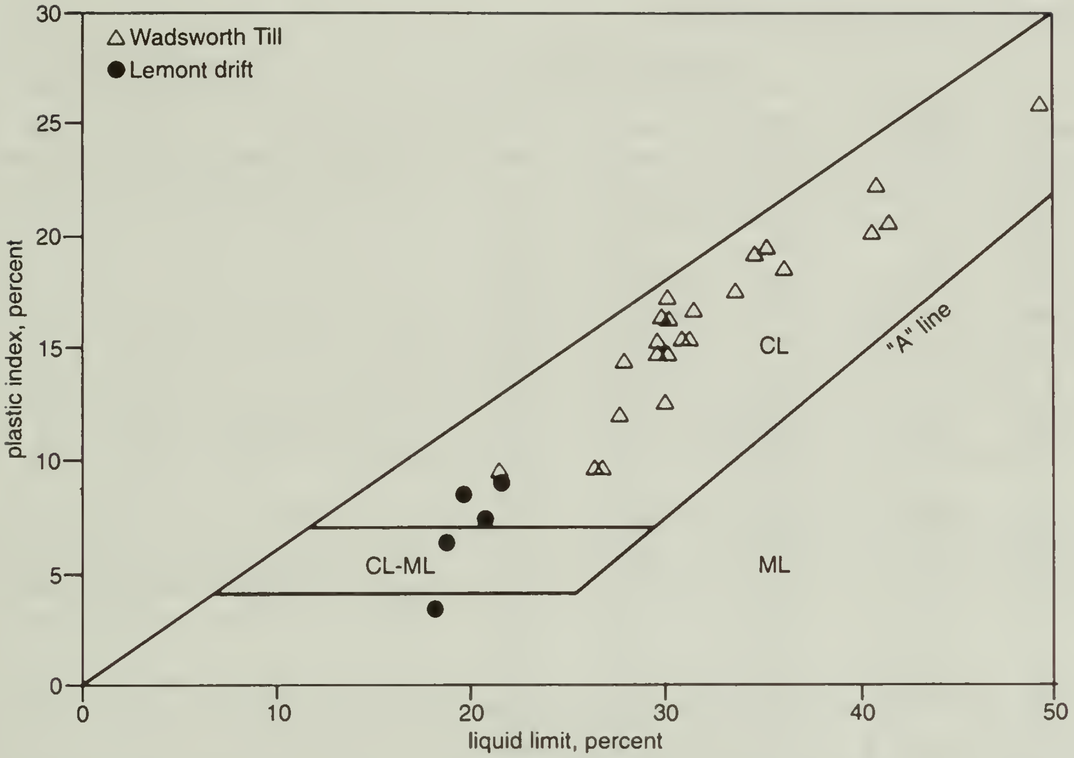


Figure 20 Casagrande's plasticity chart (Casagrande 1932) for Wadsworth and Lemont samples (see table 6) .

Joints Although previous drilling records do not note the occurrence of joints, seven boreholes drilled during this field study revealed vertical joints, none of which exceeded a depth of 20.4 feet. Joint surfaces were generally iron-stained and coated with manganese oxides. Jointing has been noted many times in field work carried out in northeastern Illinois.

Engineering data from previous drilling An analysis of the engineering characteristics of units encountered in the 1966 and 1986 drilling (Killey and Trask 1989) supports the observation of differentiation between the upper and lower units within the Wadsworth diamicton. These data generally show that, with only three exceptions, blow counts consistently increase from the upper to the lower till. Unconfined compressive strength (Qu) of the lower unit of the Wadsworth is consistently lower in all but one of the 1986 borings. The 1966 data show, however, that Qu increases or remains the same in the lower Wadsworth. This variation from the 1986 data could reflect operator or instrument differences. Variations in moisture content are negligible in the 1986 data, whereas the 1966 data show consistently lower moisture content in the lower Wadsworth. These data indicate that there is a small but fairly consistent difference between the upper and lower units of the Wadsworth.

Table 5 Summary of grain-size data for matrix of Wadsworth Till Member.

	Entire unit			Above 720 sand			Below 720 sand		
	sand	silt	clay	sand	silt	clay	sand	silt	clay
Mean %	17	44	39	18	41	41	16	47	37
Minimum %	6	35	10	12	36	10	6	35	23
Maximum %	31	59	52	31	59	52	31	57	51
Standard deviation	5.5	6.4	8.5	5.1	5.2	8.8	5.8	6.1	8.2
Number of samples		46			19			27	

Table 6 Summary of ISGS engineering test results.

			Atterberg limits %				Compaction test*		
Borehole no.	Sample ID	Sample depth (ft)	liquid limit	plastic limit	plasticity index	Specific gravity	γ_d (pcf)	W_{opt} (%)	test type
APS-2	S-3	5–7	49.4	23.4	26.0	--	--	--	--
APS-8	bag	5–7	28.0	13.6	14.4	--	--	--	--
APS-8	bag	15–17	27.7	15.7	12.0	--	--	--	--
APS-13	S-4A	8.5–10.5	31.2	15.8	15.4	--	--	--	--
APS-14	bulk	0–20	30.1	13.7	16.4	2.72	120.3	13.6	S
			31.2	15.8	15.4	2.73			
APS-15	S-4	8–9	26.6	17.0	9.6	--	--	--	--
APS-16	bulk	0–20	30.2	14.0	16.2	2.72	124.0	12.0	S
			29.8	14.5	15.3	2.75	133.0	9.8	M
APS-17	S-2	2.5–4.5	41.6	21.0	20.6	--	--	--	--
APS-17	S-4	8.5–10	30.2	13.0	17.2	--	--	--	--
APS-17	S-5	10–11	30.1	17.6	12.5	--	--	--	--
APS-18	bulk	0–20	33.7	16.1	17.6	2.74	118.9	13.8	S
			34.8	15.6	19.2	2.81			
APS-19	S-8	18–19.5	21.6	12.1	9.5	--	--	--	--
APS-20	bulk	0–20	30.0	15.3	14.7	2.76	122.5	12.5	S
			30.0	15.3	14.7	2.75	132.5	9.3	M
APS-21	S-23	80–81.5	19.8	11.3	8.5	--	--	--	--
APS-22	S-4	7.5–9.5	26.7	17.1	9.6	--	--	--	--
APS-22	S-23**	80–81.5	20.9	13.6	7.3	--	--	--	--
APS-23	bag	65–66.5	18.9	12.6	6.3	--	--	--	--
APS-23	bag	70–71.5	18.3	14.9	3.4	--	--	--	--
APS-24	S-22**	62.5–64	21.8	12.7	9.1	--	--	--	--
APS-26	S-3A	6.5–10	31.6	14.9	16.7	--	--	--	--
APS-27	bulk	15–20	40.8	18.6	22.2	2.74	113.6	16.3	S
			41.0	18.6	22.4	2.72			
APS-28	bulk	0–20	36.2	17.7	18.5	2.75	118.5	15.1	S
			35.4	15.9	19.5	2.73			

*Type compaction test: S = standard, M = modified, γ_d = dry density, W_{opt} = optimum moisture content
**Small sample (stored in a small container)

Engineering properties Twenty-three Atterberg-limits tests were run on 17 samples of Wadsworth diamicton from 14 APS boreholes (table 6). Although all of the samples exhibited somewhat higher plasticity indices (9.5 to 26.0%) than did the Lemont diamicton (3.4 to 9.1%), they were still well below the high plasticity range (50% liquid limit [LL], fig. 20). (Samples plotting more than 50% LL would be indicative of highly plastic clays, implying poor soil conditions for construction.)

A total of eight standard (ASTM standard D 698, Method A) and modified (ASTM standard D 1557, Method A) compaction tests were run on selected samples from six APS boreholes (table 6) to determine the optimum moisture–density relationship for materials likely to be used for borrow. Compaction test results show that optimum water content ranges from about 9% to slightly more than 16%, and the maximum dry density ranges from about 113 to 133 pounds per cubic foot (pcf). Expected values for required borrow material from Wadsworth till locally are more than 120 pcf and less than 13% to 14% water content. Test results differing from these values may have come from a mixture with poorer quality materials. These results demonstrate the importance of a carefully implemented quality assurance and control program for selection of backfill materials to prevent problems such as insufficient bearing capacity and differential settlement.

Specific gravity values (ASTM standard D 854) range from 2.72 to 2.81 (mean 2.74, standard deviation 0.02; table 6). These values indicate that the specific gravity is normal for soils in this region.

Taken as a whole, soil mechanics testing demonstrated that suitable borrow material is available on site for construction of the APS facility. Careful investigation of proposed borrow areas allows for segregation of good material (Wadsworth till) from poor quality material. Geotechnical properties of the Wadsworth till on the site are similar to its properties elsewhere, and the Wadsworth is a useful foundation material locally. Transmission of vibrations is dependent on the properties of the earth materials at the site. Cross- hole seismic tests were conducted by STS Consultants Ltd. in four sets of three boreholes each (APS 1-3, 4-6, 7-9, and 10-12); the results are discussed in their report to Argonne (STS Consultants 1988).

Intercalated coarse grained materials The Wadsworth contains lenses and beds of sand, sand and gravel, and silt that commonly range in thickness from a fraction of an inch to 4 feet. Texturally, these units are sandy gravel, gravelly and loamy sand, sand, silty loam, and gravelly and sandy silt; they are commonly laminated and, in contrast to the till, contain little or no clay. These pockets and lenses of gravel, sand, and silt occur in various boreholes; but, with the exception of the 720 sand discussed below, they do not seem to be continuous or to lie at a consistent elevation across the general site.

Summary The Wadsworth Till Member is a fairly uniform silty clay diamicton across the site. It contains silt and sand lenses, one of which (the 720 sand) may be more persistent than the others. The 720 sand appears to subdivide the diamicton into two units, as indicated by small but consistent differences in texture and engineering properties.

720 sand One sand appears to be more persistent than the others in the Wadsworth; it is informally called the 720 sand because it occurs at an elevation that averages about 720 feet. Killey et al. (1987) first noted this unit in their regional geological review when they examined logs of boreholes from the 1948, 1966, and 1986 drilling programs cited previously. In 1948, gravelly sand and sandy silt were logged in three boreholes north of the APS ring site at elevations of 722 to 727 feet. The 1966 borings also encountered a silty sand at an elevation of 724 feet during drilling for the A^2R^2 project on the northeastern part of the general APS site. Drilling logs from 1986 note the presence of 1 to 16 feet of clayey silt to gravelly sand at elevations of 712 to 730 feet. During the course of the study, the 720 sand was specified as requiring additional investigation because, if it were continuous and overpressured, it could be of concern if encountered during construction of the APS facility.

Before drilling began, we predicted that the 720 sand would be encountered in 16 of the APS boreholes. During drilling, we observed an interval of sandy silt to sandy gravel in 13 out of the 16 boreholes; it was found at elevations of 714 to 730 feet. In addition, continuous electronic-cone-penetrometer testing at the site of APS-14 (Strutynsky 1988) detected a sand at an elevation of 702 feet. We hypothesized that all of these occurrences might represent the same sand and mapped it accordingly (figs. 21 and 22). The thickness, elevation, and lithology of the 720 sand, as delineated in the APS boreholes on the footprint of the ring, are shown on plate 1.

The 720 sand lies at elevations of 702 to 730 feet. The top of the sand is highest in the center and southeastern parts of the ring (fig. 21) and is lowest to the west, northeast, and south. The sand reaches a maximum thickness of 16 feet to the southwest, just outside the footprint of the ring (fig. 22). Another thick zone, which has a maximum thickness of 8.5 feet, occurs north of the ring. The sand ranges from sandy loam to loam and silt loam (fig. 17). Excluding gravel (>2 mm), the deposit averages 50% sand, 39% silt, and 11% clay (table 7). Commonly, thin intervals are composed exclusively of silt, which also occurs at the top or bottom of the unit in some places. The 720 sand is more coarsely grained under the central and western parts of the ring and more finely grained under the northeastern and southwestern parts.

Early in the project, a horizontal planar (slice) map of vertical electrical soundings was constructed for the 720-foot elevation to see to what degree resistivity might reveal coarser materials at this elevation. The 720-foot elevation, however, is dominated by low "true" resistivity values associated with finer grained deposits (fig. 23). This indicated what was later confirmed by drilling: that the 720 sand, if continuous, is not a flat-lying body and may lie more above the 720-foot elevation than at or below it. Figure 23 shows the slice map at the 720 elevation and includes the 720-foot contour from figure 21 for comparison. Vertical electrical soundings failed to detect sand where known beds were less than about 1.5 feet thick along the 720 contour in the northeastern part of the ring.

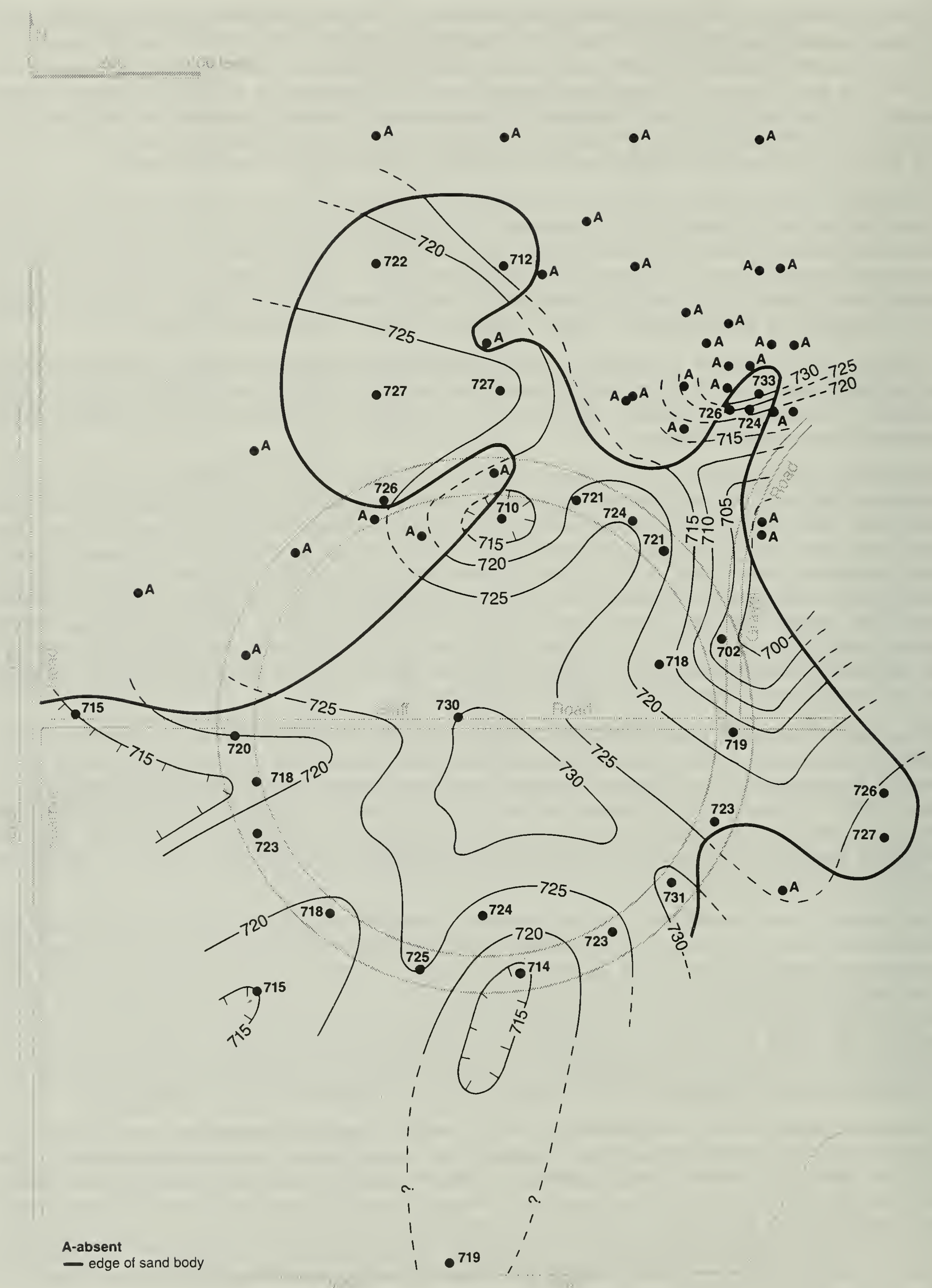


Figure 21 Elevation of the top of the 720 sand.

Figure 22 Thickness of the 720 sand.

Table 7 Summary of grain-size data for matrix (<2 mm) of 720 sand for 14 samples.

	sand	silt	clay
Mean %	50	39	11
Minimum %	29	14	5
Maximum %	77	57	20
Standard deviation	12.8	11.4	4.2

Although logs indicate that as much as 5 feet of the sand occurs near the center of the ring (fig. 22), it is at too high an elevation (725–730 ft) to be reflected on the 720-foot slice map. Four small areas with values in excess of 200 ohm-feet, however, are likely to be indicative of coarser grained deposits associated with this sand body.

Summary On the basis of the following findings, we interpret the 720 sand to be a potentially continuous unit of coarser materials within the Wadsworth Till Member: (1) previous drilling programs indicate elevations of the unit that range between 702 and 730 feet in a number of boreholes; (2) drilling for this project demonstrates that the unit occurs in 13 of the 16 boreholes in which its occurrence was predicted; (3) testing reveals differences in grain size and engineering properties in the overlying and underlying tills of the Wadsworth Till Member.

These findings indicate that the Wadsworth in this area may consist of two distinct lithologic units separated by the 720 sand. The sand ranges to a maximum of 16 feet thick. Lithologically, it is predominantly sand but commonly contains gravel and silt.

Supplementary Data

Downhole geophysical logging As stated previously, one purpose of the downhole geophysical logging conducted across the APS site was to aid in evaluating the stratigraphic continuity of near-surface deposits. In Illinois, natural gamma ray log configurations are related to the amount of clay (<4 µm) in the geologic materials surrounding the borehole. As illustrated in figure 24, the logs define five distinct natural gamma ray units. These units, which are correlative across the site, are based on in situ natural gamma radiation derived from clay content as shown by the differing API values on the logs. Although the natural gamma ray units do not correspond precisely with all of the lithologic boundaries identified from drilling and sampling, the clay percentages shown by the log configurations closely reflect those given in tables 4 and 5. For example, the upper unit of the Wadsworth averages 41% as compared with 45% on the natural gamma logs, the lower Wadsworth averages 37% as compared with 38% on the natural gamma logs, and the diamicton that dominates the upper part of the Lemont drift averages 20% as compared with 24% on the natural gamma logs. In addition, the elevations of discontinuities between these units on the natural gamma logs approximate those from borehole logs (Killey and Trask 1989). The results of this field test provide increased support for the predictability and continuity of the deposits across the site.

Seismic refraction profiling Twenty-two seismic refraction profiles were oriented east–west and 22 were oriented north–south, allowing the possibility that statistical analysis could be used to determine whether there were significant differences in the velocities of glacial drift and the bedrock surface with regard to direction. If so, these differences might have relevance to phenomena such as depositional patterns or anisotropy related to fracturing or jointing that, in turn, might have implications for vibration transmission through bedrock or glacial drift.

To test for change of velocity with direction, it was assumed that the east–west velocities and the north–south velocities came from two populations having respective means, μ_{EW} and μ_{NS}. We then had to decide between the following hypotheses:

$$H_o : \mu_{EW} = \mu_{NS}$$

$$H_1 : \mu_{EW} \neq \mu_{NS}$$

Under the null hypothesis, H_o, both sets of velocities belong to the same population.

The mean and standard deviation of the difference in sample means are given by the following equations:

$$\mu_{X_{EW} - X_{NS}} = 0$$

$$\sigma_{X_{EW}-X_{NS}} = \frac{S_{EW}^2}{N_{EW}} + \frac{S_{NS}^2}{N_{NS}}$$

where N_{EW} and N_{NS} are sample sizes. To test for differences between populations, we used the normally distributed statistic:

$$Z = \sqrt{\frac{X_{EW} - X_{NS}}{\frac{S_{EW}^2}{N_{EW}} + \frac{S_{NS}^2}{N_{NS}}}}$$

There was no significant difference between mean bedrock surface velocities obtained from east–west profiles and those obtained from north–south profiles. For drift velocities, however, there was a significant difference at the 0.05 significance level; the sample mean of the drift velocities obtained from the north–south profiles was less than the sample mean of the drift velocities obtained from east–west profiles. This finding implies that vibration attenuation characteristics of the drift may be greater in certain directions, and thus the effect of properly placed vibration-producing machinery on operation of the APS facility may be reduced. The profile orientations used in this study (north–south and east–west) may not necessarily be parallel to the maximum directions of reduced velocities; further investigation is needed to determine a more precise direction for vibration attenuation.

Hydrogeology

Most of the hydrogeologic investigations (such as hydraulic conductivity testing) were performed by Argonne's contractor. Six piezometers were placed in the Wadsworth diamicton (including two in the 720 sand), two in the Lemont, and four in bedrock. The installation of these piezometers (STS Consultants 1988) precluded their use for strictly defining potentiometric head in bedrock and specific drift units. They did allow, however, for approximation of the elevation of standing water in the APS excavation and other potential impacts of water levels on the construction of the facility. Although nearly 10 months of water level readings yielded several interesting observations, including trends related to the drought of 1988, two main observations directly related to the study were made.

The first observation is illustrated in figure 25, which summarizes our general understanding of groundwater movement in the geologic materials at the APS site. The water table is illustrated as the top of the zone of saturation in the upper part of the Wadsworth diamicton. Direction of water movement is likely to be lateral in the more permeable 720 sand; seeps may form where the 720 sand intercepts slopes along the bluffs of the Des Plaines River. The potentiometric surface of the 720 sand indicates that, if continuous, the sand may be overpressured (i.e., it may form a confined aquifer with a potentiometric surface in the overlying diamicton). Water movement below the sand and away from the bluff is in a downward direction. In the coarser sediments of the Lemont, water generally moves southward towards the bluff as well as downward. Water level readings in the bedrock piezometers indicate that the potentiometric surface is above the bedrock surface and slopes to the north. Under natural conditions, groundwater movement in the upper bedrock would probably be southeast to the Des Plaines River Valley. This northward slope of the bedrock potentiometric surface most likely is the result of pumpage by Argonne from the upper bedrock aquifer.

The second observation was the cyclicity of fluctuations noted on a continuous water level recorder placed in APS-28, which was screened in the 720 sand. Determining the cause of the cyclicity was of concern because of the possibility of unidentified sources of vibration. Argonne was particularly concerned with vibrations at 18.4 Hz and 60 Hz (Jendrzejczyk et al. 1988) because they could not determine the source (Jendrzejczyk, personal communication 1988). The continuous water level recorder detected two cycles of head reduction in this aquifer prior to mid-October 1988. One cycle of head reduction and recovery lowered the piezometric head approximately 0.25 to 0.35 foot during a period of 4 to 5 days (fig. 26) before the water level eventually recovered. The other cycle of head reduction caused the piezometric head to fluctuate several hundredths of a foot diurnally. Generally, water level decline began in late evening and ended in late morning; this episode continued unabated through the week. After mid-October, the amplitude of weekly head reduction and recovery increased from 0.25–0.35 foot to 0.7–0.9 foot,

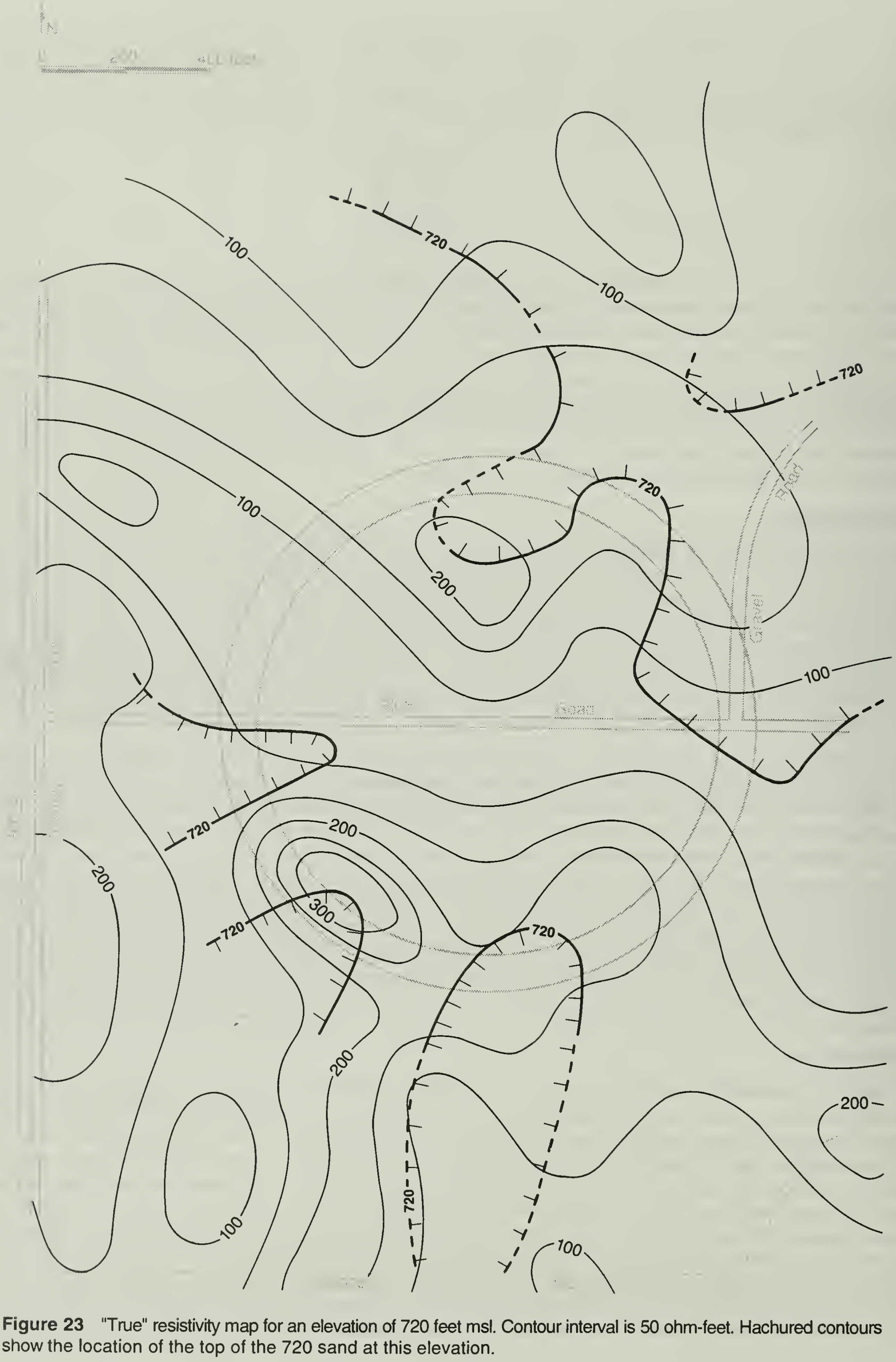


Figure 23 "True" resistivity map for an elevation of 720 feet msl. Contour interval is 50 ohm-feet. Hachured contours show the location of the top of the 720 sand at this elevation.

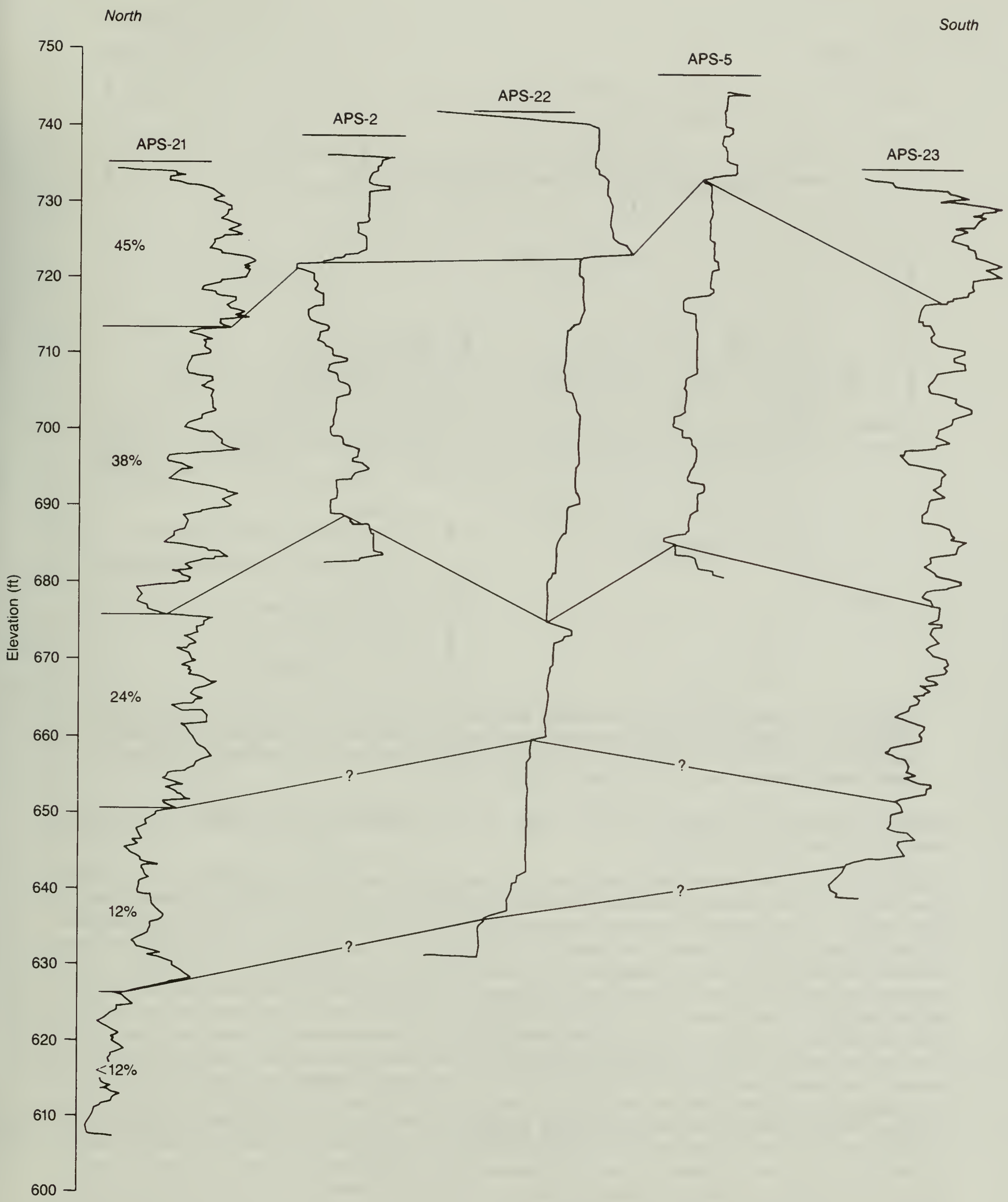


Figure 24 North–south cross section as determined from natural gamma radiation logs. Clay content decreases downward in all five logs, indicating correlatable lithologies across the APS site. Gamma radiation increases to the right.

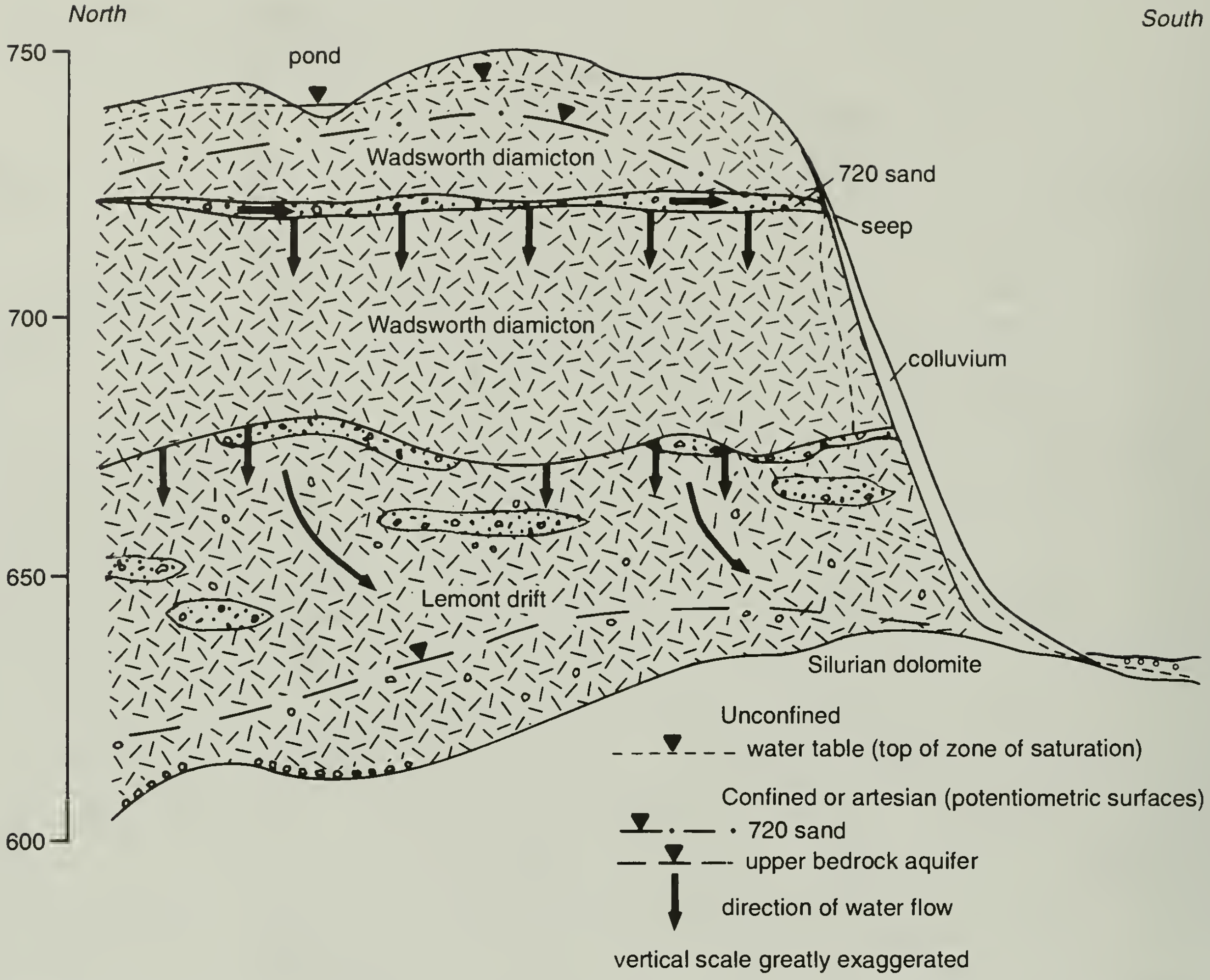


Figure 25 Probable direction of groundwater movement in glacial drift and bedrock at the APS site. Generalized potentiometric surfaces of the 720 sand and upper bedrock aquifer as well as hypothetical direction of groundwater movement are illustrated. The slope to the north and the divide in the bedrock potentiometric surface result from pumpage by Argonne's wells.

generally obscuring the diurnal cycle on the charts (fig. 27). In addition, this new pattern was repeated every 3 to 4 days (range 2–5 days).

Possible causes of these water level fluctuations could be groundwater pumping, barometric tides, or earth tides. Argonne was concerned that these fluctuations in water level might be related to vibrations detected at the APS site (Jendrzejczyk, personal communication 1989). Jendrzejczyk et al. (1990) suggested that the fluctuations might be caused by vibrations from some unknown source or by pumping at some unknown location. Component frequencies in hydrograph data from APS-28 were determined using a mathematical model in order to determine the cause of the fluctuations. A frequency with a period of approximately 12 hours is present in models of data gathered prior to October, but absent in data gathered after mid-October. A 12-hour period may indicate the influence of either barometric pressure or earth tides, which is the response of the solid earth to the same forces that produce ocean tides. Both barometric pressure and earth tides are known to fluctuate on a 12-hour cycle. An analysis of major solar and lunar harmonics for earth tides ruled the tides out as a cause for the fluctuations. Comparisons of water levels and barometric pressure for three periods of time (August 28 to September 19, September 24 to October 4, and October 18 to 31; figs. 28, 29, and 30, respectively), however, clearly show the dependence of depth to water on barometric pressure through October. After mid-October, changing weather patterns apparently resulted in barometric pressure patterns that did not exhibit the prominent 12-hour period. Thus, the 12-hour cycle and longer cycles of water level fluctuations resulted from changes in barometric pressure.

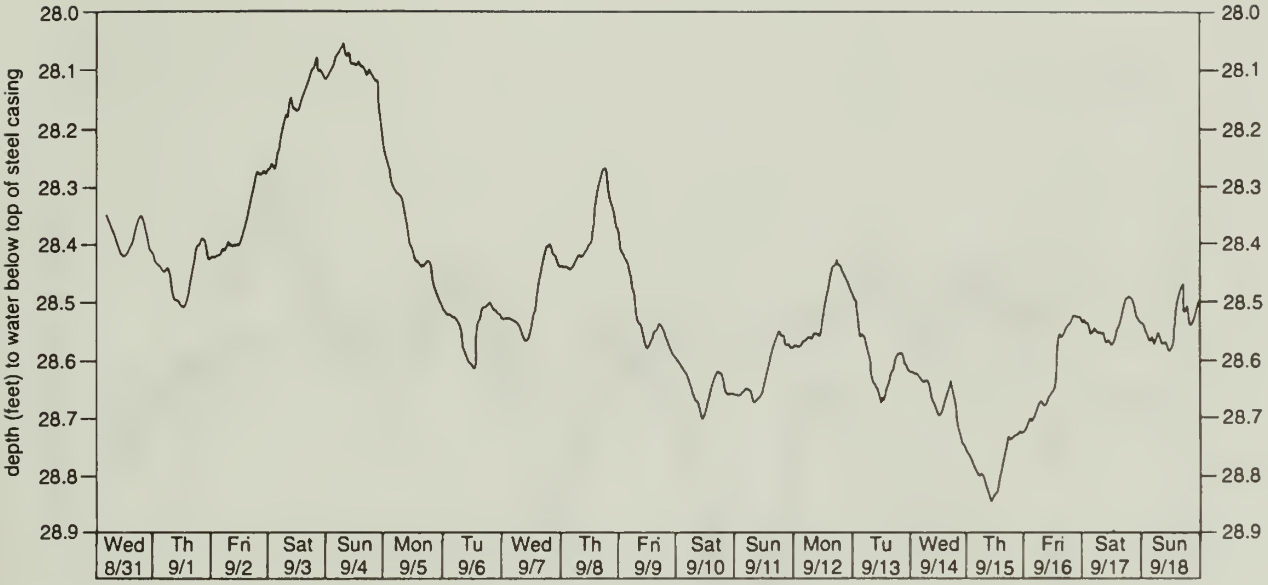


Figure 26 Hydrograph of the continuous water level recorder at APS-28 from August 31, 1988 to September 18, 1988. Head reduction and recovery of about 0.25 to 0.35 foot amplitude during a 4- to 5-day period are illustrated.

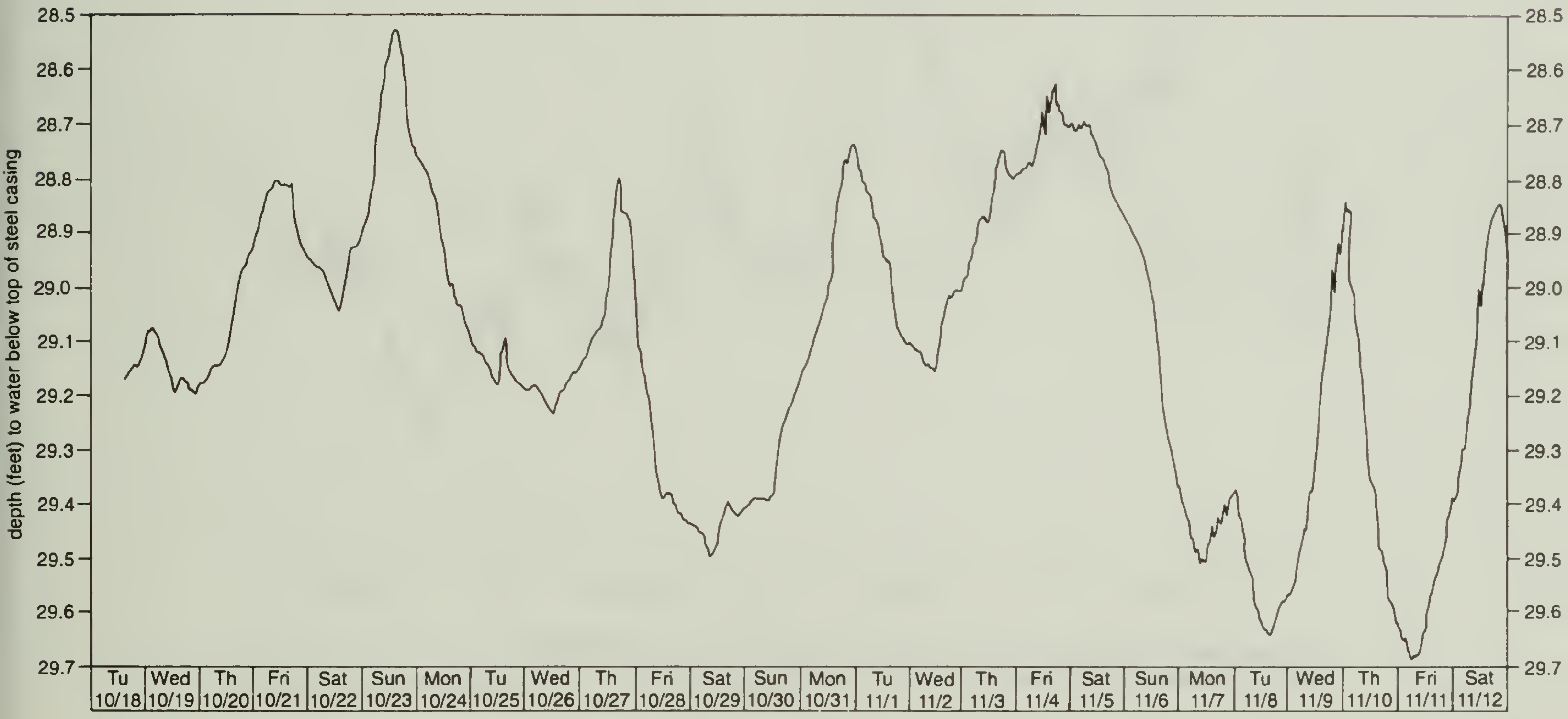


Figure 27 Hydrograph of the continuous water level recorder at APS-28 from October 18, 1988 to November 12, 1988. Head reduction and recovery of about 0.7 to 0.9 foot amplitude approximately twice a week are illustrated.

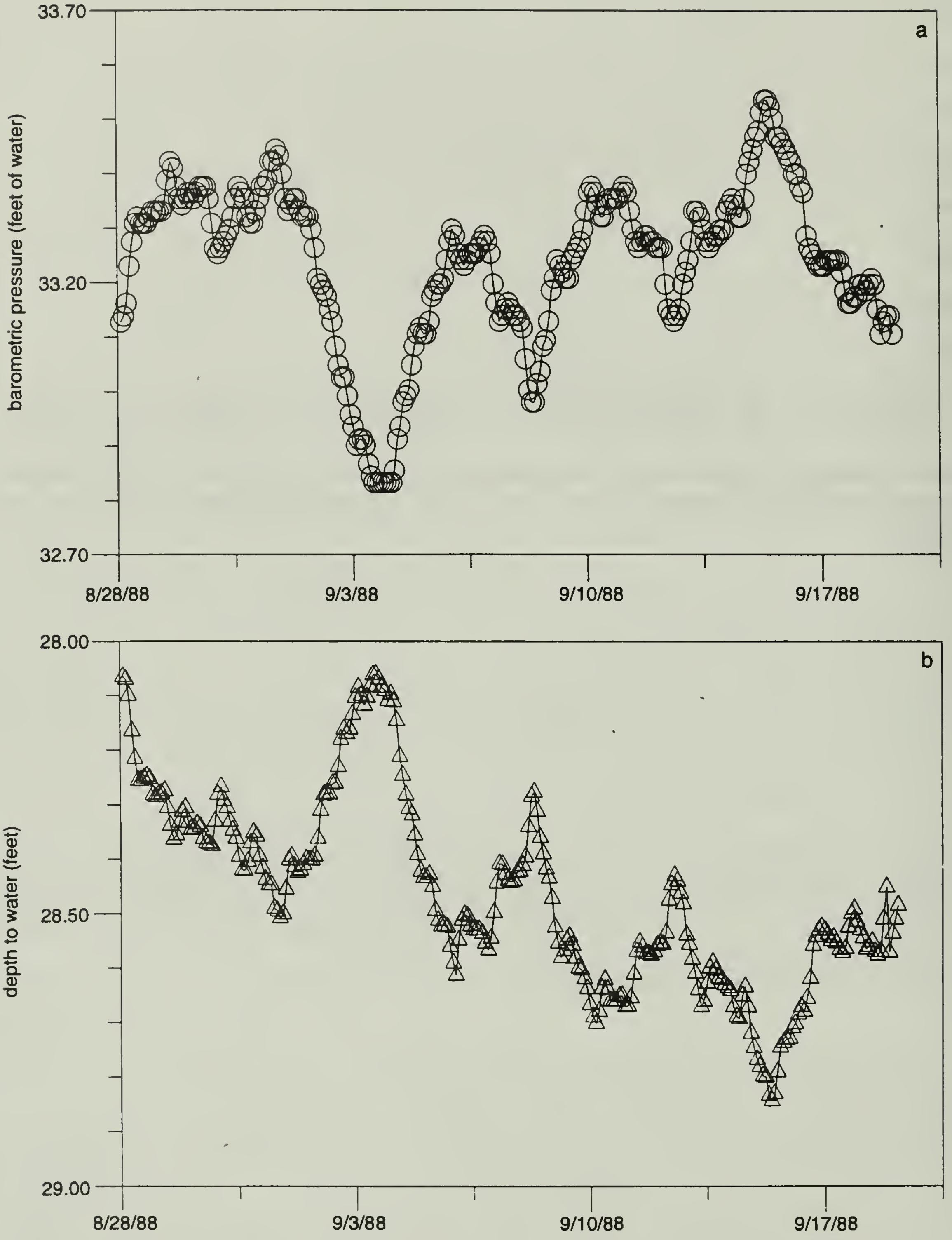


Figure 28 Barometric pressure (a) and depth to water (b) in APS-28 for the period August 28 through September 19, 1988.

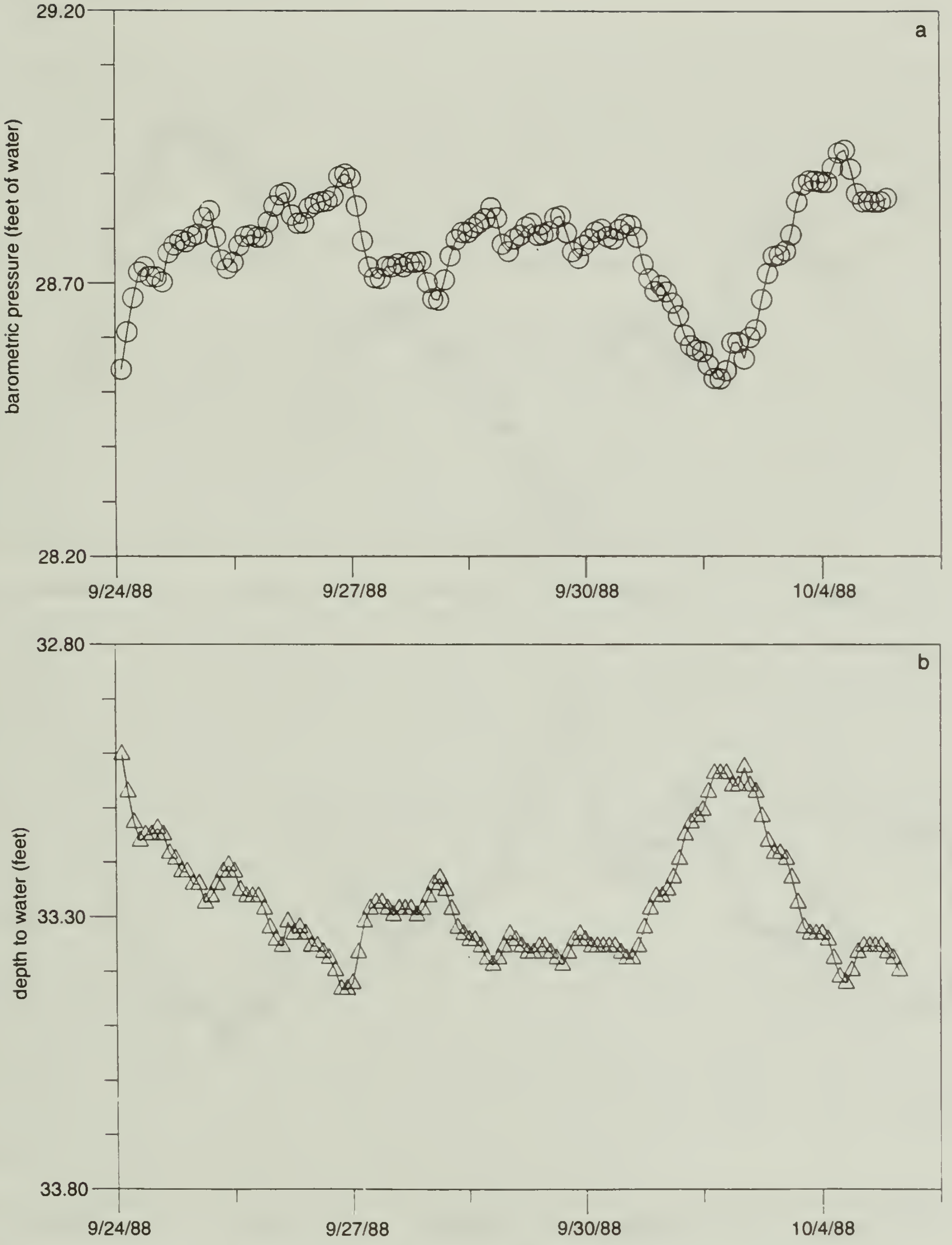


Figure 29 Barometric pressure (a) and depth to water (b) in APS-28 for the period September 24 through October 4, 1988.

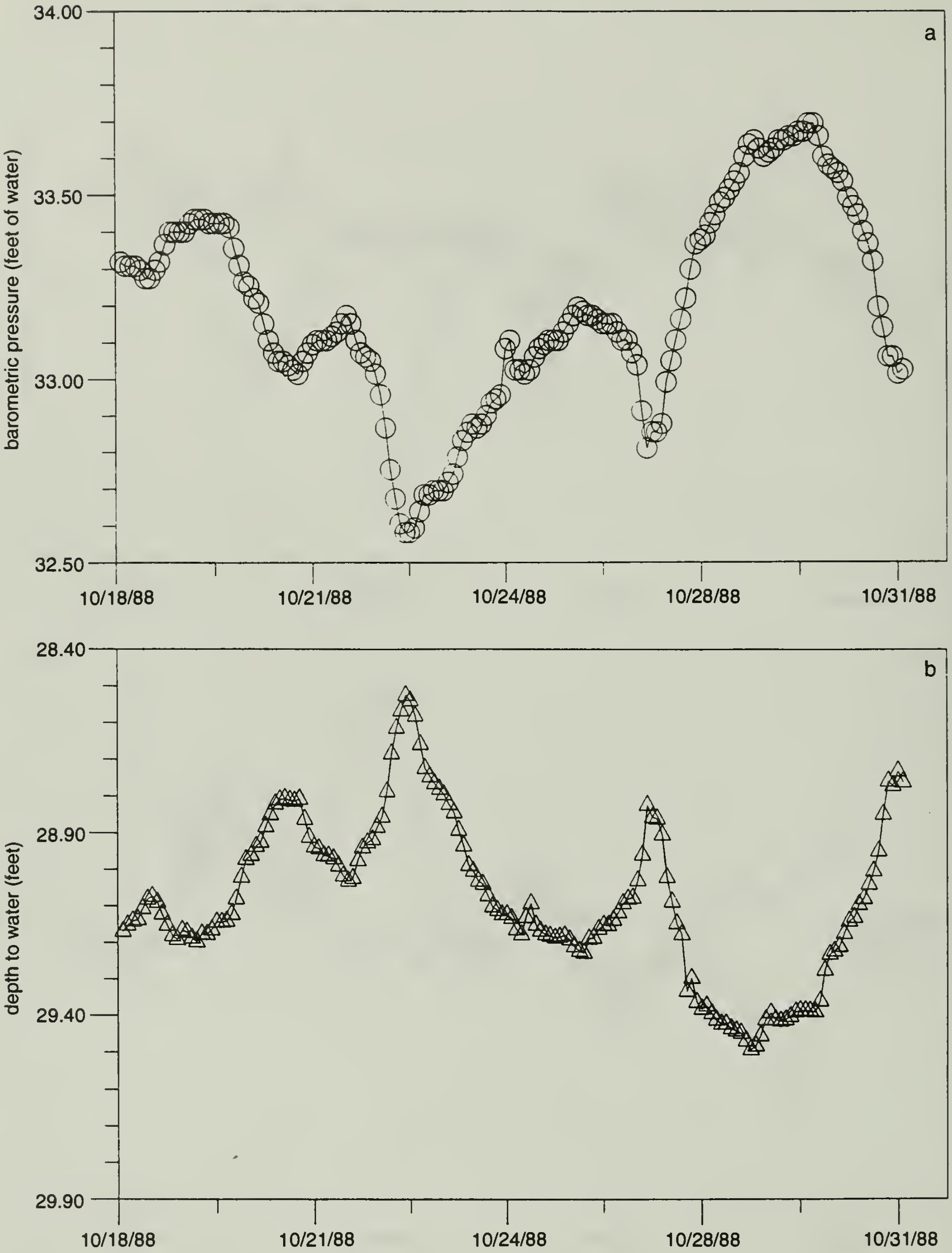


Figure 30 Barometric pressure (a) and depth to water (b) in APS-28 for the period October 18 through October 31, 1988.

SUMMARY AND CONCLUSIONS

Summary

The geologic setting of the construction site for the APS facility consists of dolomite bedrock of Silurian age overlain by two units of glacial origin: the lithologically variable Lemont drift and the relatively uniform silty clay diamicton of the Wadsworth Till Member, which composes the surficial unit across the area. Dolomite at and near the bedrock surface generally consists of fractured, light gray, cherty dolomite with a vuggy sucrosic texture, clay partings, and fossiliferous zones. It is relatively unweathered, possibly contains two joint sets, and is overlain by broken bedrock rubble. Its surface is highest in elevation (more than 640 feet) on the south, and it decreases in elevation to the north, east, and west. No unbroken bedrock core sufficient for testing of unconfined compressive strength was obtained.

The overlying Lemont drift is composed of silty, pebbly, dolomitic diamictons having numerous beds of silt, sand, and gravel; its average thickness is approximately 58 feet, and the top of the unit averages approximately 682 feet in elevation. The character of the Lemont drift at the APS site does not appear to differ significantly from regional observations of the unit. Lemont diamictons test in the low plasticity range. The Wadsworth Till Member averages about 60 feet thick and is a fairly uniform silty clay diamicton having interbedded sand and silt lenses, one of which is informally referred to as the 720 sand. The 720 sand appears to be more persistent than other sands and subdivides the diamicton into two units, as is indicated by the small but consistent differences in texture and engineering properties between the two. The Wadsworth till on the Argonne campus is similar to foundation material found regionally.

Water-level data yielded a general picture of groundwater movement in the bedrock and glacial materials. The potentiometric surface of the bedrock is in the overlying Lemont drift. The surface slopes to the north instead of toward the Des Plaines River, probably because of pumpage by Argonne from the upper bedrock aquifer. In the coarse sediments of the Lemont, water generally moves southward towards the bluff. The water table across the site is in the upper part of the Wadsworth diamicton. The potentiometric surface of the 720 sand indicates that, if continuous, the sand may be overpressured.

Statistical analysis of seismic refraction profiles revealed no significant difference in bedrock velocities, but it did indicate that vibration attenuation characteristics of the drift may be greater in certain directions. A cyclicity of water level fluctuations indicated the possibility of an unknown source of vibrations. The cyclicity was analyzed and found to be caused by changes in barometric pressure.

Conclusions

The data collected from the field and laboratory testing programs, as well as supplementary data from downhole geophysical logging, confirmed that the geology of the APS site is predictable and consistent with the regional geologic framework. The thickness and relative uniformity of the Wadsworth Till Member should prove satisfactory both as a foundation for construction of the APS facility and as a source of borrow material. In addition, the thickness of the Wadsworth generally isolates most of the construction and foundation work from the variable sediment sequences and lesser known hydrogeological characteristics of the Lemont drift. Our geological and hydrogeological studies revealed no conditions that would enhance artificial or naturally occurring vibrations in the area.

One of the outgrowths of our investigation was the recognition of the presence of the 720 sand and the potential impact of its continuity within the Wadsworth Till Member; it could be overpressured hydrologically and cause problems if unexpectedly encountered during construction. Although more detailed sedimentological and hydrogeological data would be required to confirm its continuity, knowledge of its existence allows for consideration of potential problems during planning and construction.

The characterization of the bedrock and glacial drift at the APS site helped to ensure that no unexpected geological or hydrogeological conditions would be encountered as construction of the APS proceeded. The geology of the site should produce no major problems and should prove suitable for successful construction and operation of the APS facility.

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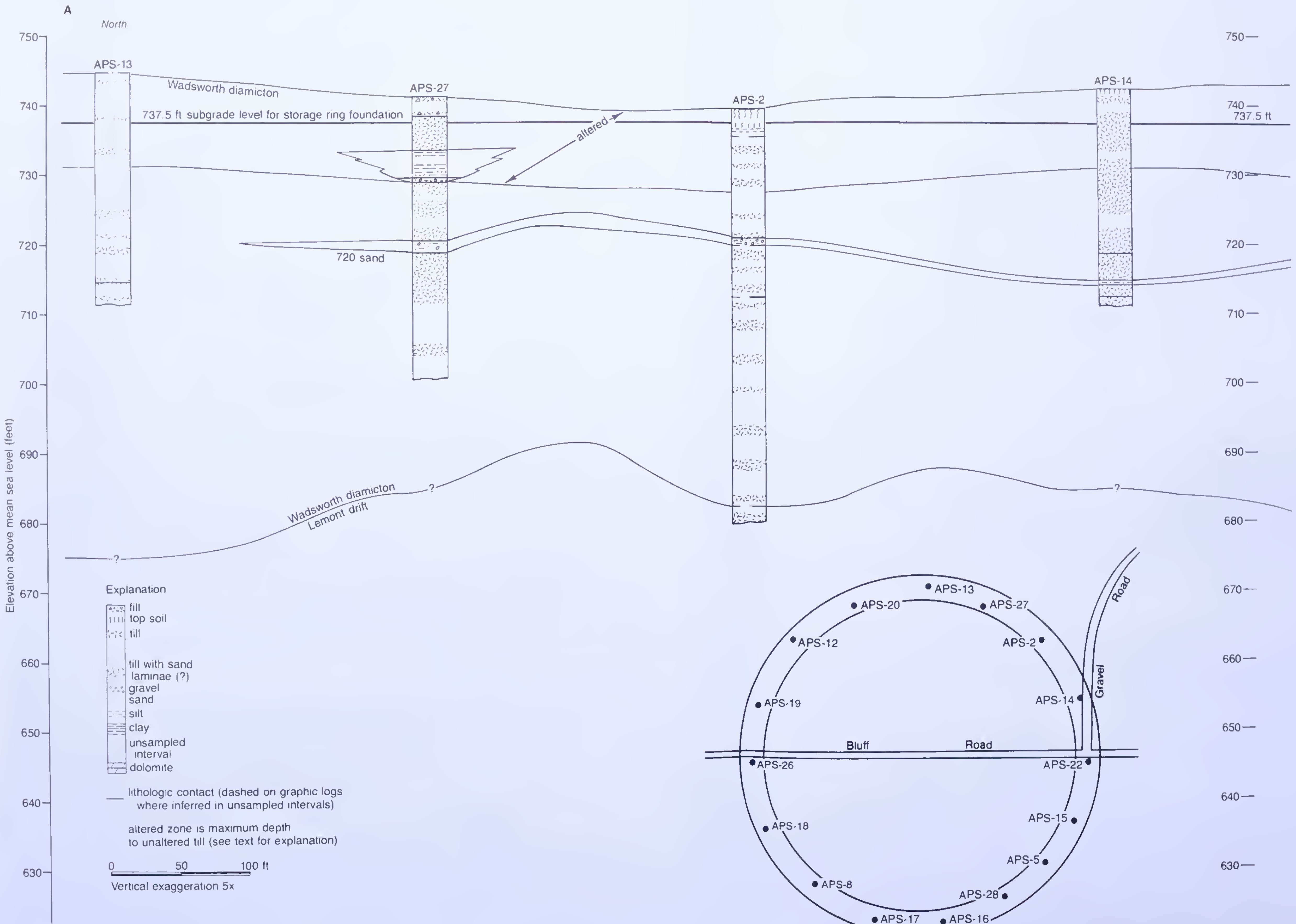
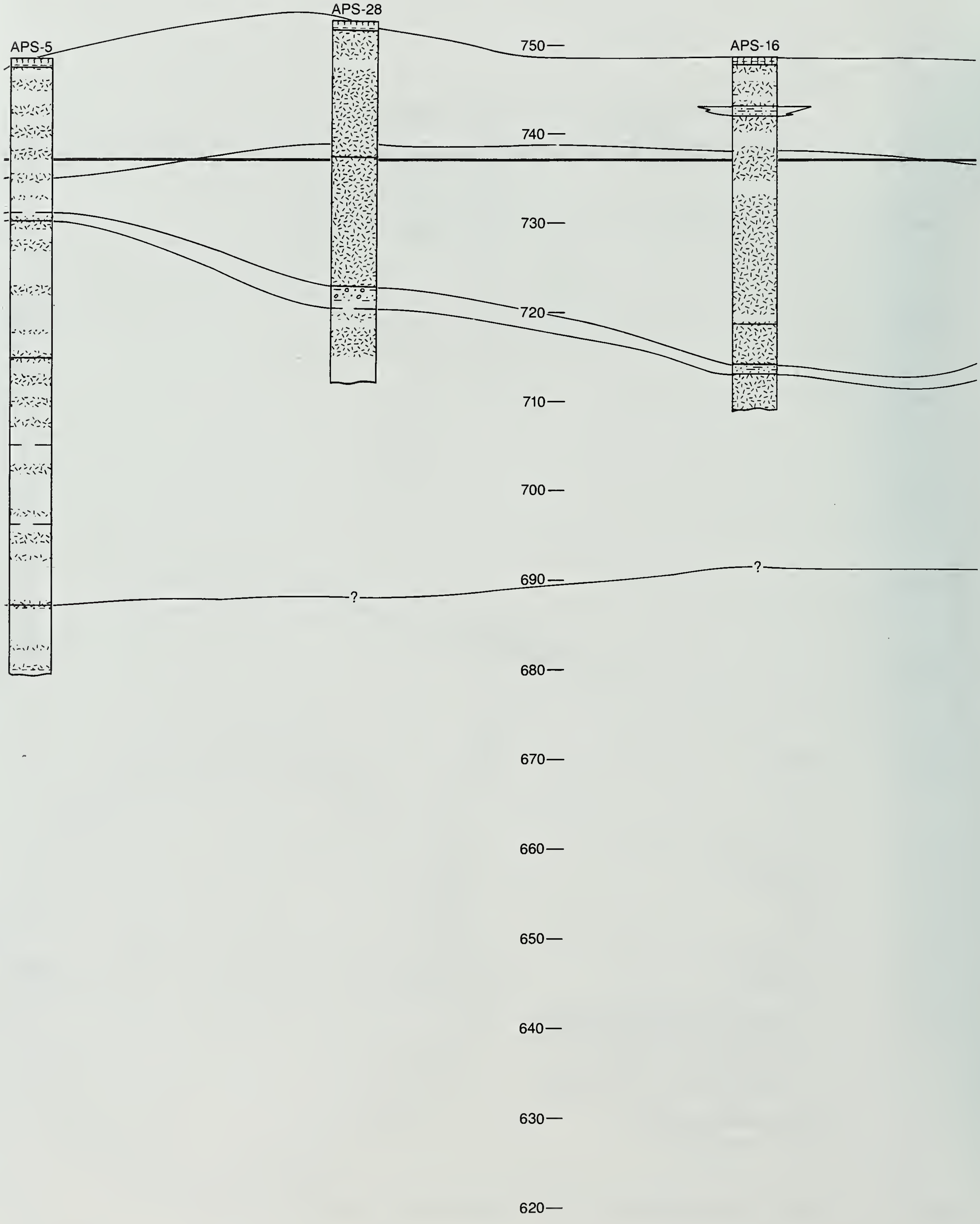


Plate 1 Geologic cross section of lithologies beneath the APS storage ring.


APS-5
APS-28
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750
740
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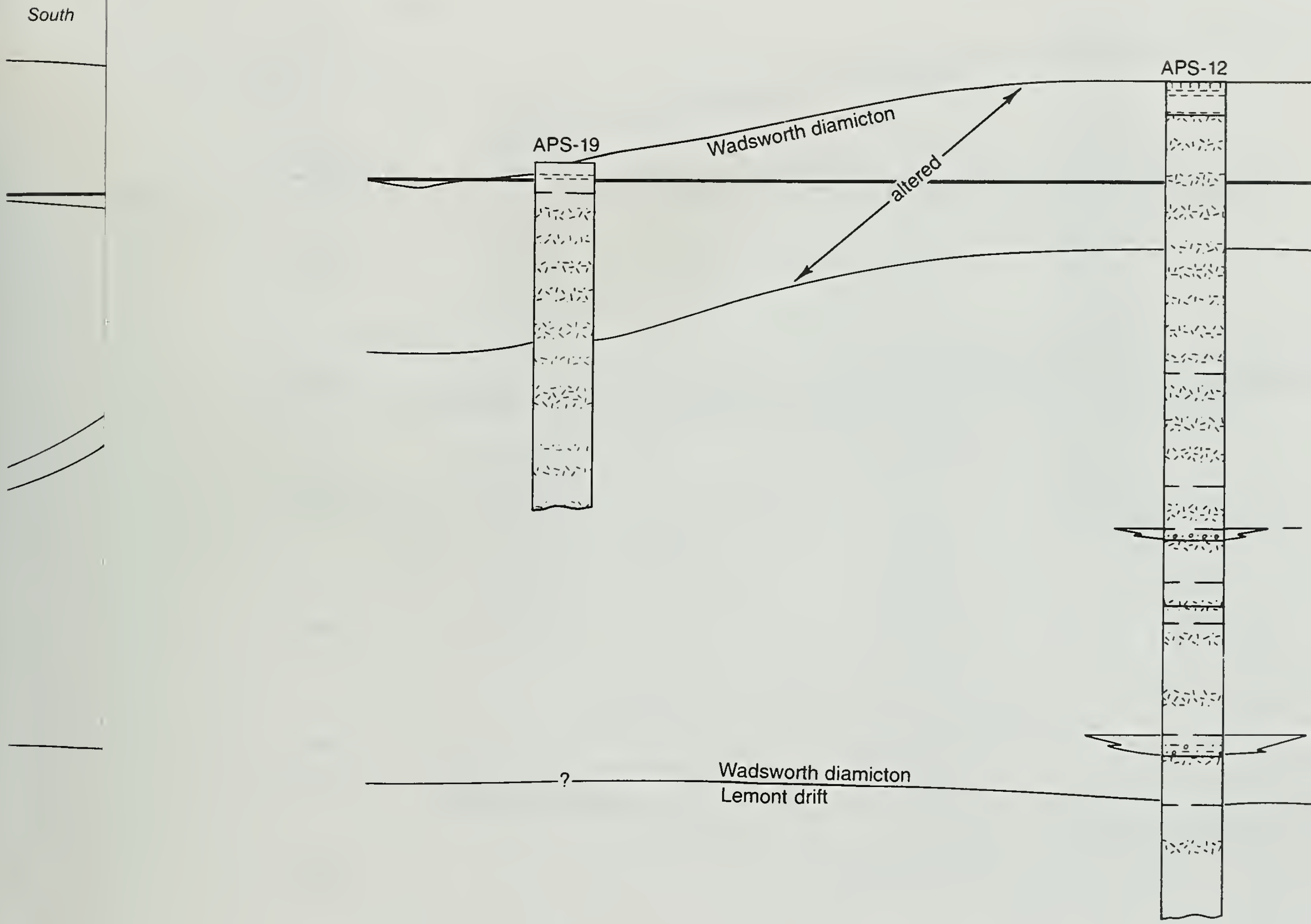
South
APS-12
APS-19
Wadsworth diamicton
altered
?
Wadsworth diamicton
Lemont drift


East
South
APS-22
APS-15
APS-5
APS-28
APS-16
Wadsworth diamicton
altered
720 sand
Wadsworth diamicton
Lemont drift
?
?
?
Bedrock
750
740
730
720
710
700
690
680
670
660
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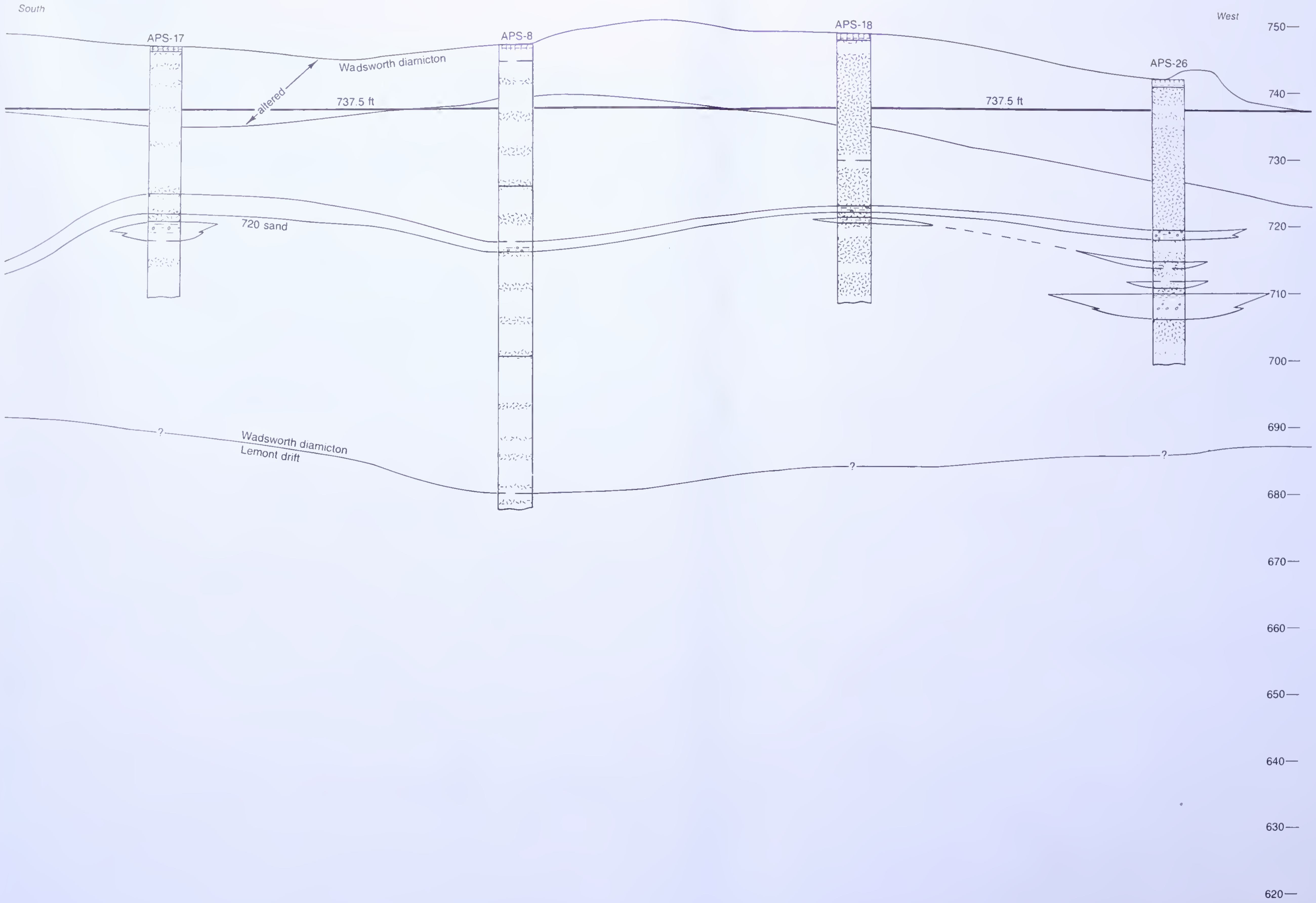
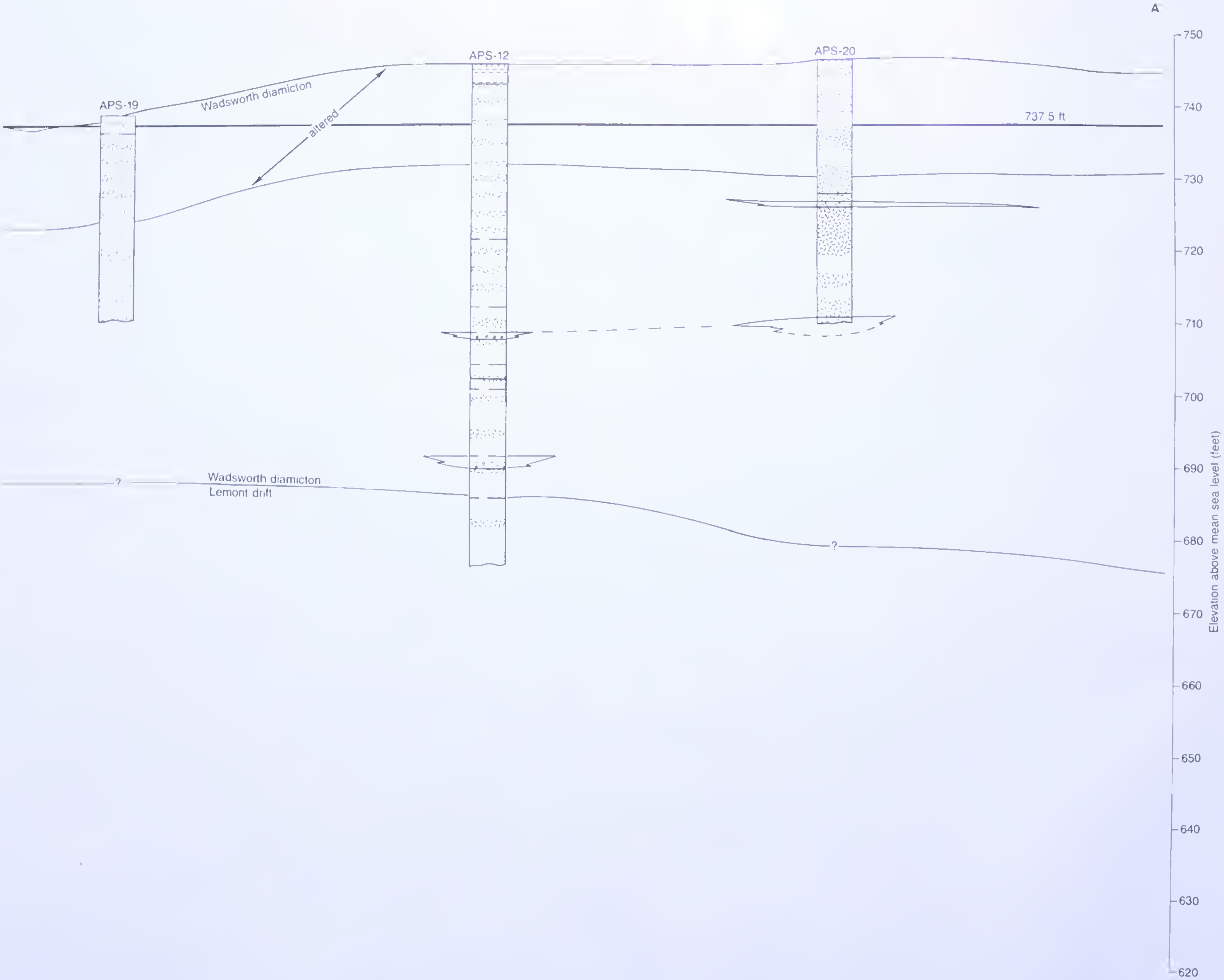
620


South
West
APS-17
APS-8
APS-18
APS-26
Wadsworth diamicton
altered
737.5 ft
737.5 ft
720 sand
?
Wadsworth diamicton
Lemont drift
?
?
750
740
730
720
710
700
690
680
670
660
650
640
630
620


A'
APS-19
APS-12
APS-20
Wadsworth diamicton
altered
737.5 ft
?
Wadsworth diamicton
Lemont drift
?
750
740
730
720
710
700
690
680
670
660
650
640
630
620
Elevation above mean sea level (feet)