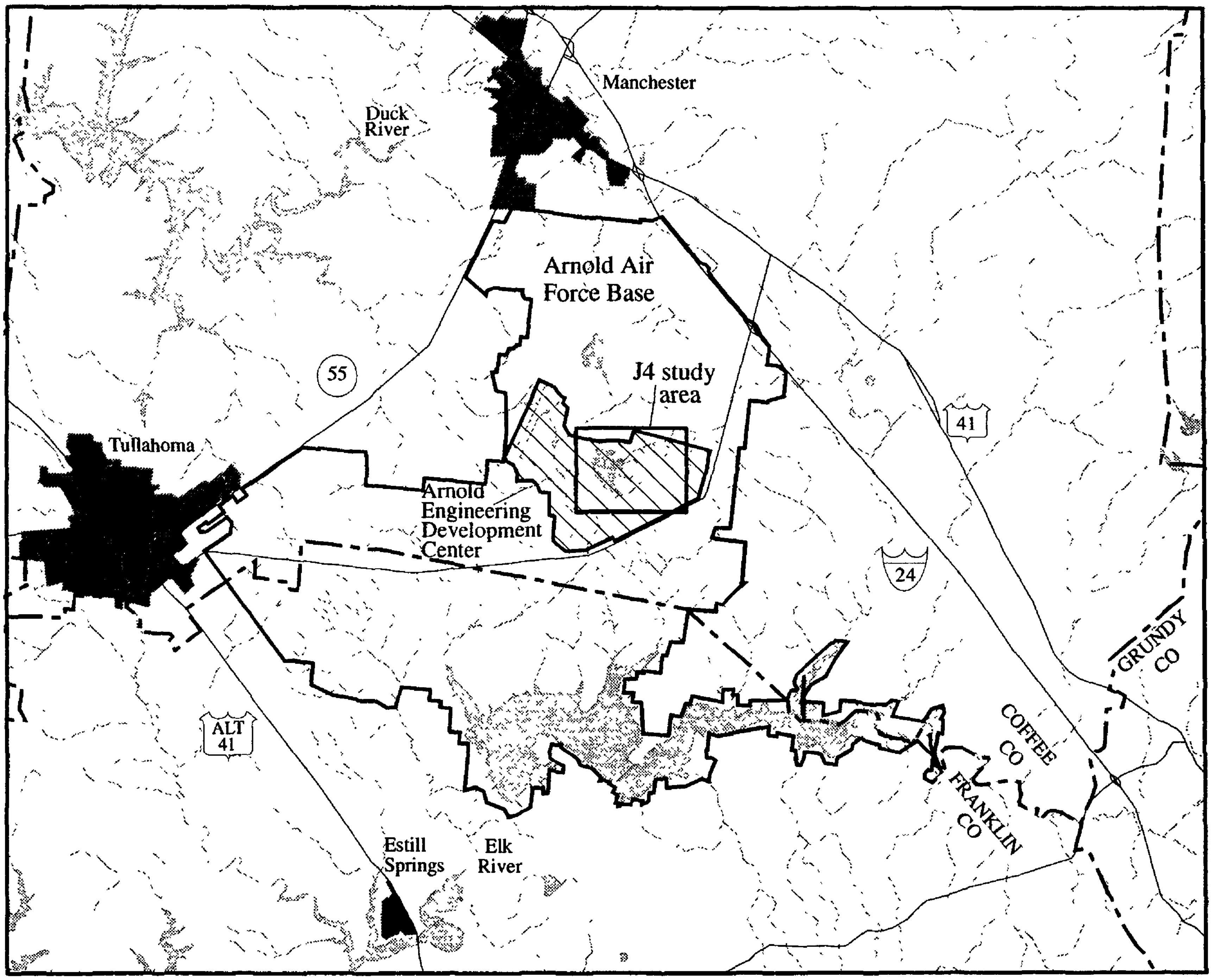
Hydrogeology of the Area Near the J4 Test Cell, Arnold Air Force Base, Tennessee

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 96-4182



Prepared in cooperation with the
UNITED STATES AIR FORCE,
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Cover illustration. See figure 1, page 3.

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Nashville, Tennessee
1996

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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Denver, Colorado 80225-0286

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
foot per day (ft/d)	0.3048	meter per day
gallon per minute (gal/min)	0.06308	liter per second

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 x °C + 32

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Hydrogeology of the Area Near the J4 Test Cell, Arnold Air Force Base, Tennessee

By Connor J. Haugh

EXECUTIVE SUMMARY

The U.S. Air Force operates a major aerospace systems testing facility at Arnold Engineering Development Center (AEDC) in Coffee County, Tennessee. Dewatering operations at one of the test facilities, the J4 test cell, has affected the local ground-water hydrology. The J4 test cell is approximately 100 feet in diameter, extends approximately 250 feet below land surface, and penetrates several aquifers. Ground water is pumped continuously from around the test cell to keep the cell structurally intact. Because of the test cell's depth, dewatering has depressed water levels in the aquifers surrounding the site. The depressions that have developed exhibit anisotropy that is controlled by zones of high permeability in the aquifers. Additionally, contaminants — predominately volatile organic compounds — are present in the ground-water discharge from the test cell and in ground water at several other Installation Restoration Program (IRP) sites within the AEDC facility. The dewatering activities at J4 are drawing these contaminants from the nearby sites.

The effects of dewatering at the J4 test cell were investigated by studying the lithologic and hydraulic characteristics of the aquifers, investigating the anisotropy and zones of secondary permeability using geophysical techniques, mapping the potentiometric surfaces of the underlying aquifers, and developing a conceptual model of the ground-water-flow system local to the test cell.

Contour maps of the potentiometric surfaces in the shallow, Manchester, and Fort Payne aquifers (collectively, part of the Highland Rim aquifer system) show anisotropic water-level depressions centered on the J4 test cell. This anisotropy is the result of features of high permeability such as chert-gravel zones in the regolith and fractures, joints, and bedding planes in the bedrock. The presence of these features of high permeability in the Manchester aquifer results in complex flow patterns in the Highland Rim aquifers near the J4 test cell. The occurrence, distribution, and orientation of these features has a great effect on ground-water flow to the J4 test cell. The depression caused by dewatering extends out horizontally through the aquifers along the most permeable pathways. Since the aquifers above the Chattanooga Shale are not separated by distinct confining units, areas in adjacent aquifers above and below these zones of high permeability in the Manchester aquifer are also dewatered.

Conditions in all Highland Rim aquifers approximate steady-state equilibrium because ground-water withdrawal at the test cell has been continuous since the late 1960's. The average ground-water discharge from the dewatering system at the J4 test cell was 105 gallons per minute, for 1992-95.

The ground-water capture areas in each aquifer extend into all or parts of landfill #2 and leaching pit #2 (IRP site 1), the main testing area (IRP site 7), and the old fire training area (IRP site 10). IRP sites 8 and 12 are outside the ground-water capture areas.

Of the 35 sampled wells in the J4 area, 10 produced water samples containing chlorinated organic compounds such as 1,2-dichloroethane (1,2-DCA), 1,1-dichloroethylene (1,1-DCE), and trichloroethylene (TCE) in concentrations which

exceeded the Tennessee Department of Environment and Conservation Maximum Contaminant Levels (MCL's) for public water-supply systems. The highest concentrations were detected in samples from well AEDC-274 with 45 micrograms per liter (µg/L) 1,2-DCA, 320 µg/L 1,1-DCE, and 1,200 µg/L TCE. These compounds are synthetic and do not occur naturally in the environment. A sample of the ground-water discharge from the J4 test cell also contained concentrations of these compounds that exceed MCL's. Chlorinated organic compounds, including 1,2-DCA; 1,1-DCE; and TCE also have been detected at IRP sites 1, 7, 8, and 10.

The six dewatering wells surrounding the J4 test cell penetrate the Chattanooga Shale and are open to the Highland Rim aquifer system, thereby introducing water from the overlying Highland Rim aquifers into the underlying upper Central Basin aquifer system before it drains to the sump at the bottom of the J4 test cell. However, the possibility that some water could move laterally into the upper Central Basin aquifer system and cross-contaminate the aquifers is highly unlikely. Drilling records indicate that no zones of significant permeability exist in the upper Central Basin aquifer system within the study area. Therefore, the pathway of least resistance for this water to leave the ground-water system is through the dewatering network at the J4 test cell rather than through the upper Central Basin aquifer system.

INTRODUCTION

Arnold Air Force Base (AAFB) occupies about 40,000 acres in Coffee and Franklin Counties, Tennessee (fig.1). The primary mission of AAFB is to support the development of aerospace systems. This mission is accomplished through test facilities at Arnold Engineering Development Center (AEDC), which occupies about 4,000 acres in the center of AAFB. The J4 test cell is one of the main test facilities located at AEDC.

The J4 test cell was constructed in the early 1960's to support the testing of rocket motors. The cell is approximately 100 feet in diameter, extends approximately 250 feet below land surface, and penetrates several aquifers. Ground water is pumped continuously from around the test cell to keep it structurally intact. Because of its depth, dewatering has depressed water levels in the aquifers around the site. The depressions that have developed exhibit anisotropy that is controlled by zones of high permeability in the aquifers. Additionally, contaminants—predominantly volatile organic compounds (VOC's)—are present in the ground-water discharge from the test cell. VOC's also have been detected in ground water at several other sites within the AEDC facility. The dewatering activities at J4 are drawing these contaminants from nearby sites. As part of the United States Air Force (USAF) Installation Restoration Program (IRP), the U.S. Geological Survey (USGS), in cooperation with the USAF and AAFB, is conducting a hydrogeologic investigation of the effects of dewatering at the J4 test cell.

Objectives of the investigation are to: (1) define the subsurface lithology; (2) describe the characteristics of the underlying aquifers; (3) determine the extent of water-level depressions that have developed in each aquifer from dewatering at the test cell; (4) determine the potential for introduction of contaminants from aquifers overlying the Chattanooga Shale, a regional confining unit, to the aquifers underlying this unit; and (5) document current water-quality characteristics in each aquifer and in the discharge from dewatering at J4.

Purpose and Scope

This report describes the results of the hydrogeologic investigation of the area around the J4 test cell. This investigation was conducted in 1994 and 1995. The focus of the report is to document the effects that dewatering operations at the J4 test cell have on the local hydrology. The report includes a definition of the lithologic and hydraulic properties of the aquifers, a description of ground-water flow, estimates of the extent of the water-level depressions and ground-water capture areas resulting from dewatering at the J4 test cell, descriptions of ground-water quality, and a conceptualization of the ground-water-flow system in the J4 area. This information should aid AAFB personnel in making decisions about the protection and management of the ground-water resources.

Approach

The J4 hydrogeologic investigation used existing and new data and several investigative methods to address the objectives of the study. Methods used

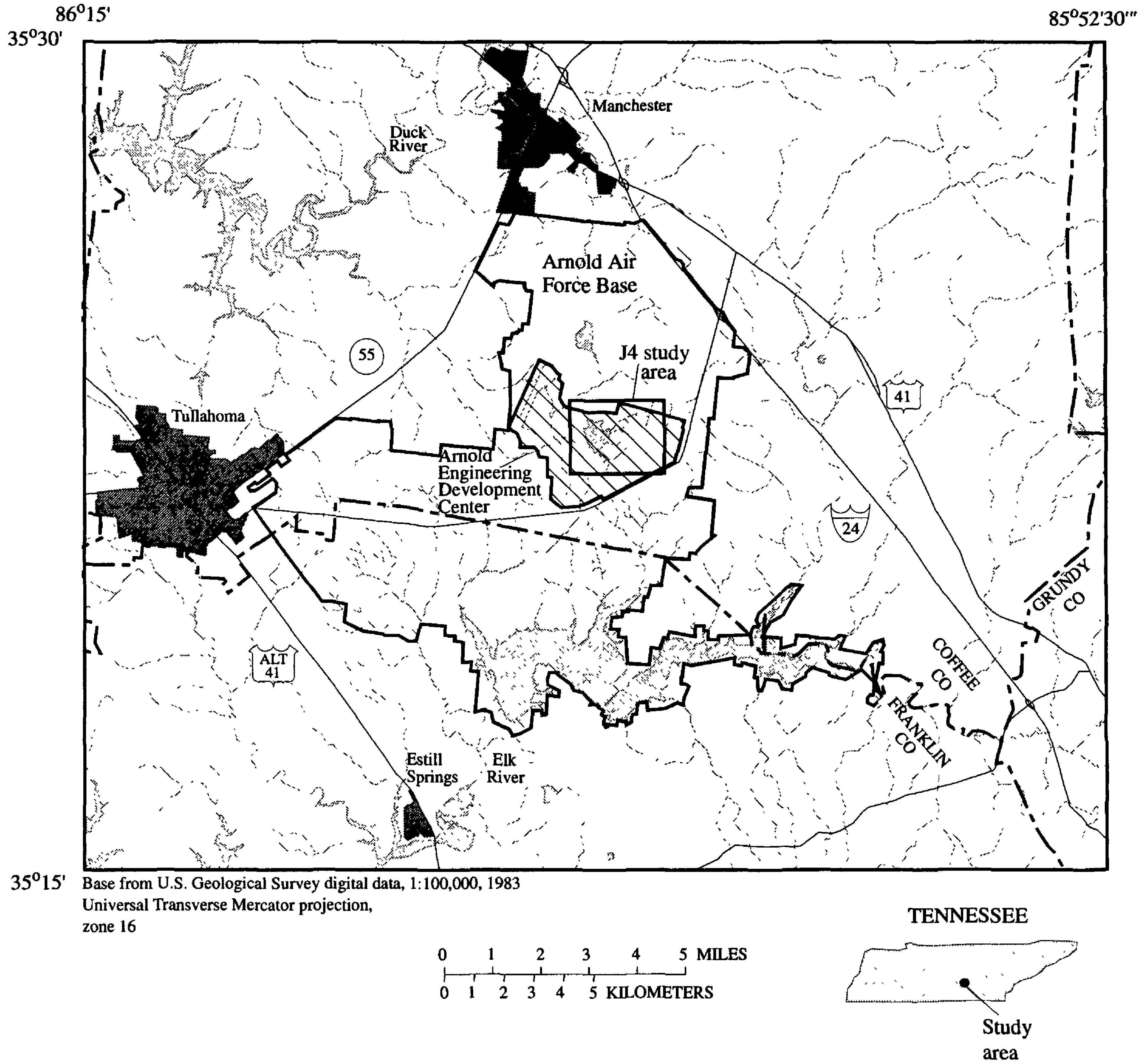


Figure 1. Location of the study area at Arnold Air Force Base, Tennessee.

included studying lithologic and hydraulic characteristics of subsurface units, investigating anisotropy and zones of secondary permeability using geophysical techniques, mapping the potentiometric surfaces in the underlying aquifers, and developing a conceptual model of the ground-water-flow system.

Data available from previous studies on approximately 120 wells in the J4 study area were collected and entered into a computer data base to produce geologic and hydrologic maps. Regional data on the subsurface geometry and lithology of the major geologic units were refined based on the study area data. Lineations from a previous study (Haugh and Mahoney, 1994) were further assessed. These data were evaluated and initial concepts of the flow system and the effects of dewatering at J4 on the system were formulated. Areas needing additional data were identified.

Twenty-seven monitoring wells were drilled by the USGS to collect additional information to help understand the ground-water-flow system. These wells provided necessary lithologic information and hydrologic data concentrated near the J4 test cell. Borehole geophysical logs were made in 20 wells to assist lithologic interpretations. Water samples were collected from the J4 test cell ground-water discharge, 26 of the wells drilled for this study, and 9 pre-existing wells. Information about the 35 wells sampled is published in Haugh (1996).

Continuous water-level data were collected from 14 wells to monitor annual water-level fluctuations. Discharge data from the J4 test cell were collected to quantify the amount of ground water pumped from around the cell. Rainfall data also were collected at AEDC (Haugh, 1996).

Surface-geophysical surveys were conducted at three sites to gather data on anisotropy and orientations of features of secondary permeability. Methods used included azimuthal square-array direct-current resistivity techniques and azimuthal electromagnetic (EM) terrain-conductivity surveys.

Water-level measurements were made in approximately 150 wells in the study area. Potentiometric-surface maps were constructed for each aquifer. From these maps, the capture areas from dewatering at the J4 test cell were estimated for each aquifer.

DESCRIPTION OF STUDY AREA

The study area encompasses 4 mi^2 of the main testing area at AEDC (fig. 2). The J4 test cell is located on the western side of the AEDC testing facilities. The Duck River-Elk River drainage divide runs through the eastern and southern edges of AEDC testing facilities. Land-surface elevations across the AEDC testing facilities range from about 1,120 feet above sea level at the Duck River-Elk River drainage divide to about 1,030 feet above sea level at the western boundary of the facilities. West of the J4 test cell is a large retention pond. Discharge water from J4 flows through a ditch to the retention pond. Dewatering operations also occur at the Mark I test facility, located on the eastern side of the AEDC testing facilities. Dewatering here only occurs from a depth of about 30 feet; therefore, it has a limited effect on the ground-water system.

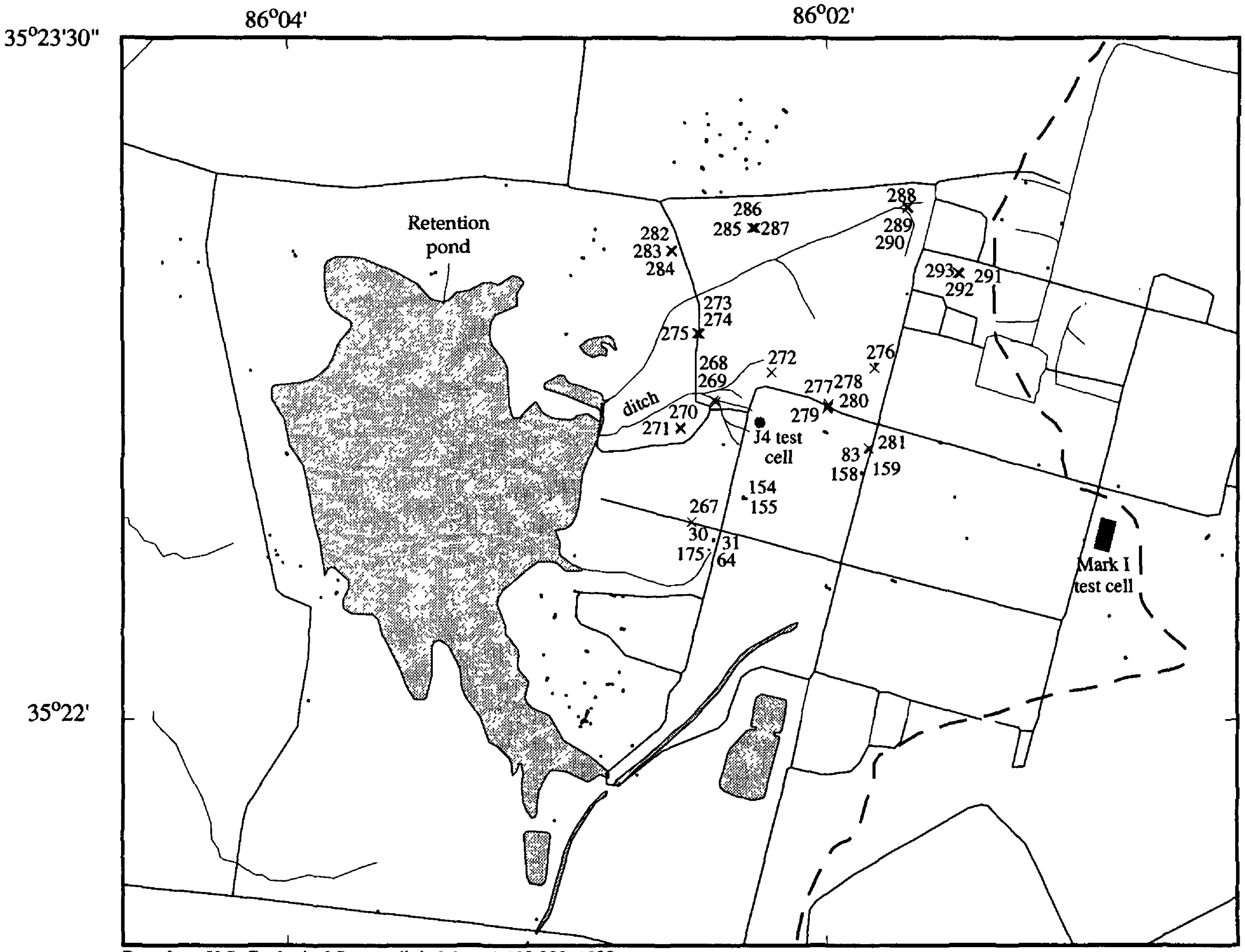
GEOLOGY

The AAFB area is located in the eastern part of the Highland Rim physiographic region of Tennessee (Miller, 1974). The Highland Rim is the remnant of an extensive erosional surface developed on Paleozoic strata that once covered the area now occupied by the Central Basin.

The stratigraphy underlying the AEDC area consists predominantly of impure carbonate rocks, but shales also are present (fig. 3). From oldest to youngest, the strata are Ordovician undifferentiated formations, Devonian and Mississippian Chattanooga Shale; and Mississippian Fort Payne Formation, Warsaw Limestone, and St. Louis Limestone. Regolith formed by weathering of the underlying bedrock occurs throughout the study area (fig. 3).

The Ordovician undifferentiated formations consist of green-gray to blue-gray to light gray limestone, green-gray calcareous shale, mudstone, and silty shale. Individual formations are difficult to identify because many have similar characteristics. During drilling of wells for this investigation, the bedrock below the Chattanooga Shale appeared to be a lithologically uniform, thick, dense limestone.

The Ordovician formations are unconformably overlain by the Chattanooga Shale. This formation ranges from 20 to 25 feet thick in the study area and is dark grayish black, fissile, and carbonaceous. The Chattanooga Shale is an important marker bed throughout parts of the eastern United States because



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection,
zone 16

0 1,000 2,000 3,000 FEET

0 250 500 750 METERS

EXPLANATION

— — SURFACE-WATER DRAINAGE DIVIDE

× 267 WELL LOCATION AND NUMBER- Well drilled for this study

• WELL LOCATION- Well existing previous to this study. Well number included if ground water from well was sampled

Figure 2. Location of wells installed by the U.S. Geological Survey and other wells in the J4 study area at Arnold Engineering Development Center.

<table>
<tr><th>Stratigraphy</th><th>Thickness of unit, in feet</th><th>Lithology</th><th colspan="2">Hydrogeologic Unit</th></tr>
<tr><td rowspan="2">Regolith derived from in-situ weathering of the St. Louis Limestone, Warsaw Limestone and/or Fort Payne Formation</td><td rowspan="2">45-100</td><td>Clay, silt, and sand with some chert and rock fragments.</td><td rowspan="4">Highland Rim aquifer system</td><td>Shallow aquifer</td></tr>
<tr><td>Rock fragments, chert gravel and rubble with some clay.</td><td>Manchester aquifer, upper part</td></tr>
<tr><td rowspan="2">Fort Payne Formation</td><td rowspan="2">10-40</td><td>Fractured and dissolutioned cherty limestone and siltstone.</td><td>Manchester aquifer, lower part</td></tr>
<tr><td>Dark gray siltstone and dense, cherty limestone, bedded chert. Few fractures.</td><td>Fort Payne aquifer</td></tr>
<tr><td>Chattanooga Shale</td><td>20-25</td><td>Dark, grayish black, carbonaceous shale.</td><td colspan="2">Chattanooga confining unit</td></tr>
<tr><td>Ordovician formations, undifferentiated</td><td>Greater than 300</td><td>Limestone with some siltstone and calcareous shale.</td><td colspan="2">Central Basin aquifer system, upper part</td></tr>
</table>

Figure 3. Stratigraphy, lithology, and hydrogeologic units near the J4 test cell at Arnold Engineering Development Center.

it is a widespread unit and its characteristics are consistent.

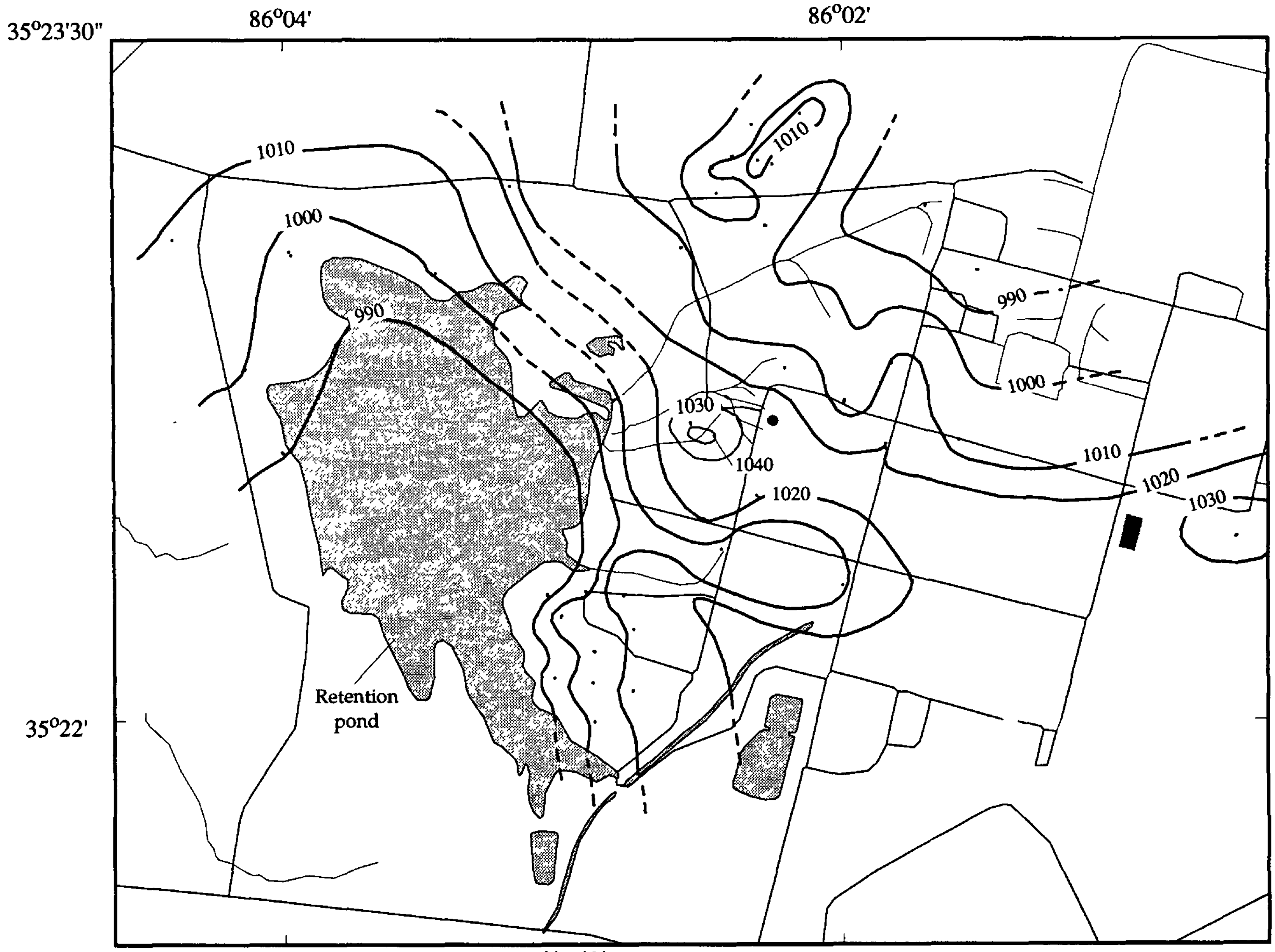
The Chattanooga Shale is overlain by the Fort Payne Formation. The Fort Payne Formation as rock at AEDC ranges from 10 to 40 feet thick and consists of dark gray siltstone and cherty limestone with thin beds of crinoidal limestone and minor amounts of shale. Fracturing is evident within this unit. The largest fractures generally are near the bedrock/regolith contact where they have been enlarged through dissolution.

Regolith derived from weathering of Mississippian carbonate rocks (including in ascending order, the Fort Payne Formation, Warsaw Limestone, and/or St. Louis Limestone) typically is 45 to 100 feet thick in the AEDC area. The Warsaw and St. Louis Limestones have been completely reduced to chert, silt, sand, gravel, and clay. Weathering of the Fort Payne Formation has occurred to irregular depths and may be structurally controlled in some areas (fig. 4). Chert gravels are prevalent at various horizons in the regolith in the study area.

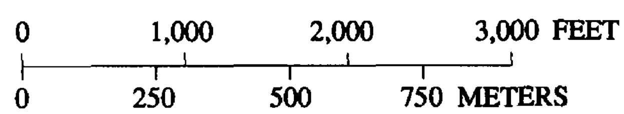
Origins of Chert Gravels

Chert gravels, present in abundance in regolith throughout the study area, are believed to be the result of an early diagenesis where silica was reorganized and focused as chert deposits in areas associated with bioherms. Thus, the occurrence and distribution of the chert gravels in some cases may be controlled by the locations and extent of bioherms.

Bioherms and biostromes are masses of rock composed of calcareous remains of sedentary sea-dwelling organisms. They differ from one another primarily in morphology and sometimes paleontology. Bioherms usually are mound-like or lenticular and



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection,
zone 16



EXPLANATION

—— 990 – – – TOP OF ROCK CONTOUR--Shows altitude of the top of the bedrock surface. Dashed where approximately located. Contour interval 10 feet. Datum is sea level

• WELL--Provided control point on top of the bedrock surface

Figure 4. Altitude of the top of the bedrock surface in the Fort Payne Formation in the J4 study area at Arnold Engineering Development Center.

consist of organisms associated with reef structures such as algae, corals, and stromatoporoids. In aerial extent, bioherms may be tens to hundreds of feet wide and hundreds to thousands of feet long. Biostromes are sheetlike or blanketing and consist of beds of similar organisms. The major diagnostic features are the presence of a basal fossiliferous shale mound in bioherms and the presence of sedimentary structures in biostromes (Marcher, 1962a,1963; Razem, 1976; Milici and others, 1979; Ausich and Meyer, 1990). Lenses of shale or mudstone also may be present in biostromes but are limited in extent and thickness.

The presence and paleontology of bioherms and biostromes in the Mississippian formations of central Tennessee, south-central Kentucky, and northern Alabama is well documented (Marcher, 1962a, 1963; Chowns and Elkins, 1974; Razem, 1976; Moran, 1977; Milici and others, 1979; MacQuown and Perkins, 1982; Ausich and Meyer, 1990). The Fort Payne Formation and the Warsaw Limestone are significantly noted as containing such structures. These limestones are proposed to be of shallow-water, peritidal, or supratidal origin. The organisms documented in these structures are predominately crinoids, followed by brachiopods, blastoids, bryozoans, ostracods, endothyroid foraminifera, and sponge spiculites.

As these structures weather and the soluble material is dissolved and removed, the insoluble chert, clay, and silt remain to form a component of the regolith. In some locations, the chert remains as hard bedded layers within a clay and silt matrix. In other locations, it exists as chert-gravel zones. When these chert-gravel zones are below the water table, particularly when they occur near the top of the bedrock surface, they form zones of high permeability that transmit water more readily than areas where chert is absent. The zones may be tens to hundreds of feet wide and hundreds to thousands of feet long.

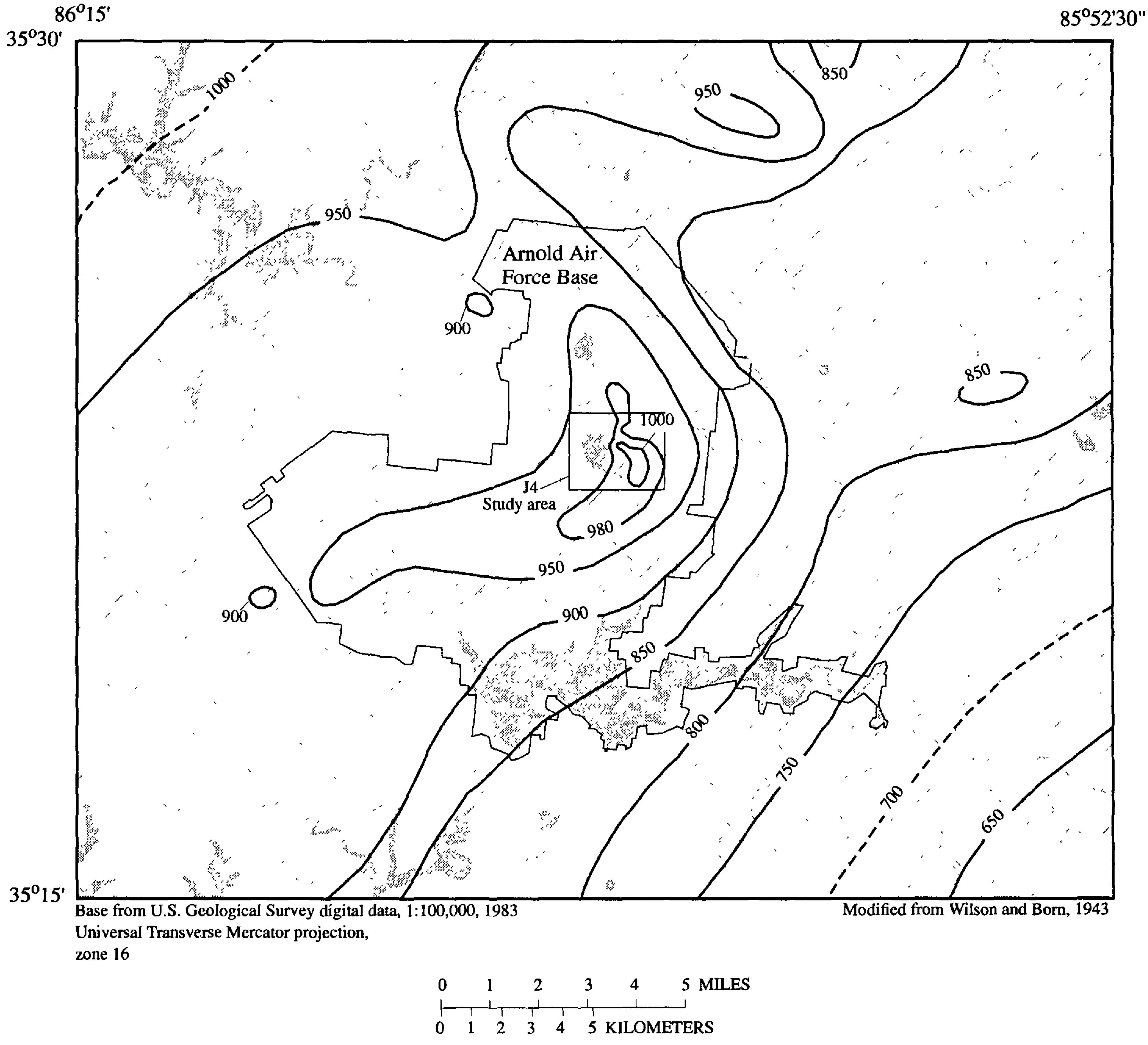
Fractured Bedrock

The geologic structure in the AAFB area has been affected by regional tectonic activity and local, small-scale folding. The rocks of the AAFB area range from gently dipping to nearly horizontal. Superimposed on the regional structure are local folds and flexures. A previous study by Haugh and Mahoney (1994) identified a northeast-southwest trending anticline in the Chattanooga Shale underlying the AAFB (fig. 5). The crest of this anticline is directly beneath the J4 area (fig. 6). Pressures that formed the anticline likely have influenced fracture development, and the extent and degree of interconnection of these features undoubtedly influence the hydrogeology of the area. Data documenting the occurrence of fractures and the geologic structure in the AAFB area are contained in various site-specific reports (Dames and Moore, 1975; Engineering Science, 1984; Battelle Columbus Division, 1988, 1989a, 1989b; U.S. Army Corps of Engineers, Mobile District, 1988a, 1988b; Battelle Denver Operations, 1989; Benham Group, 1989a, 1989b; Oak Ridge National Laboratory, 1989a, 1989b; Post, Buckley, Schuh and Jernigan, Inc., 1989a, 1989b, 1989c, 1989d, 1989e, 1989f; and Haugh and others, 1992).

The folding of beds and attendant stresses have resulted in the development of vertical fractures in bedrock throughout the area. Fracturing occurred in response to tectonic stresses that caused the regional or local folding episodes. These fractures typically are vertical or nearly vertical and have developed in an orthogonal pattern that defines the structural grain of the area. Lineations, possibly correlating with fracture traces, were identified from low-altitude color aerial photographs of the AAFB (fig. 7) (Haugh and Mahoney, 1994). The photographs were viewed as stereographic pairs to enhance observation of topography, alignment of stream channels, soil-tonal variation, or surface depressions that identify the lineaments (Siddiqui and Parizek, 1971). The minimum length for a feature to be delineated was 100 feet.

Lineations mapped throughout the AAFB area show major orientations centered at N. 35° W. and N. 50° E. (Haugh and Mahoney, 1994). Lineations within the AEDC main testing area were analyzed to see if the area surrounding the J4 test cell showed a similar orientation (fig. 8). The group of lineations having the highest frequency of occurrence in the J4 area lies between N. 50° W. and N. 30° W. and is centered at N. 40° W. A secondary grouping of lineations occurs between N. 30° E. and N. 40° E. and is centered at N. 35° E.

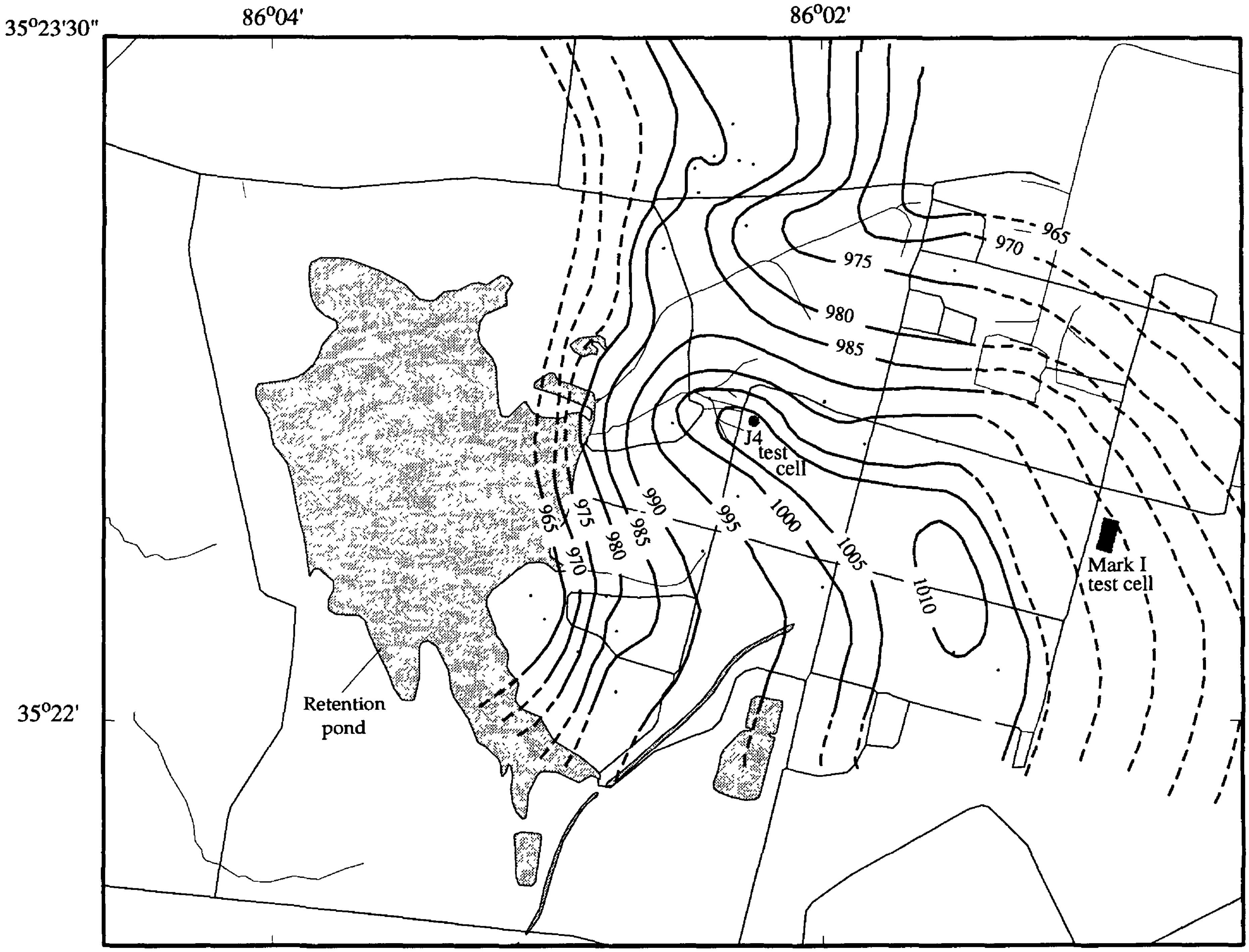
The orientation of lineations, which may correspond with the subsurface fractures, helps define structural grain in an area, particularly where hydrogeologic features are nonhomogeneous and anisotropic. Most commonly, these lineations are thought to represent diffuse effects from several parallel features; but in some cases, they represent a single fault or fracture. Lattman and Parizek (1964) suggest that lineations apparent from aerial photography may represent subsurface zones containing many fractures.



EXPLANATION

——900 - - - STRUCTURE CONTOUR--Shows altitude of the top of the Chattanooga Shale. Dashed where approximately located. Contour interval 5 feet. Datum is sea level

Figure 5. Generalized altitude of the top of the Chattanooga Shale in the Arnold Air Force Base area.



Base from U.S. Geological Survey digital data, 1:100,000 1983
Universal Transverse Mercator projection,
zone 16

0 1,000 2,000 3,000 FEET
0 250 500 750 METERS

EXPLANATION

—— 995 – – – STRUCTURE CONTOUR--Shows altitude of the top of the Chattanooga Shale. Dashed where approximately located. Contour interval 5 feet. Datum is sea level

• WELL--Provided control point on top of the Chattanooga Shale

Figure 6. Altitude of the top of the Chattanooga Shale in the J4 study area at Arnold Engineering Development Center.

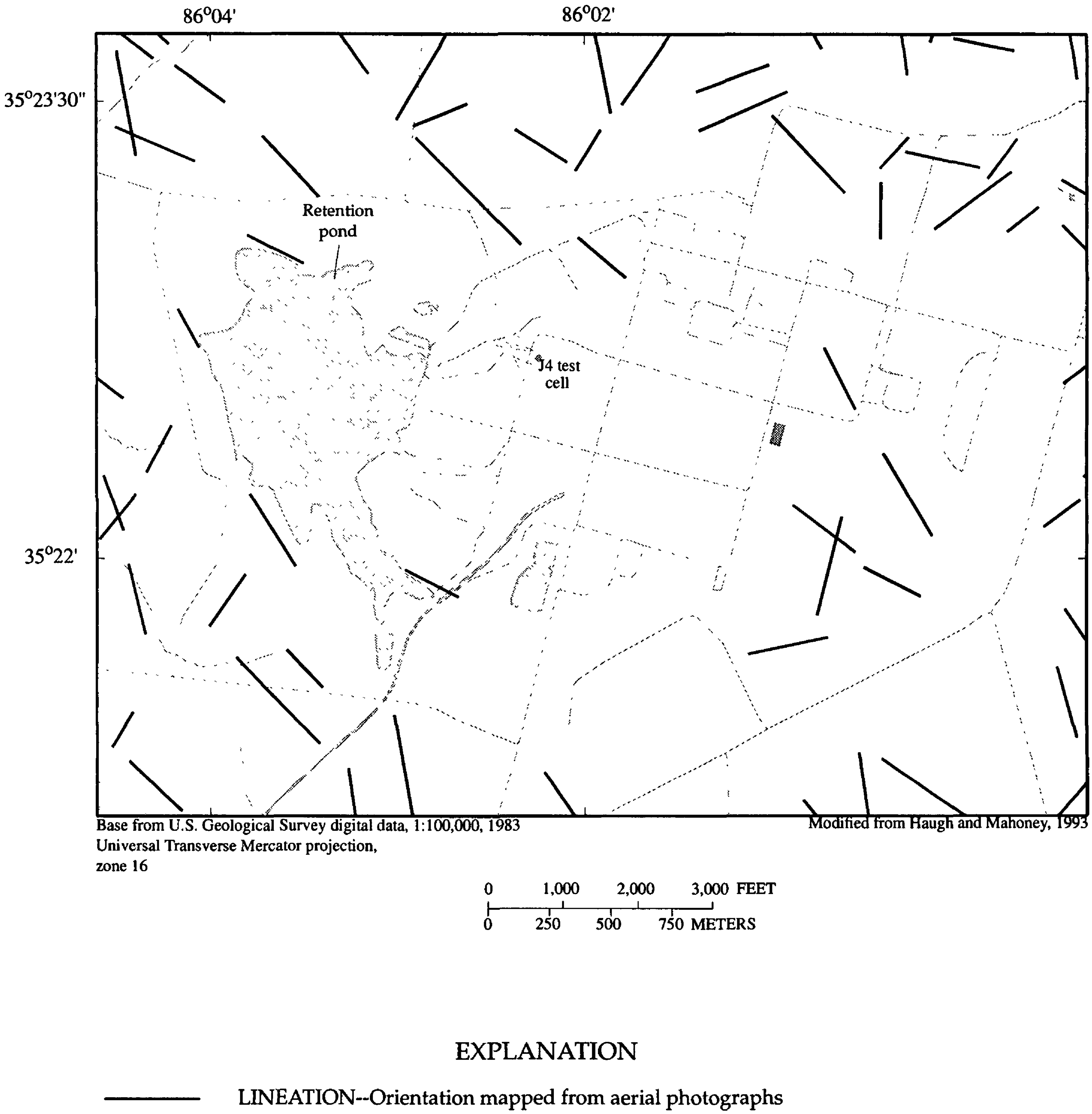
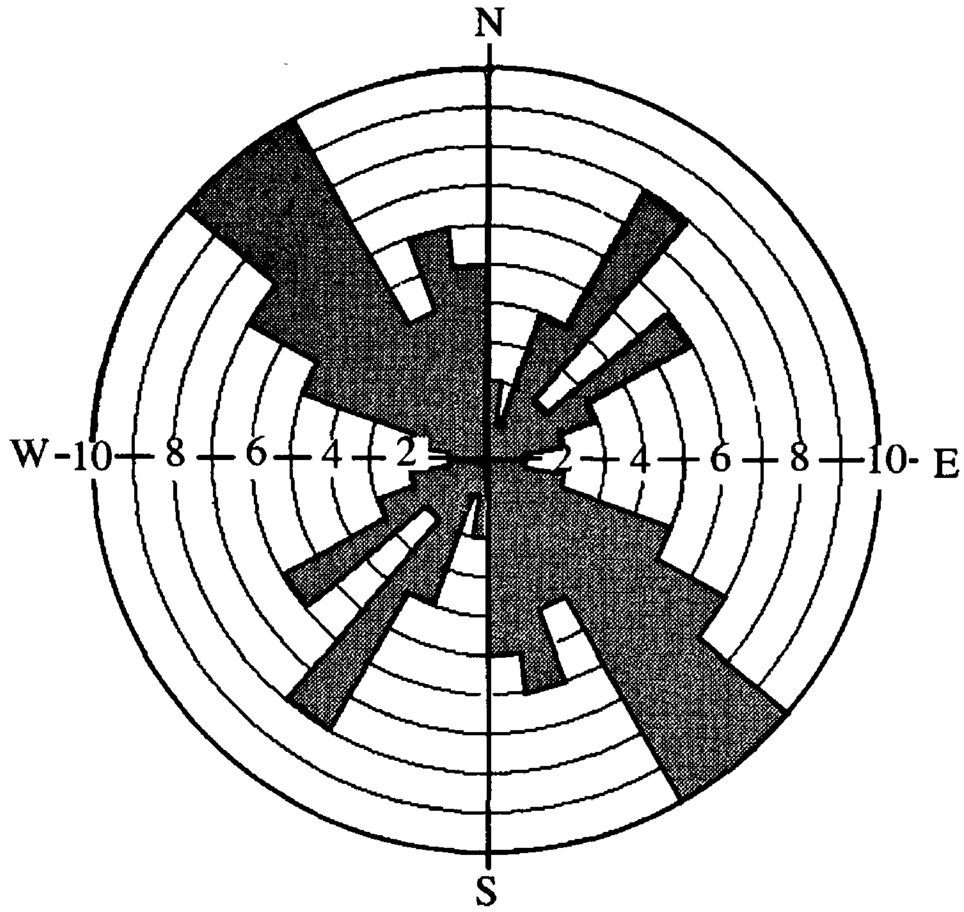


Figure 7. Lineations in the J4 study area at Arnold Engineering Development Center.



Number of observations: 79

Frequency of observation shown by length of radius for that bearing

Figure 8. Rose diagram showing frequency and orientation of lineations in the J4 study area at Arnold Engineering Development Center.

HYDROGEOLOGY

Two ground-water systems have been defined in the study area: the Highland Rim aquifer system and the upper Central Basin aquifer system (Brahana and Bradley, 1986a, 1986b). The Chattanooga Shale functions as a confining unit separating these two systems (fig. 3).

Aquifers

The Highland Rim aquifer system in the study area includes three main water-bearing zones (from youngest to oldest): the shallow aquifer, the Manchester aquifer, and the Fort Payne aquifer. They differ from each other in degree of weathering, amount of chert, and type of weathering product; however, they are not separated by confining units of any significant lateral extent in the study area, so water is free to flow between these zones at most locations. The Chattanooga Shale forms the base of this flow system and functions as a confining unit separating this system from the underlying upper Central Basin system (fig. 3). The upper Central Basin aquifer system consists of units below the Chattanooga Shale. The potential for flow through the Chattanooga Shale appears to be small, if existent at all, based on drilling and water-quality data. The upper Central Basin aquifer system is not a major water-bearing unit within the study area.

Hydraulic-conductivity data available from approximately 40 slug tests and 8 aquifer tests made in wells in the Highland Rim aquifers range from 0.02 to 84 ft/day (Haugh and Mahoney, 1994). The highest conductivities are reported for the shallow and Manchester aquifers. No hydraulic-conductivity data are available in the study area for the upper Central Basin aquifer system, but drilling records and geophysical logs from four wells drilled at AAFB that are within 1,000 feet of the J4 test cell indicate that no significant zones of permeability exist in the upper Central Basin aquifer system (Haugh and others, 1992; Haugh and Mahoney, 1994; Haugh, 1996).

The shallow aquifer consists of silt and clay, rock fragments, and minor amounts of chert. Ground water occurs under water-table conditions and may be perched in some locations. Based on 17 measurements, hydraulic conductivity within the shallow aquifer ranges from 0.9 to 18 ft/day with a median value of 9 ft/day. The thickness of the shallow aquifer in the J4 study area ranges from 30 to 45 feet.

The Manchester aquifer supplies water to most domestic wells in the area. This aquifer can be subdivided into two zones. The upper part of the Manchester aquifer consists of water-bearing chert gravel in the regolith. The lower part of the Manchester aquifer consists of fractures and solution openings in the upper part of the bedrock of the Fort Payne Formation (Burchett and Hollyday, 1974). Drawdown distributions from three aquifer tests in the upper part of the Manchester aquifer show anisotropic features believed to be related to directional dependent transmissivity (Woodward-Clyde Consultants, 1990). Within the lower part of the Manchester aquifer, fractures trending northeast-southwest and northwest-southeast appear to create a fracture-flow system, based on measurements, hydraulic conductivity ranges from 0.1 to 69 ft/day, with a median value of 28 ft/day. The Manchester aquifer in the J4 study area ranges in thickness from 20 to 40 feet (Haugh and Mahoney, 1994).

The Fort Payne aquifer consists of dense limestone that ranges in thickness from 10 to 40 feet in the J4 study area. Based on 10 measurements, the hydraulic conductivity ranges from 0.02 to 8.6 ft/day, with a median value of 1.6 ft/day (Haugh and Mahoney, 1994).

Anisotropy and Heterogeneity

Well yields in the AAFB area vary from less than 1 gal/min to more than 500 gal/min (Burchett, 1977; Haugh and Mahoney, 1994). Well yields in the 27 wells drilled for this study ranged from less than 1 gal/min to more than 250 gal/min (Haugh, 1996). This variability in well yields results from heterogeneities within the aquifers and can be observed over distances as short as 100 feet. In the lower part of the Manchester aquifer, wells that intercept a fracture or fracture zone produce more water than those that do not. Similarly, in the upper part of the Manchester aquifer, wells screened in a chert-gravel zone produce more water than those outside a gravel zone. The presence within the aquifer of these features of high permeability creates a system that is heterogeneous and anisotropic on a local scale.

The occurrence, distribution, and orientation of these features of high permeability have a strong effect on ground-water flow to the J4 test cell. Several surface-geophysical techniques were applied to investigate the occurrence and orientation of these features. Techniques applied consisted of azimuthal square-array direct-current resistivity surveys, azimuthal electromagnetic (EM) terrain conductivity surveys, and very low frequency (VLF) EM surveys. Each of these techniques was applied at three sites near the J4 test cell (fig. 9).

Square-Array Direct-Current Resistivity Surveys

Azimuthal square-array direct-current resistivity soundings were used to investigate anisotropy in the subsurface at three sites near the J4 test cell. Data were collected for eight different square sizes ranging from 16.4 feet to 164 feet (tables 1, 2, and 3). The different square sizes allow the soundings to be interpreted as a function of depth. The sounding depth is approximately equal to the square size. For each square size, the array is rotated and a measurement made to investigate directional variations. Measurements are made every 15 degrees for positions from 0 to 165 degrees. For plotting purposes, data for positions from 180 to 345 degrees are determined by adding 180 degrees to the set of measured positions. A complete discussion of the square array and methods of data analysis is provided by Habberjam (1972, 1975, 1979).

Variations in azimuthal resistivities can be attributed to anisotropy in the subsurface environment. If the azimuthal resistivities plot as a circle, no variation in direction is evident, and the subsurface environment is interpreted to be laterally homogeneous and isotropic. If the azimuthal resistivities plot as an ellipse, variation in direction is evident and the subsurface environment is interpreted to be anisotropic. Under anisotropic conditions, the orientation of the highest conductivity is in the direction of the minimum resistivity. In the J4 study area, depending on the square size and associated depth of investigation, the high-conductivity orientation could correspond to the fracture-strike orientation in the bedrock or the orientation of more permeable gravels in the regolith. Each of the three sites surveyed in the study area show anisotropic effects at all depth soundings (figs. 10, 11, and 12).

For each depth sounding at all three sites, the highest conductivity orientation was determined graphically and analytically (table 4). Both methods yield similar results. At site A, the first four squares sound to depths which sample the regolith and have calculated conductivity orientations from N. 11° E. to N. 22° E. with an average of N. 16° E. The sixth and seventh squares sound to depths that encompass the bedrock as well. The sixth square has a calculated

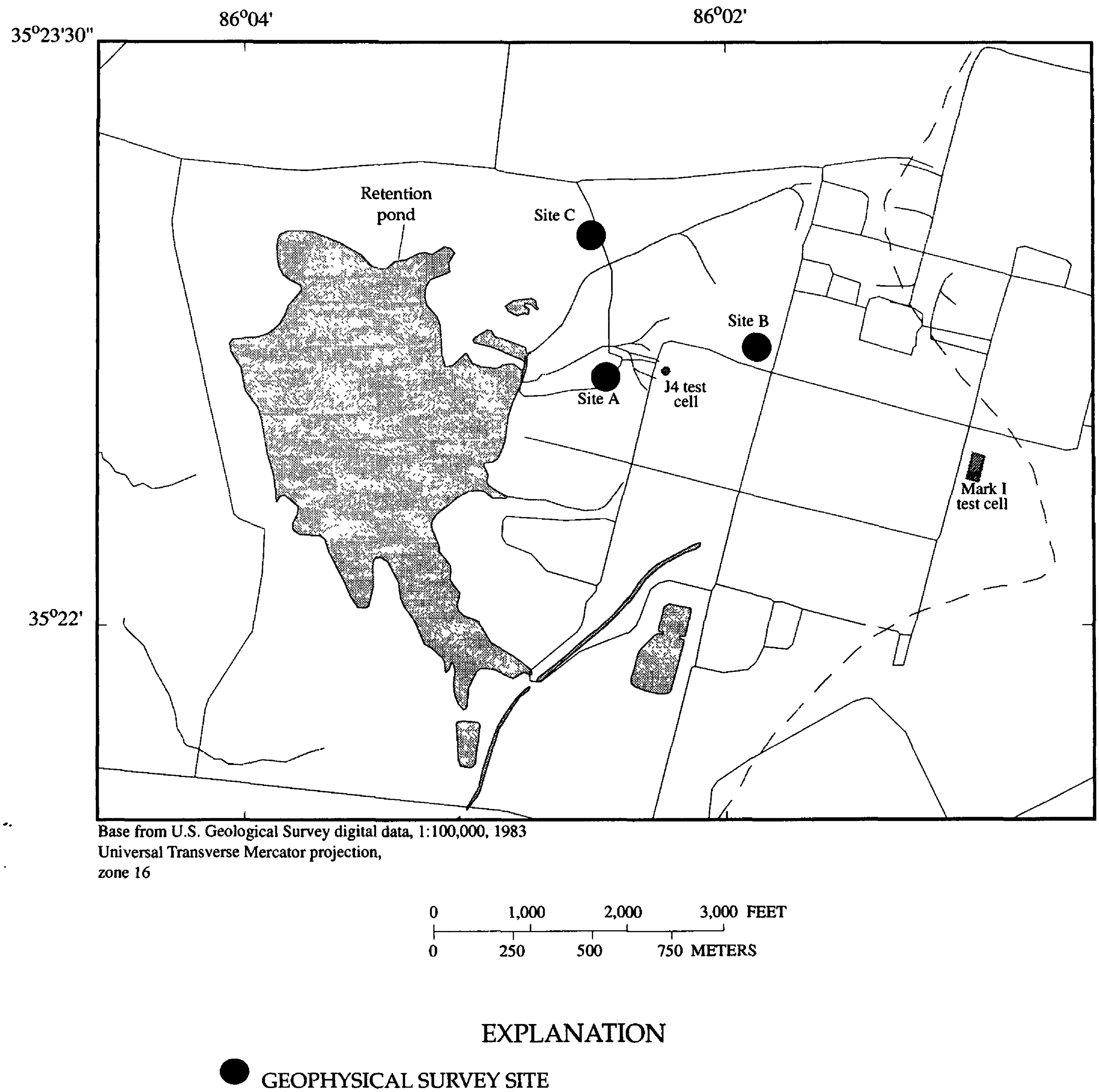


Figure 9. Location of sites where geophysical surveys were performed in the J4 study area at Arnold Engineering Development Center.

Table 1. Azimuthal apparent resistivities collected from site A in the J4 study area at Arnold Engineering Development Center

Square number	Square size (feet)	Mean resistivity	Azimuthal apparent resistivities, in ohm-meters											
			0	15	30	45	60	75	90	105	120	135	150	165
1	16.4	209	202	150	188	205	217	226	226	238	242	215	202	202
2	23.3	234	211	171	206	222	236	258	275	270	274	241	225	215
3	32.8	253	229	192	216	225	248	272	301	300	297	265	249	244
4	46.3	272	249	217	218	228	249	288	331	330	326	289	275	267
5	65.6	293	277	245	226	238	277	310	340	341	346	314	304	302
6	92.8	295	296	264	236	248	301	301	309	318	317	322	321	307
7	131	284	293	277	239	255	308	312	299	310	325	247	249	289
8	164	257	296	286	256	101	309	299	279	307	304	85	290	277

Table 2. Azimuthal apparent resistivities collected from site B in the J4 study area at Arnold Engineering Development Center

Square number	Square size (feet)	Mean resistivity	Azimuthal apparent resistivities, in ohm-meters											
			0	15	30	45	60	75	90	105	120	135	150	165
1	16.4	267	271	311	304	286	286	304	342	368	335	300	260	267
2	23.3	253	281	311	302	323	345	321	354	351	376	301	297	253
3	32.8	285	286	312	314	342	392	406	416	432	445	391	353	285
4	46.3	361	357	400	409	422	483	497	517	503	484	441	407	361
5	65.6	397	426	405	426	433	494	546	516	454	435	455	392	397
6	92.8	339	346	356	358	379	412	485	441	432	435	416	335	339
7	131	262	266	255	256	279	288	347	336	265	246	305	227	262
8	164	259	326	223	354	232	220	19	211	211	39	374	484	259

Table 3. Azimuthal apparent resistivities collected from site C in the J4 study area at Arnold Engineering Development Center

Square number	Square size (feet)	Mean resistivity	Azimuthal apparent resistivities, in ohm-meters											
			0	15	30	45	60	75	90	105	120	135	150	165
1	16.4	372	341	328	312	339	360	355	390	391	429	420	405	398
2	23.3	417	385	363	333	352	403	394	427	427	506	500	460	455
3	32.8	461	421	408	362	390	421	433	485	500	560	550	516	484
4	46.3	499	437	455	431	428	480	498	572	551	567	562	518	490
5	65.6	524	460	496	498	458	526	552	632	591	563	535	489	490
6	92.8	511	405	407	436	441	519	609	746	628	545	500	443	451
7	131	517	313	401	450	436	443	506	1097	617	479	467	478	515
8	164	405	305	360	412	409	405	399	411	299	421	461	528	450

Table 4. Interpreted high-conductivity orientations from square-array data in the J4 study area at Arnold Engineering Development Center

[--, not analyzed]

Square number	Square size (feet)	Site A		Site B		Site C	
		Analytical method	Graphical method	Analytical method	Graphical method	Analytical method	Graphical method
1	16.4	N13°E	N15°E	N19°E	N15°E	N34°E	N30°E
2	23.3	N11°E	N15°E	N11°E	N15°E	N37°E	N30°E
3	32.8	N17°E	N15°E	N23°E	N15°E	N36°E	N30°E
4	46.3	N22°E	N15°E	N15°E	N15°E	N26°E	N30°E
5	65.6	N26°E	N30°E	N7°E	N-S	N8°E	N-S
6	92.8	N32°E	N30°E	N16°E	N15°E	N4°E	N-S
7	131	--	N30°E, N37.5°W	--	N37.5°E N45°W	--	N-S W-E

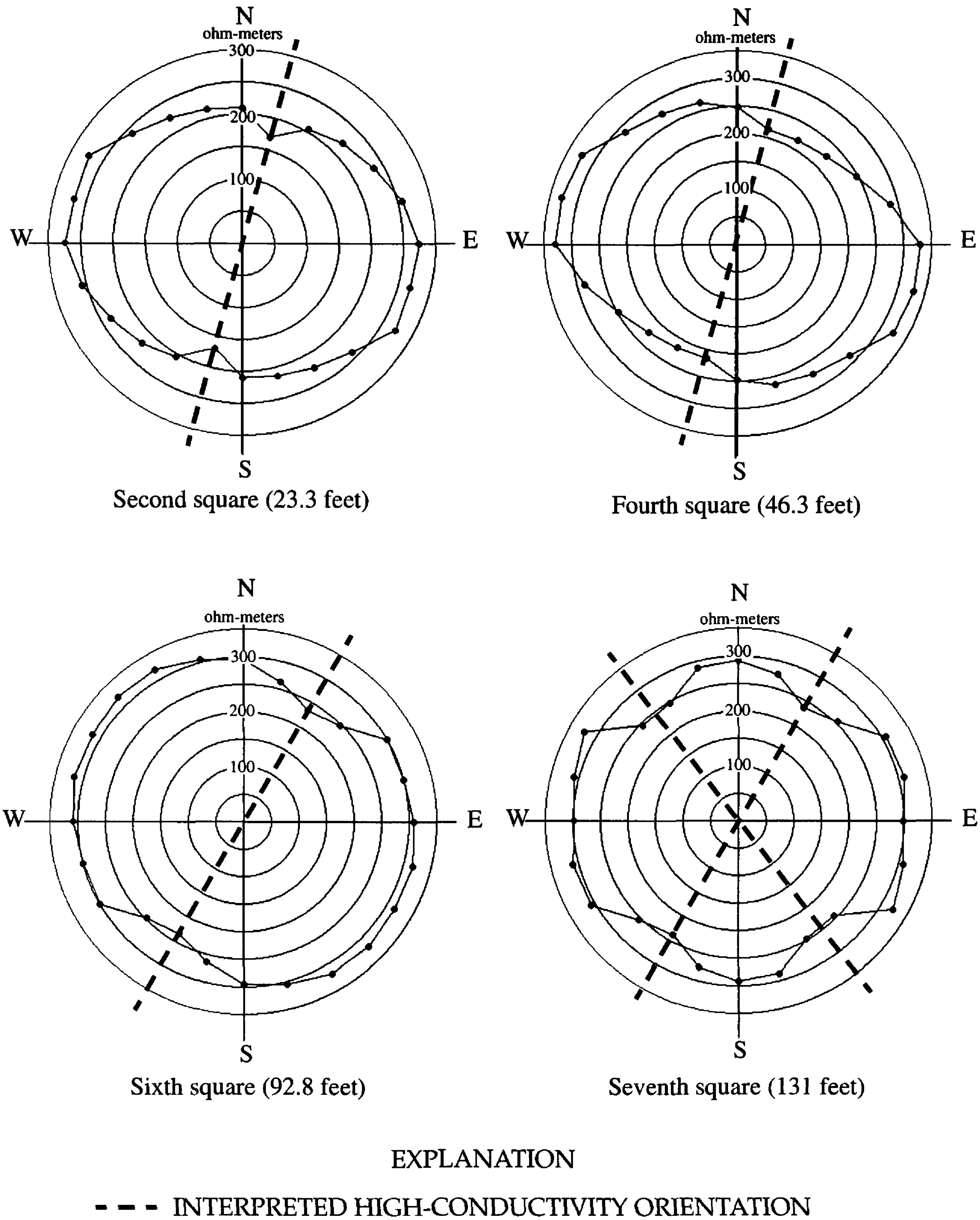


Figure 10. Square-array apparent resistivity plotted against azimuth for selected squares at site A in the J4 study area at Arnold Engineering Development Center.

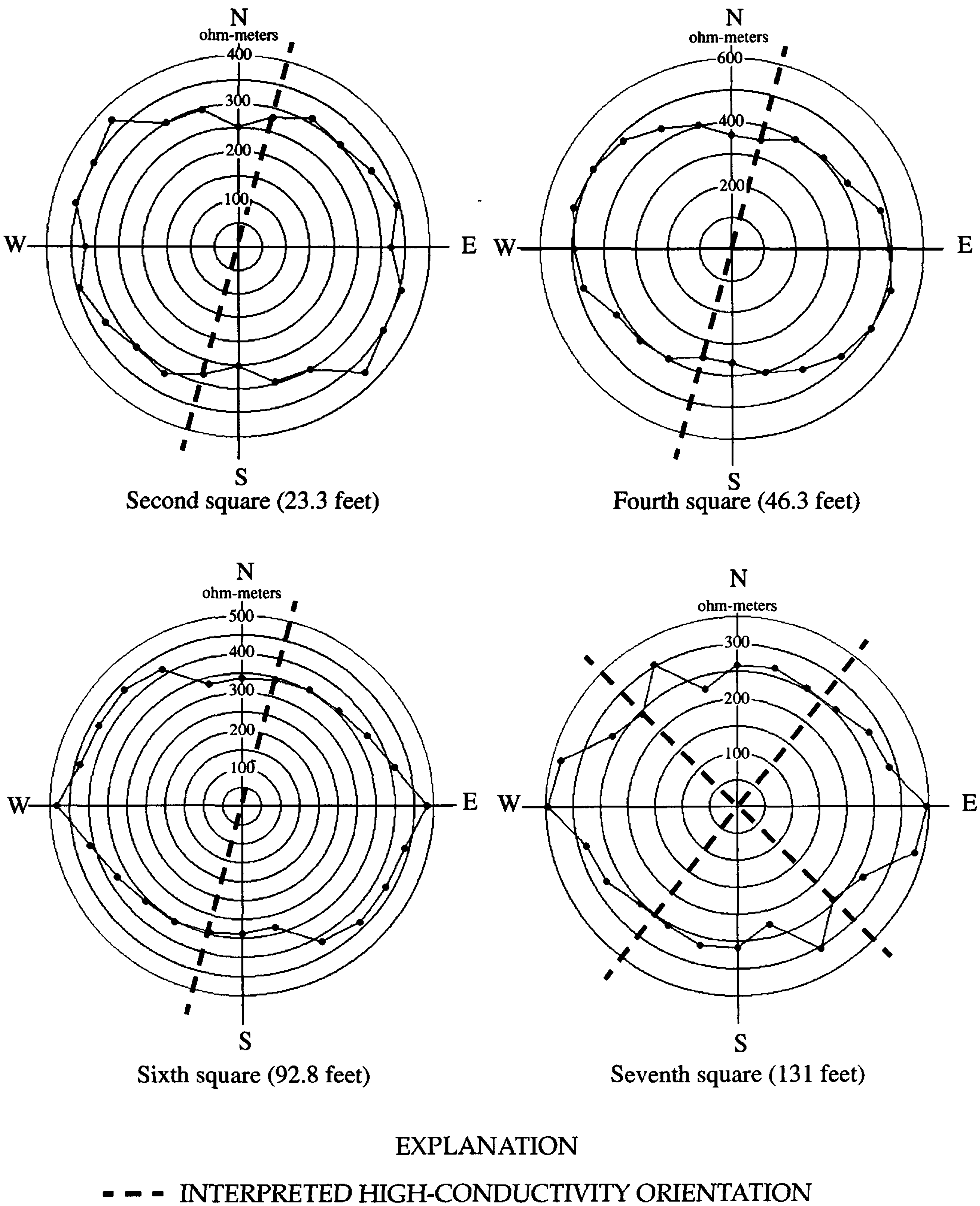


Figure 11. Square-array apparent resistivity plotted against azimuth for selected squares at site B in the J4 study area at Arnold Engineering Development Center.

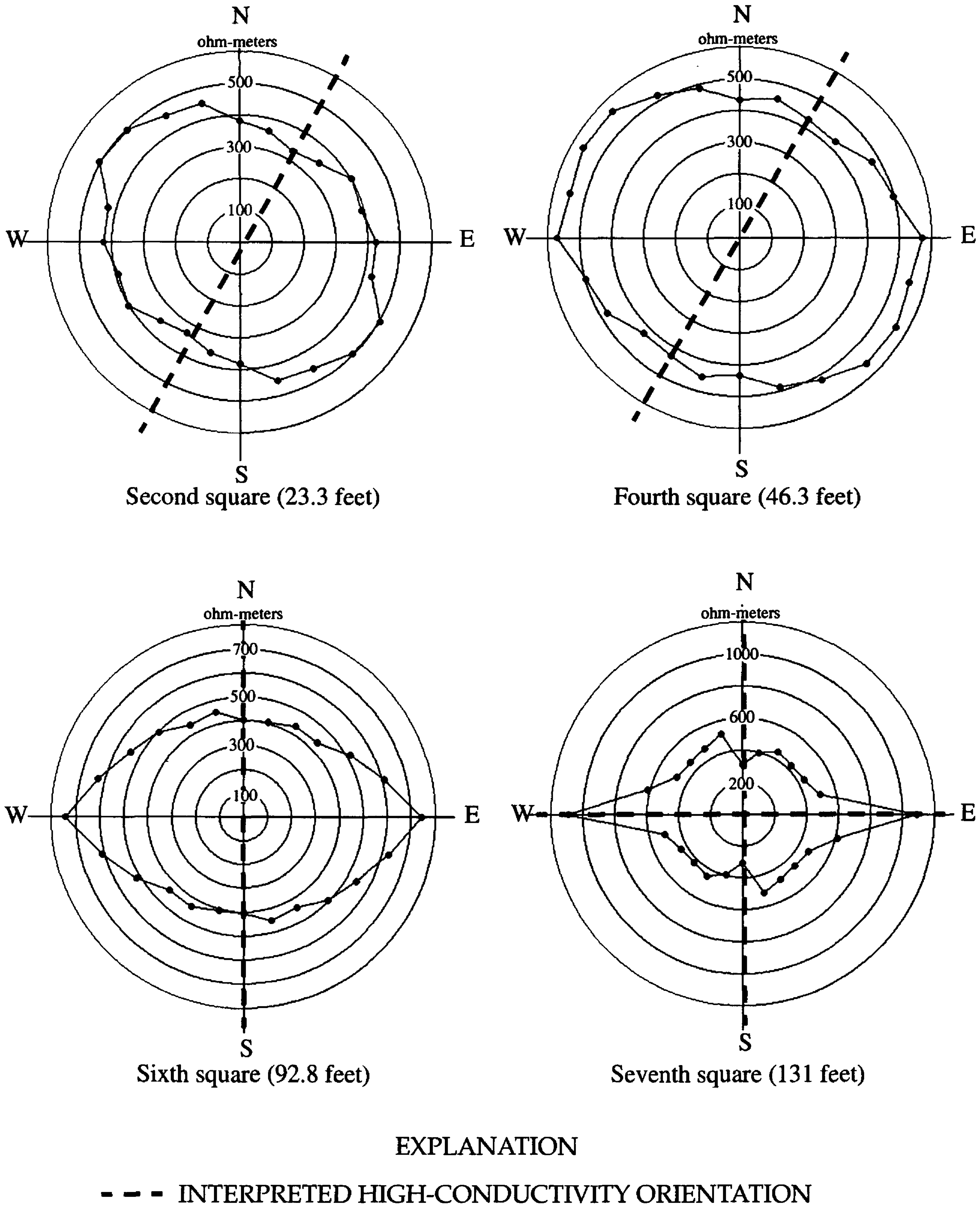


Figure 12. Square-array apparent resistivity plotted against azimuth for selected squares at site C in the J4 study area at Arnold Engineering Development Center.

conductivity orientation of N. 32° E. In the seventh square, a second orientation also is present. Graphically, the orientations are determined to be N. 30° E. and N. 37.5° W. (fig. 10). These orientations agree closely with the mapped lineation orientations of N. 35° E. and N. 40° W. These data suggest that a single higher conductivity orientation exists in the regolith and two orientations exist in the bedrock at this site (fig. 10). Orientations in the regolith could correspond to more permeable gravel zones, while orientations in the bedrock could correspond to a fracture or fracture set.

At site B, the first four squares sound to depths that sample the regolith and have calculated conductivity orientation from N. 11° E. to N. 23° E. with an average of N. 17° E. These results are similar to site A. The sixth square has calculated orientations of N. 16° E. As with site A, the seventh square at this site also appears to have two orientations: graphically, the orientations are determined to be N. 37.5° E. and N. 45° W. (fig. 11). Both squares sound to depths that encompass the bedrock. As with site A, a shift in the orientation is noted as the soundings deepen to penetrate the bedrock. The measurements at site B show more variability than site A. This variability may be the result of cultural interferences from buried cables, pipes, and railroad tracks located near the site.

At site C, the first four squares sound to depths corresponding to the regolith and have calculated conductivity orientations ranging from N. 26° E. to N. 37° E. with an average of N. 33° E. This orientation is rotated about 15° to the east compared to those observed at sites A and B. The sixth square has a calculated conductivity orientation of N. 4° E. and a high-resistive feature along the west-east line (fig. 12). The seventh square also shows a high-resistivity feature along the west-east line and a high conductivity orientation along the north-south line (fig.12). Both of these squares sound to depths that encompass the bedrock. The high resistivity feature may represent the orientation of a fracture that is filled with a higher resistive material relative to the bedrock.

At all three sites, the high-conductivity orientations in the regolith (squares 1 through 4) are similar. These most likely correspond to the presence and orientation of more permeable gravel zones. More variability exists in the higher conductivity orientations in the bedrock (squares 6 and 7). Although squares 6 and 7 at each site sound to depths that encompass the bedrock, some effects from the regolith may be present in the number 6 squares. At all the sites, the seventh square data show two higher conductivity orientations. These orientations could correspond to fractures or fracture sets in the bedrock. At all three sites, the number 5 squares encompass portions of the regolith and bedrock and therefore give a mixed response. The square-array method samples a small local volume of the subsurface environment. The interpreted fracture orientation locally may or may not be representative of the dominant pattern of the area. Of the three sites, the interpreted orientations at site A are the most consistent with the dominant orientation from the mapped lineations.

Azimuthal Electromagnetic Terrain-Conductivity Surveys

Azimuthal electromagnetic (EM) terrain-conductivity surveys were conducted at the same three sites where the square-array resistivity data were collected. For these EM surveys, the depth of investigation is dependent on the intercoil spacing, the operating frequency, and the orientations of the coils. In general, when the coils are in the horizontal-dipole mode, the instrument responds to the subsurface environment from the surface to a depth of about 0.75 times the coil spacing and is most sensitive to shallow subsurface layers. In the vertical-dipole mode, the instrument responds to the subsurface environment to a depth of about 1.5 times the coil spacing and is most sensitive to layers at about 0.4 times the coil spacing. Near-surface layers have little effect in the vertical-dipole mode. At each site, the transmitter and receiver coils were rotated at 15° increments about a fixed center point. Horizontal and vertical dipole mode measurements were collected at intercoil spacings of 33 (vertical dipole only), 66, and 132 feet to produce soundings at various depths.

Variations in terrain conductivity at different azimuths is an indication of anisotropy in the subsurface environment. This anisotropy may be controlled by the orientations of fractures, joints, or bedding planes in the underlying bedrock or lithologic variations in the regolith. If anisotropy is not present, then the conductivity data would plot as a circle. If anisotropy is present, then the resulting plots will be elliptical. The ellipse will be elongated in the direction of the highest conductivity.

The EM survey results compare favorably with those from the square-array surveys (table 5, fig. 13). The EM interpreted high-conductivity orientations from sites A and B agree with the square-array interpretations within 15°. However, the EM surveys are more susceptible to cultural interferences and may have been affected by nearby buried pipes, power lines, and railroad tracks; therefore, the results are not as consistent as the square-array surveys. In particular, EM data from site C showed more variability at different sounding depths.

Very Low Frequency Electromagnetic Terrain-Resistivity Surveys

Very low frequency electromagnetic terrain-resistivity surveys have been used to detect coarse-grained drift within fine-grained drift in glacial aquifers (Haeni, 1986). This technique was applied at the three survey sites near the J4 test cell to investigate whether course-grained chert-gravel zones could be delineated within the fine-grained clay and sand in the regolith. Several transects were made at each of the three sites to identify variations in subsurface properties for distinguishing chert-gravel zones. Analysis of the data failed to distinguish the chert-gravel zones. This failure may be because the technique sounded to a depth below the Chattanooga Shale, and thus may have encompassed up to four distinct layers rather than only the regolith. This large sounding depth may have caused difficulty in distinguishing differences in properties of the regolith. Also, many nearby cultural features such as buried pipes, power lines, and railroad tracks may have interfered with the data, making interpretations more difficult.

Water levels

Seasonal fluctuations in ground-water levels in the J4 study area are related to seasonal changes in precipitation, evapotranspiration, and thus to changes in ground-water recharge. Ground-water levels are normally highest during the spring months following the winter period of higher precipitation and lower evapotranspiration. Water levels recede during the summer in response to diminishing precipitation and higher evapotranspiration, and are at the lowest levels in the fall. Hydrographs of water levels in wells at the AAFB exhibit these characteristic seasonal fluctuations (Haugh and Mahoney, 1994).

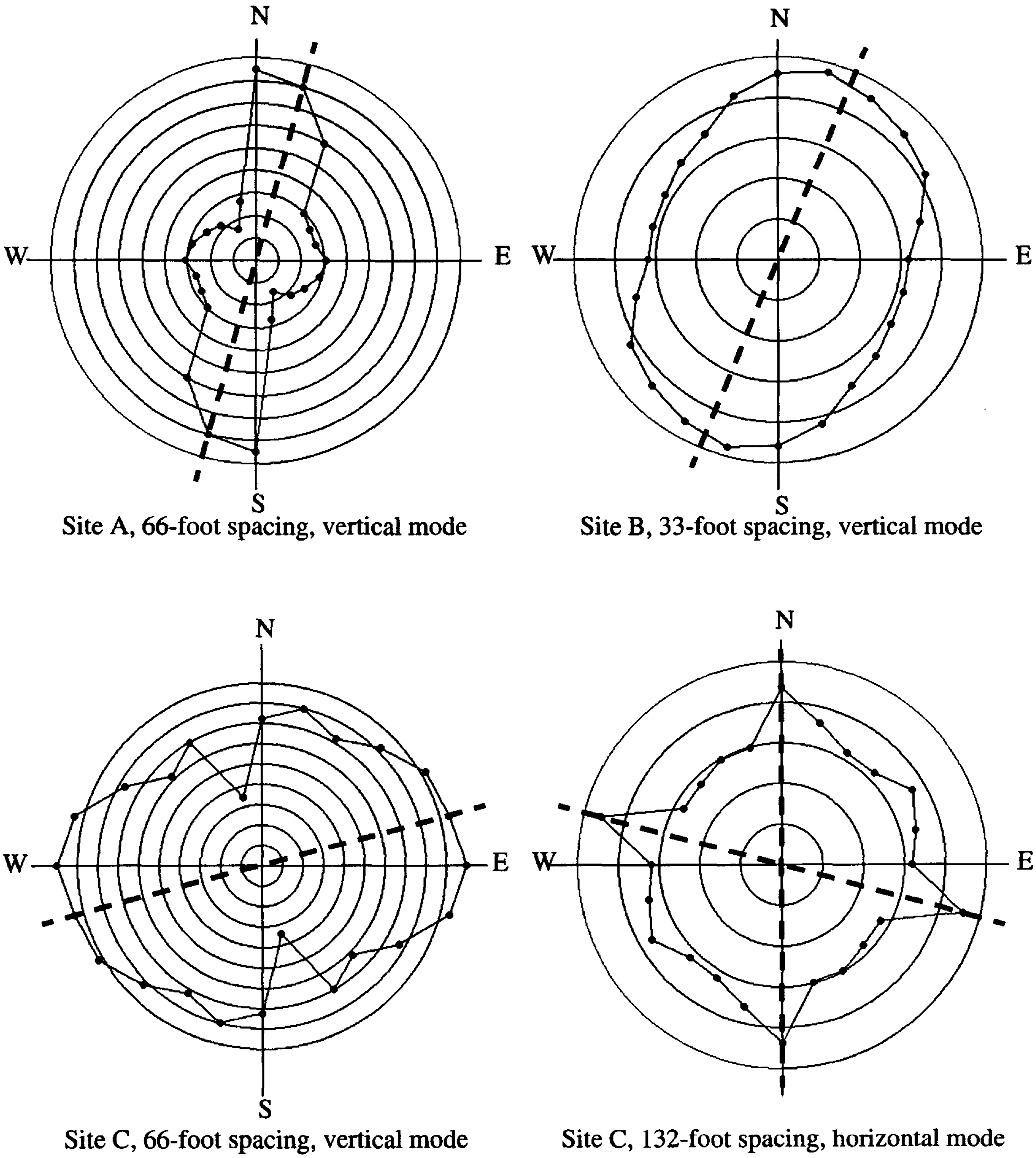
Water levels in wells within the depression in the potentiometric surface near the J4 test cell show little seasonal fluctuation relative to wells outside the depression. Water levels in these wells tend to be held at a more constant level in equilibrium with the steady withdrawal of water at the J4 test cell. Hydrographs for wells AEDC-154 and -155 illustrate this effect (fig. 14). Annual water-level fluctuations in these wells are only 2 feet or less. Two other wells, AEDC-273 and -274, located within the area of water-level depression show a similar effect with annual fluctuations of about 5 feet (fig. 15). In contrast, wells AEDC-285 and -286 are located outside the depressions and show annual water-level fluctuations of about 10 feet (fig. 16).

AEDC and the J4 test cell are located in the recharge area for the regional ground-water-flow system. In this area, natural vertical gradients are from the shallow aquifer downward to the Manchester aquifer and from the Manchester aquifer downward to the Fort Payne aquifer. This characteristic can be seen in the water-levels for wells AEDC-285 and -286 (fig.16). The vertical gradient between these wells is

Table 5. Interpreted high-conductivity orientations from azimuthal electromagnetic terrain-conductivity surveys in the J4 study area at Arnold Engineering Development Center

[N., north; S., south; E., east; W., west; --, cultural interference too strong to interpret data]

Coil spacing (feet)	Dipole mode	Site A	Site B	Site C
33	Vertical	N.-S.	N. 22.5° E.	isotropic
66	Horizontal	N.-S.	N. 30° E.	N. 7.5° E., N. 75° W.
66	Vertical	N. 15° E.	N. 30° E.	N. 75° E.
132	Horizontal	N. 15° E.	--	N. 75° W., N.-S.
132	Vertical	--	--	W.-E.



EXPLANATION

- - - INTERPRETED HIGH-CONDUCTIVITY ORIENTATION

Figure 13. Electromagnetic terrain conductivity plotted against azimuth for selected intercoil spacings at sites A, B, and C in the J4 study area at Arnold Engineering Development Center.

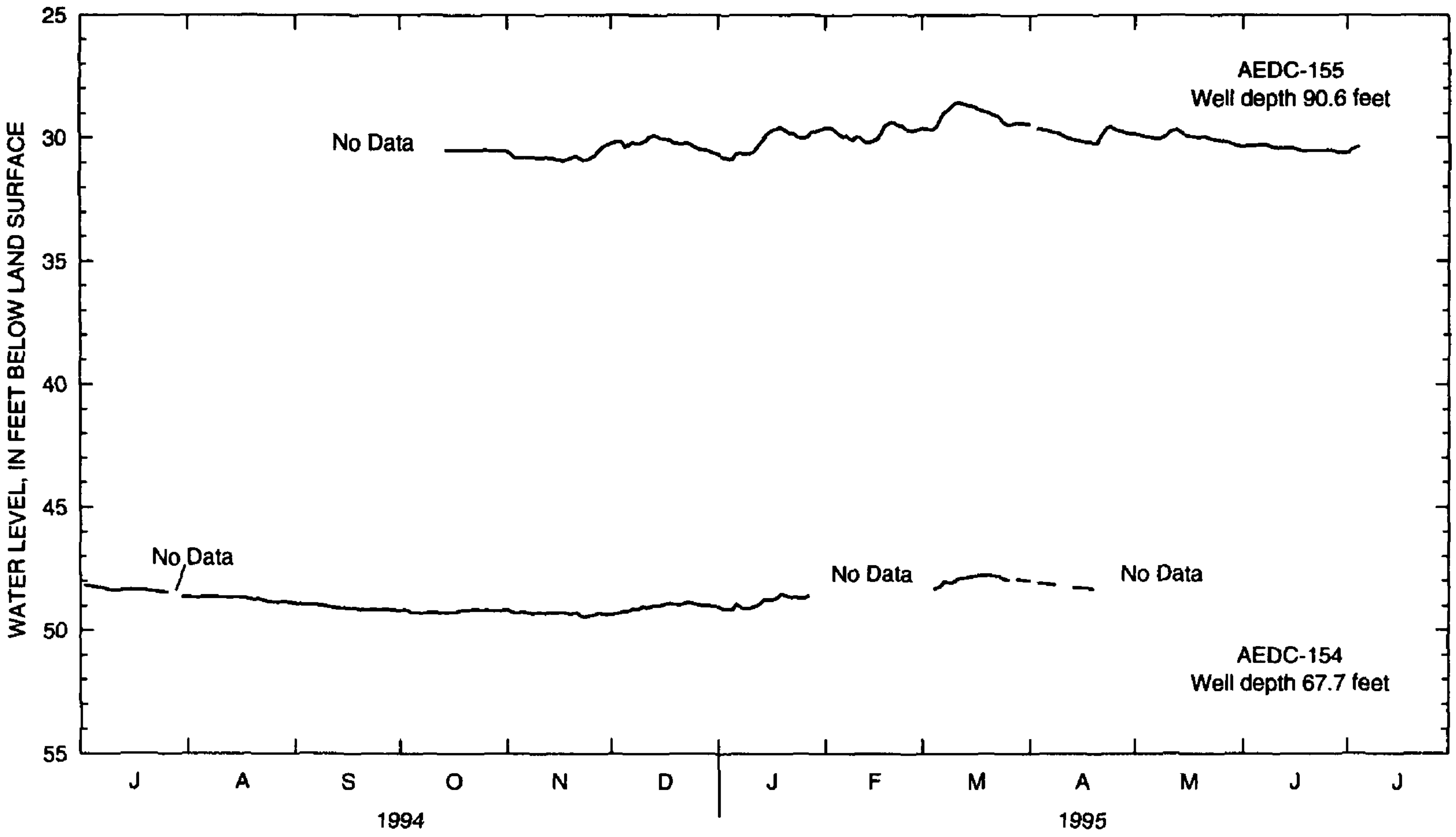


Figure 14. Water levels in wells AEDC-154 and -155 from July 1994 through June 1995.

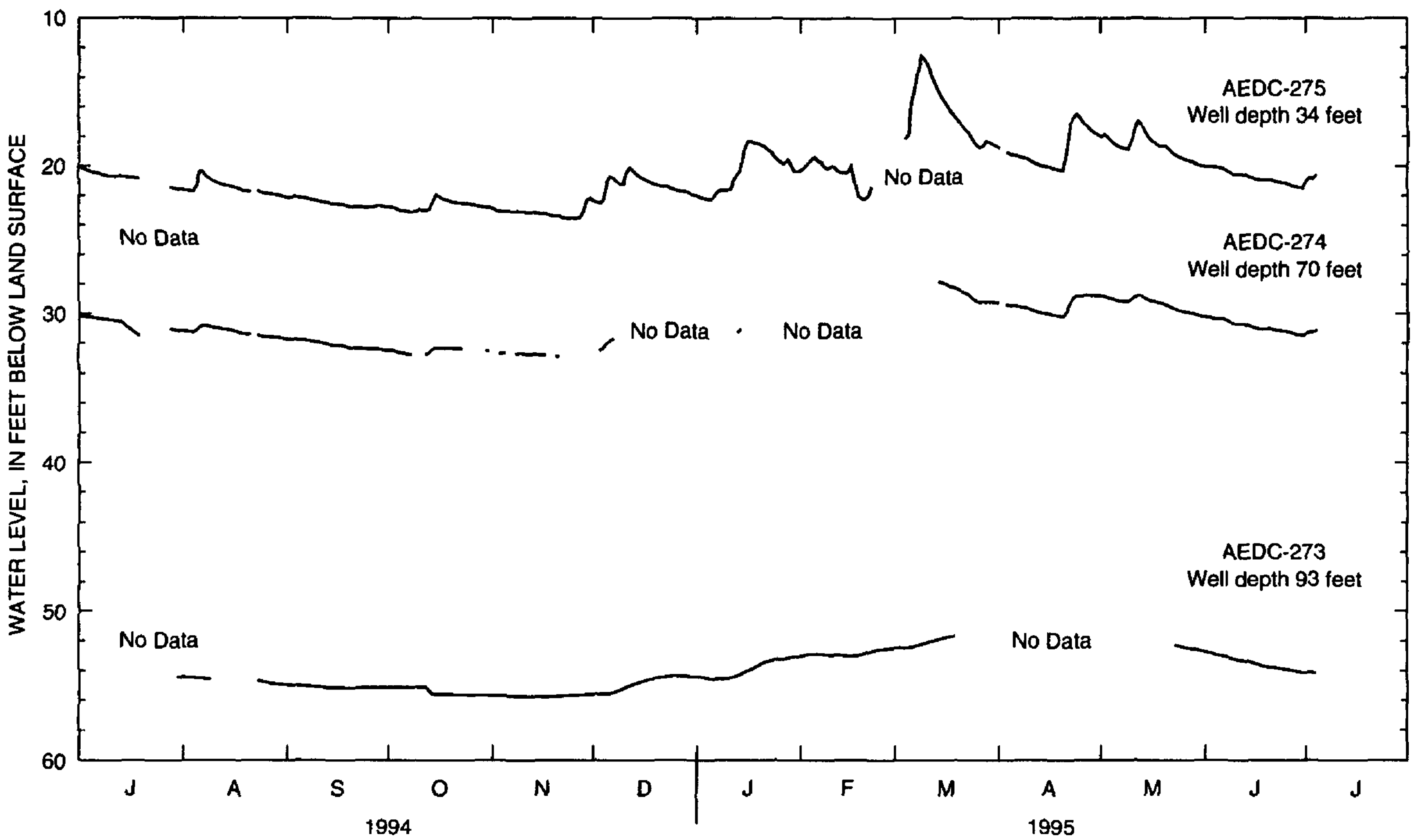


Figure 15. Water levels in wells AEDC-273, -274, and -275 from July 1994 through June 1995.

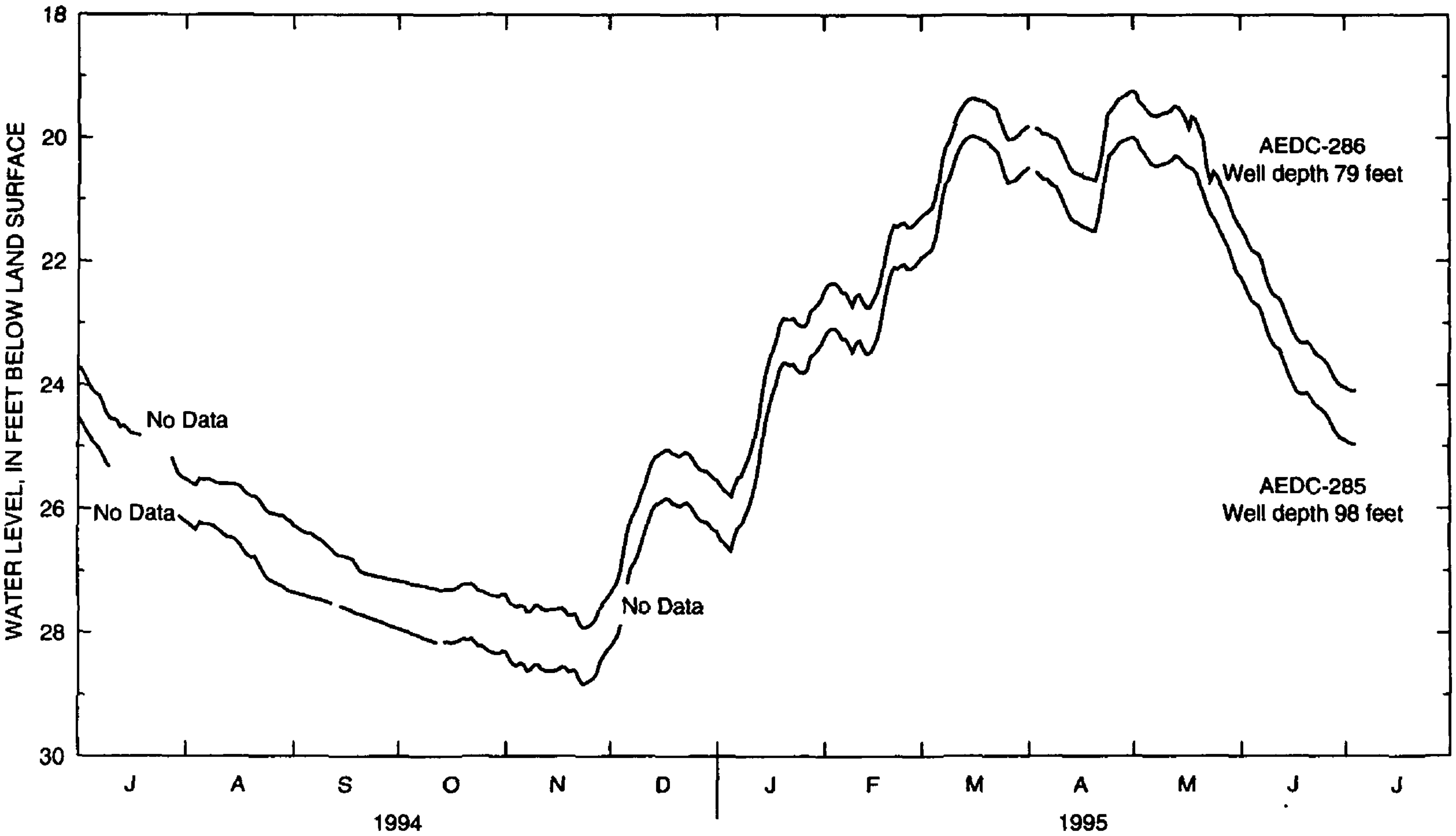


Figure 16. Water levels in wells AEDC-285 and -286 from July 1994 through June 1995.

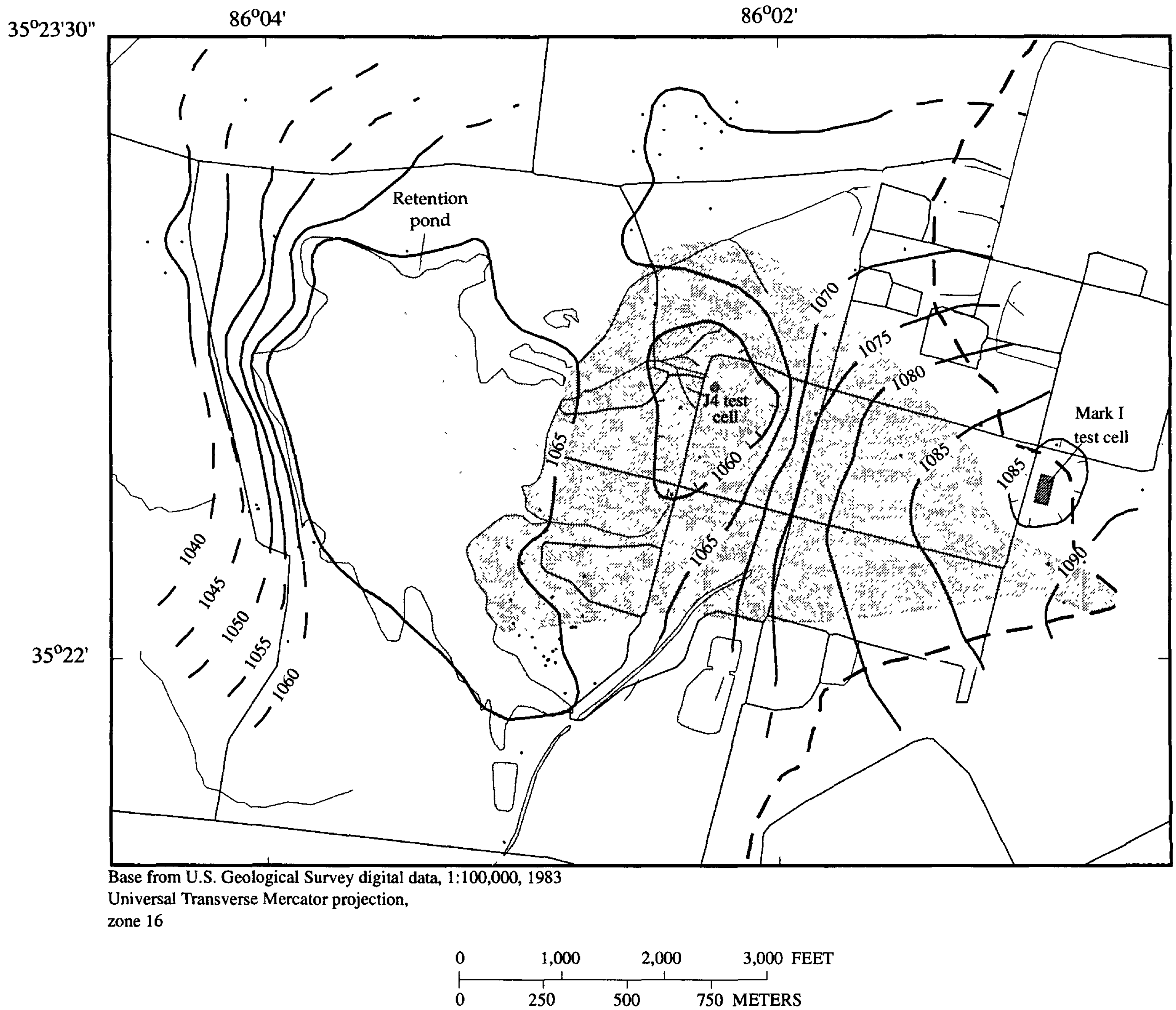
about 1 foot. Vertical gradients in wells affected by the dewatering at J4 are as much as 15 feet greater than those not affected. In some well clusters affected by dewatering at J4, the lowest water level is in the Fort Payne aquifer, with a downward gradient from the Manchester aquifer to the Fort Payne aquifer, and a downward gradient from the shallow aquifer to the Manchester aquifer (fig. 15). In other well clusters affected by dewatering at J4, the lowest water level is in the Manchester aquifer, with an upward gradient from the Fort Payne aquifer to the Manchester aquifer, and a downward gradient from the shallow aquifer to the Manchester (fig. 14). This condition is believed to be the result of zones of higher lateral hydraulic conductivity in the Manchester aquifer relative to the overlying and underlying aquifers and, thus, preferential dewatering of this zone.

Potentiometric maps of water levels in the shallow, Manchester, and Fort Payne aquifers show an anisotropic water-level depression centered on the J4 test cell due to the dewatering activities. This anisotropy is interpreted as resulting from linear features such as chert-gravel zones in the regolith (upper part of the Manchester aquifer) and fractures, joints, and bedding planes in the bedrock (Fort Payne and the lower part of the Manchester aquifers, undifferentiated) that are more permeable than the surrounding material (figs. 17, 18, and 19).

Ground-Water Flow

A ground-water divide, approximately coinciding with the Duck River-Elk River surface-water divide, underlies the AEDC facility to the west and south of the main testing area (figs. 2 and 17) (Haugh and Mahoney, 1994). In the J4 study area, ground water flows westward from the divide area to the discharge areas, which are the major streams, lakes, and reservoirs around the base. Much of the ground water recharged to the main testing area is captured by the dewatering system at the J4 test cell and is pumped to the surface before it reaches natural discharge areas. The depressions in water levels that have developed around the J4 test cell vary in shape and extent in the different aquifers. In the Manchester and Fort Payne aquifers, the shape of the depression is strongly influenced by features with high secondary permeability. In all the aquifers, the size and shape of the depressions are in equilibrium because ground-water withdrawal at the test cell has been continuous since the late 1960's.

Locally, ground water flows to the J4 test cell from all directions because water in the aquifers immediately surrounding the cell is continuously drained through a network of six wells. The depressions in the potentiometric surfaces in all the Highland Rim aquifers at the test cell show anisotropy that results from preferential dewatering along zones of high permeability.



EXPLANATION

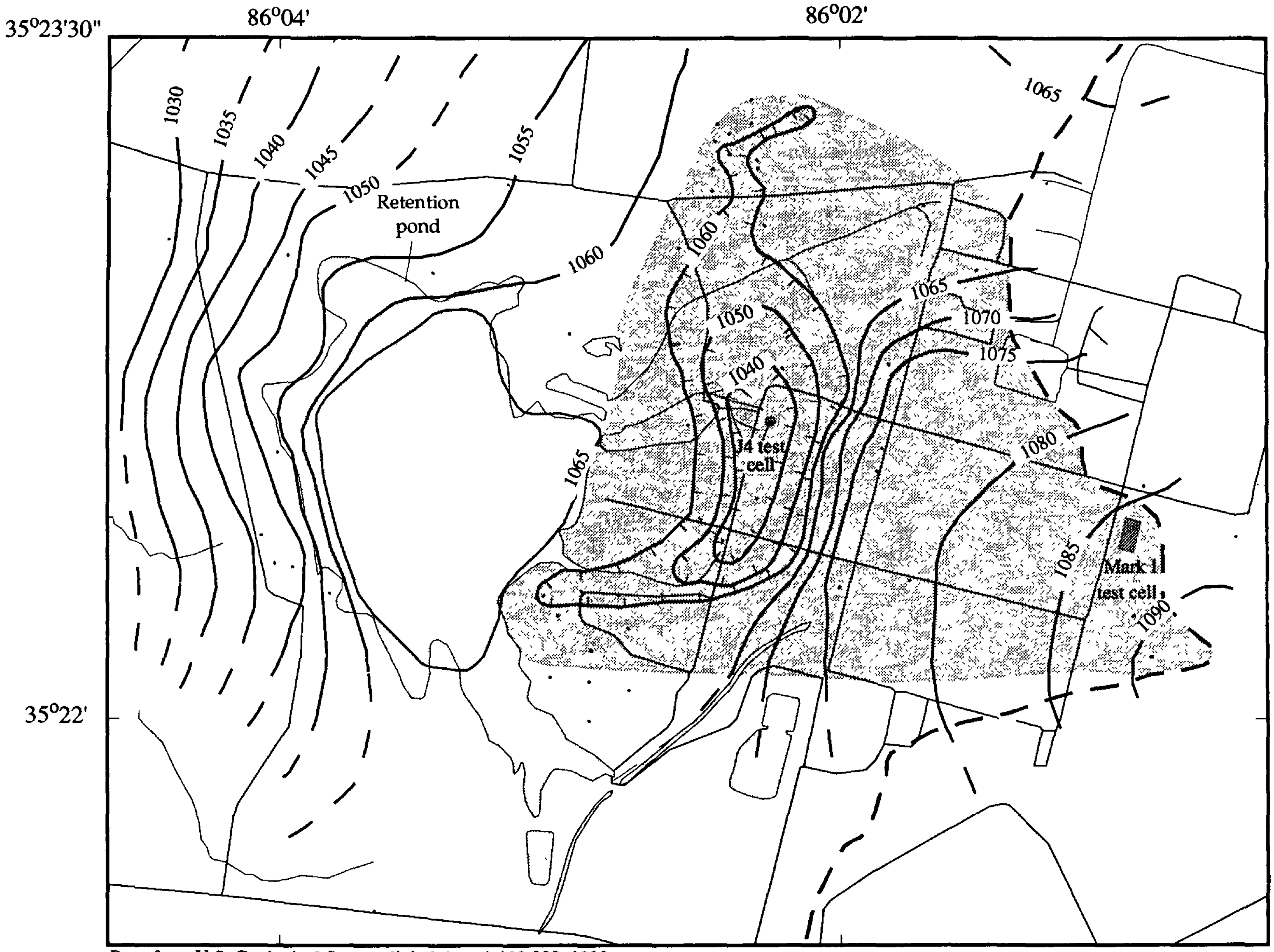
CONTRIBUTING AREA--Shows area of the shallow aquifer in which ground water is captured by the J4 test cell dewatering system

———1080 - - - POTENTIOMETRIC SURFACE CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Dashed where approximately located. Contour interval 5 feet. Datum is sea level

— — — — SURFACE-WATER DRAINAGE DIVIDE

• WELL--Water-level measurement made in July 1994 and used for control

Figure 17. Potentiometric surface in the shallow aquifer in the J4 study area at Arnold Engineering Development Center, July 1994.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection,
zone 16

0 1,000 2,000 3,000 FEET
0 250 500 750 METERS

EXPLANATION

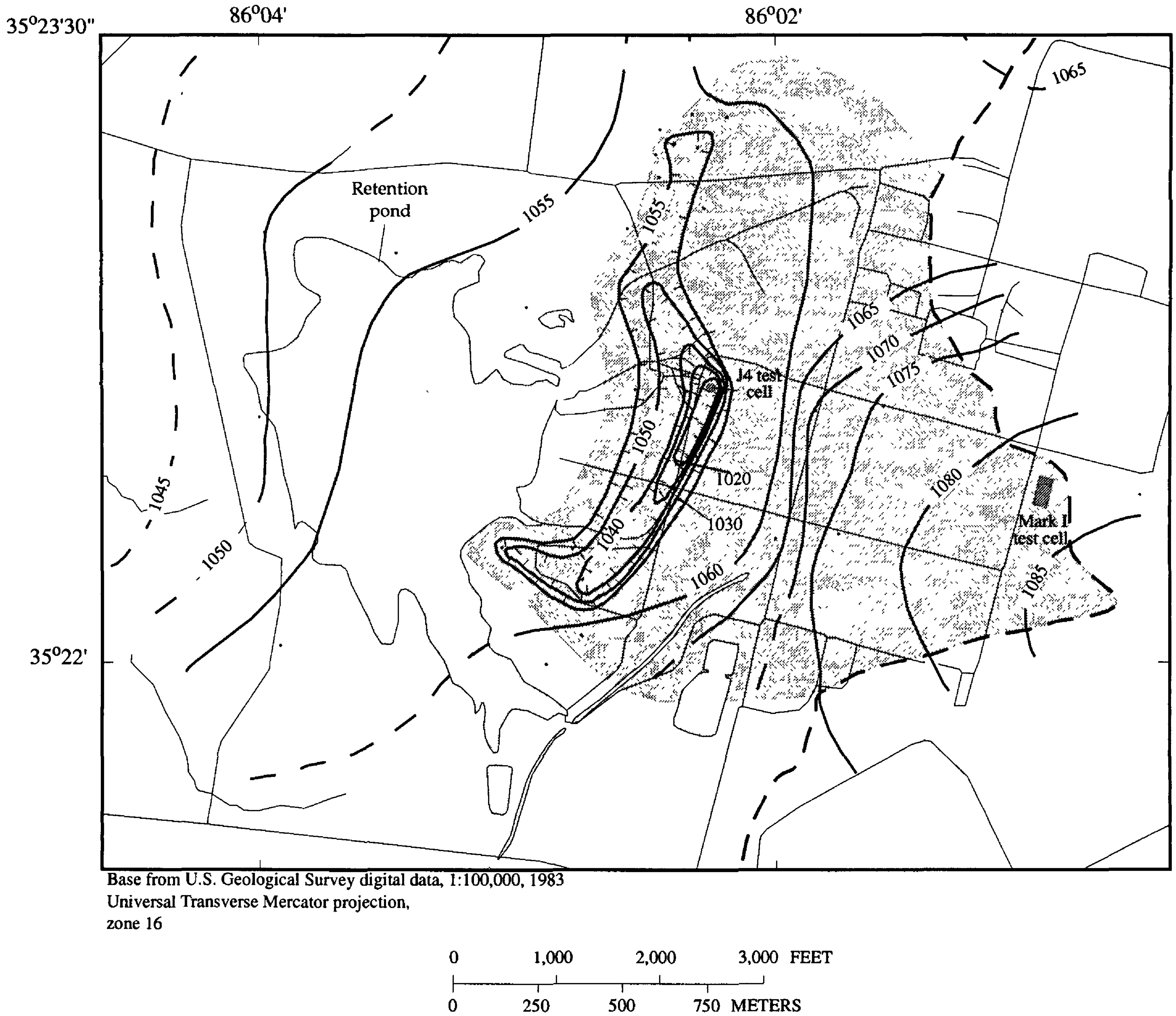
CONTRIBUTING AREA--Shows area of the upper part of the Manchester aquifer in which ground water is captured by the J4 test cell dewatering system

—— 1070 – – – · POTENTIOMETRIC SURFACE CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Dashed where approximately located. Contour interval 5 feet. Datum is sea level

— — — — SURFACE-WATER DRAINAGE DIVIDE

• WELL--Water-level measurement made in July 1994 and used for control

Figure 18. Potentiometric surface in the upper part of the Manchester aquifer in the J4 study area at Arnold Engineering Development Center, July 1994.



EXPLANATION

CONTRIBUTING AREA--Shows area of the Fort Payne and the lower part of the Manchester aquifers, undifferentiated, in which ground water is captured by the J4 test cell dewatering system

—— 1060 – – POTENTIOMETRIC SURFACE CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Dashed where approximately located. Contour interval 5 feet. Datum is sea level

– – – – SURFACE-WATER DRAINAGE DIVIDE

• WELL--Water-level measurement made in July 1994 and used for control

Figure 19. Potentiometric surface in the Fort Payne and the lower part of the Manchester aquifers, undifferentiated, in the J4 study area at Arnold Engineering Development Center, July 1994.

These zones of higher permeability have developed primarily along and within fractures, joints, bedding planes of the lower part of the Manchester aquifer and the chert gravels of the upper part of the Manchester aquifer. Because all of the Highland Rim aquifers are interconnected, anisotropy is seen to a lesser extent, in the shallow aquifer (figs. 17, 18, and 19).

Ground-Water Chemistry

Water-quality samples were collected from the J4 test cell ground-water discharge and 35 monitoring wells in the J4 study area at AEDC. Samples were analyzed for major inorganic constituents, trace metals, and volatile organic compounds (VOC's). Sampling procedures and complete analytical results are published in Haugh (1996).

Inorganic Constituents

Chemical analyses of water and geochemical interpretations provide additional insight in understanding the ground-water-flow system in the study area. The water-quality data show variations in water chemistry between the aquifers. Trilinear diagrams illustrate the geochemical differences between the aquifers.

A trilinear diagram shows that water from eight wells in the shallow aquifer is of the mixed cation bicarbonate type with some samples showing chloride as the dominant anion (fig. 20). Water collected from 17 wells completed in the Manchester aquifer is of the calcium bicarbonate type (fig. 21). Water from most of the six wells completed in the Fort Payne aquifer is of the calcium bicarbonate type; however, some wells produced water of a mixed cation type, and one sample shows sulfate as the dominant anion (fig. 22). Water from the four wells completed in the upper Central Basin aquifer is of the sodium sulfate chloride type (fig. 23).

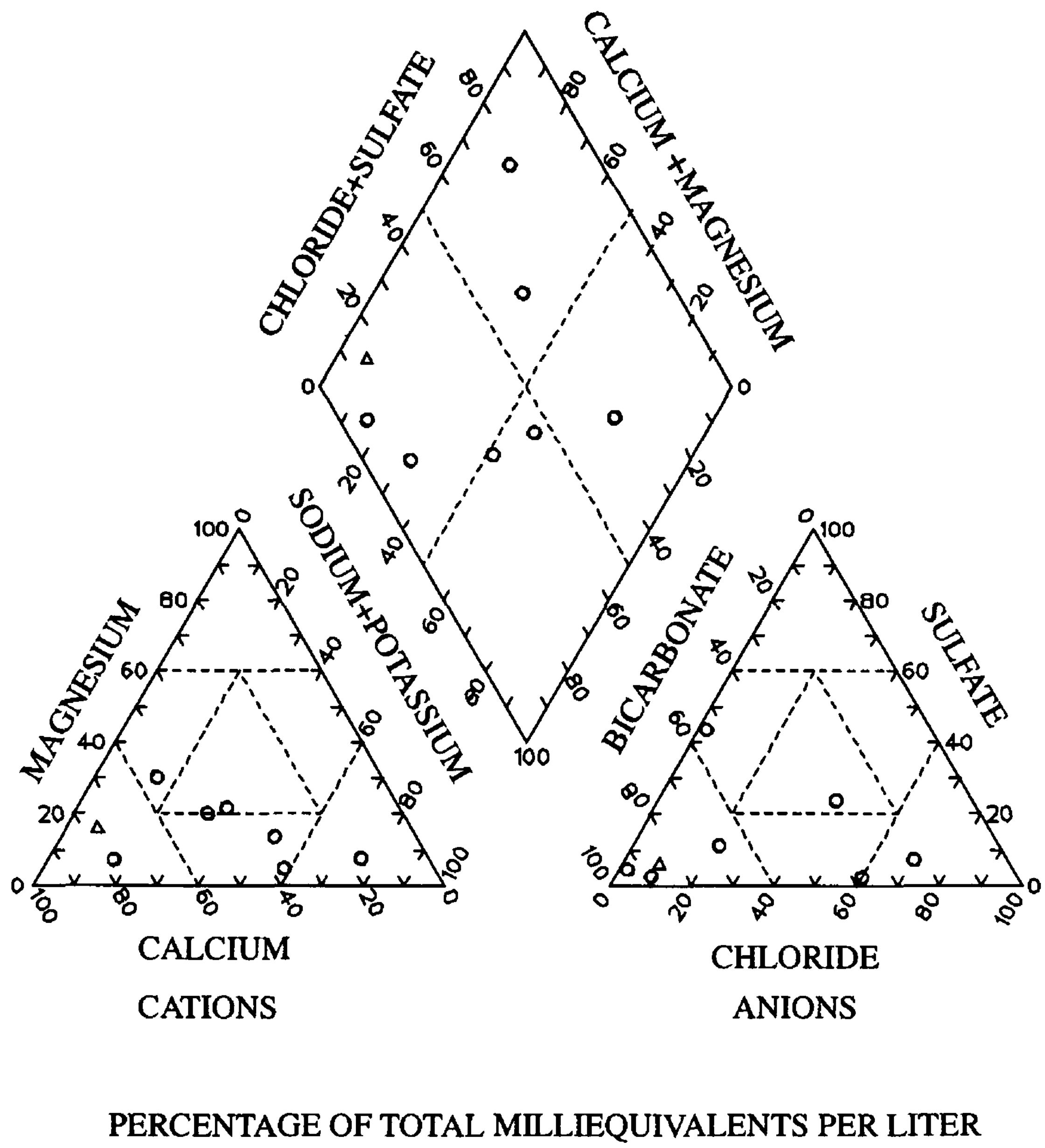
Dissolved-solids concentrations for water from all aquifers ranged from 16 to 8,060 milligrams per liter (mg/L). The range and median values of dissolved-solids concentrations for each aquifer are as follows: shallow aquifer, 16 to 210 mg/L, 52 mg/L; Manchester aquifer, 40 to 250 mg/L, 96 mg/L; Fort Payne aquifer, 163 to 1,280 mg/L, 240 mg/L; and upper Central Basin aquifer, 1,100 to 8,060 mg/L, 2,140 mg/L (table 6). Most of the inorganic constituents follow a similar trend with the lowest concentrations occurring in the shallow and Manchester aquifers and the highest concentrations occurring in the upper Central Basin aquifer. These data are consistent with water-quality data from wells previously sampled in the area (Haugh and others, 1992; Haugh and Mahoney, 1994).

Water sampled from the J4 test cell is of the calcium bicarbonate type. The plotting position of the J4 test cell sample data on a trilinear diagram shows that it most resembles water from the Manchester aquifer (fig. 21). With a dissolved-solids concentration of 171 mg/L, the J4 sample lies between the median dissolved-solids concentrations of the Manchester and Fort Payne aquifers.

Volatile Organic Compounds

Many of the analyzed VOC's were less than the reporting level of 0.2 microgram per liter (µg/L) (Haugh, 1996). However, some compounds were detected in concentrations exceeding 0.2 µg/L. Water from all wells completed below the Chattanooga Shale in the upper Central Basin aquifer (AEDC-268, -277, -281, and -175) contained concentrations of volatile aromatic hydrocarbons such as benzene, toluene, ethylbenzene, and xylenes (BTEX) (Haugh, 1996). These compounds occur naturally in association with petroleum deposits (natural gas and crude oil) and shale lithologies, as well as in many refined petroleum products (Swanson, 1960; Slaine and Barker, 1990). During the drilling of each of these wells, small amounts of natural gas were produced. The occurrence of BTEX in the upper Central Basin aquifer is documented in reports by Haugh and others (1992) and Haugh and Mahoney (1994).

Several wells produced water containing chlorinated organic compounds such as 1,2-dichloroethane (1,2-DCA), 1,1-dichloroethylene (1,1-DCE), and trichloroethylene (TCE) that exceeded the Tennessee Department of Environment and Conservation Maximum Contaminant Levels (MCL's) for public water-supply systems (Tennessee Department of Environment and Conservation, 1994). These wells are AEDC-64, -83, -159, -269, -271, -272, -273, -274, -275, and -278. The highest concentrations were detected in well AEDC-274 with 45 µg/L 1,2-DCA, 320 µg/L 1,1-DCE, and 1,200 µg/L TCE. These compounds are synthetic and do not occur naturally in the environment. A sample of ground-water discharge from the J4 test cell also contained concentrations of these compounds that exceed MCL's. Additionally, several wells contained some of these chlorinated



EXPLANATION

- o SHALLOW AQUIFER SAMPLE
- Δ J4 TEST CELL SAMPLE

Figure 20. Chemical composition of water from wells completed in the shallow aquifer and the J4 test cell in the J4 study area at Arnold Engineering Development Center.

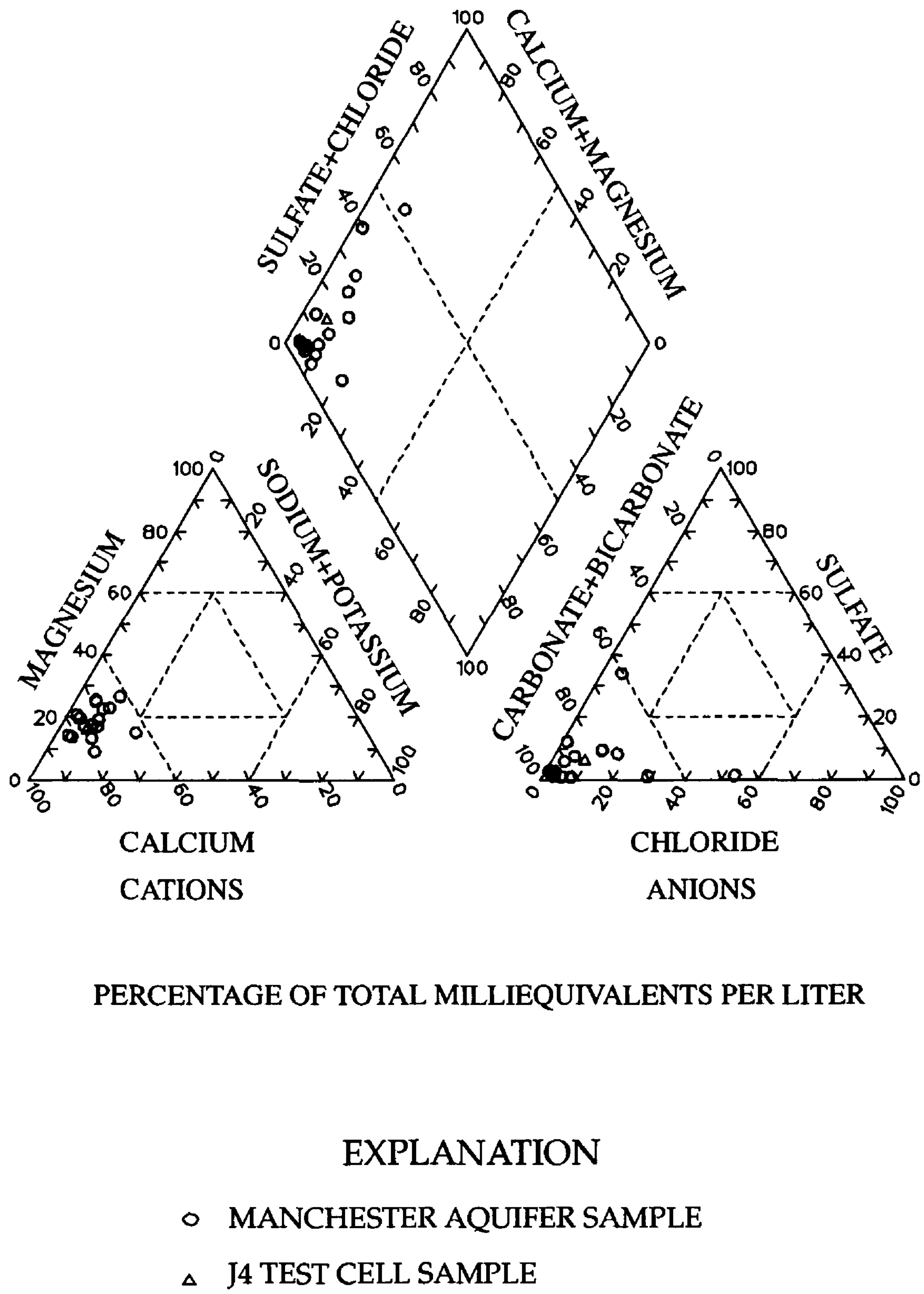
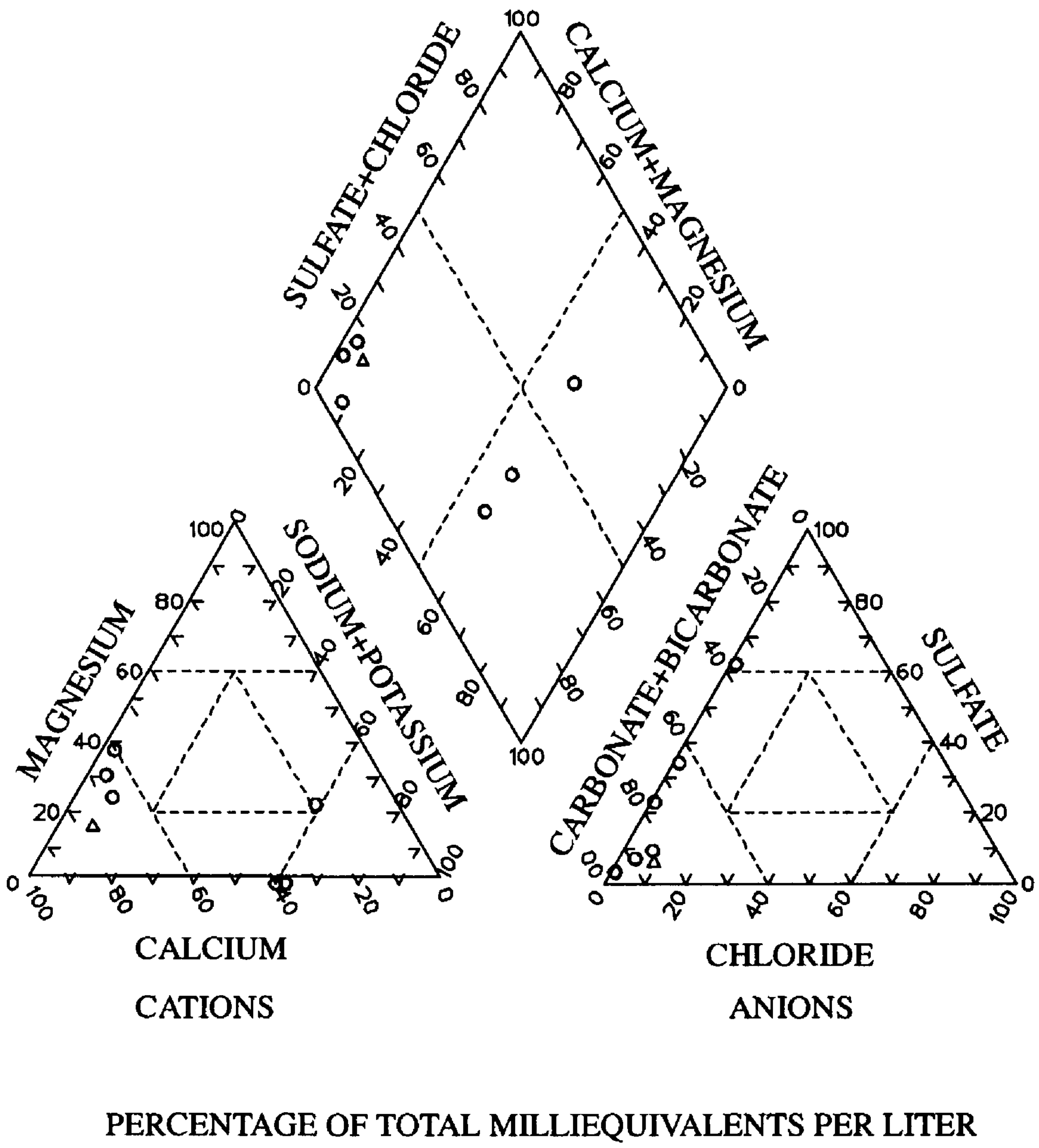


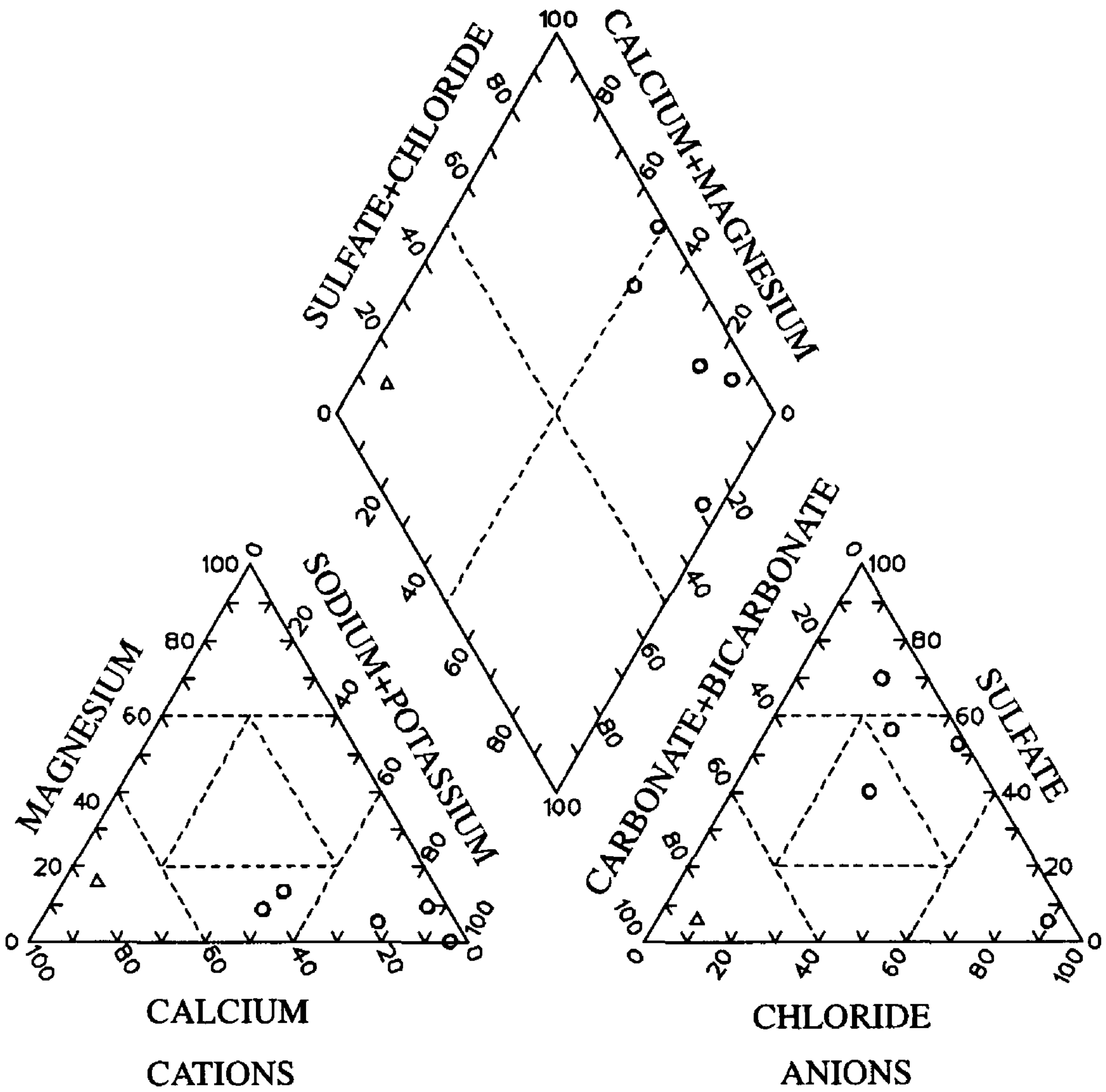
Figure 21. Chemical composition of water from wells completed in the Manchester aquifer and the J4 test cell in the J4 study area at Arnold Engineering Development Center.



EXPLANATION

- o FORT PAYNE AQUIFER SAMPLE
- Δ J4 TEST CELL SAMPLE

Figure 22. Chemical composition of water from wells completed in the Fort Payne aquifer and the J4 test cell in the J4 study area at Arnold Engineering Development Center.



PERCENTAGE OF TOTAL MILLIEQUIVALENTS PER LITER

EXPLANATION

○ UPPER CENTRAL BASIN AQUIFER SAMPLE

△ J4 TEST CELL SAMPLE

Figure 23. Chemical composition of water from wells completed in the upper Central Basin aquifer and the J4 test cell in the J4 study area at the Arnold Engineering Development Center.

Table 6. Range and median values of selected physical properties and inorganic constituents in water from wells sampled near the J4 test cell in the J4 study area at Arnold Engineering Development Center

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; °C, degrees Celsius; µg/L, micrograms per liter; <, less than]

Physical property/ Constituent	Number of samples, by aquifer												
	8			17			6			4			
	Shallow aquifer			Manchester aquifer			Fort Payne aquifer			Upper Central Basin aquifer			J4
	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	Minimum	Maximum	Median	
Specific conductance (µS/cm)	19	295	90	53	456	160	305	3,340	425	1,680	13,200	3,615	297
pH (standard units)	4.9	7.0	5.4	5.3	7.8	6.3	7.4	10.1	8.7	7.1	11.4	9.2	6.9
Alkalinity (mg/L as $CaCO^3$)	6	73	20	24	232	76	142	570	176	77	398	316	126
Hardness (mg/L as $CaCO^3$)	5	89	17	20	230	75	76	330	165	46	930	510	140
Calcium (mg/L)	1.0	23	4.6	6.4	67	22	14	130	51	17	250	84	45
Magnesium (mg/L)	.48	7.7	.74	.90	15	3.9	.14	16	9.9	.6	150	33	5.9
Sodium (mg/L)	.80	36	4.6	1.1	5.7	1.8	1.3	35	8.6	100	2,500	290	4.9
Potassium (mg/L)	<0.1	3.8	1.0	.20	2.1	.60	.2	320	33	74	340	180	.2
Chloride (mg/L)	.70	60	2.0	.50	22	2.9	1.0	11	4.4	100	4,300	340	9.2
Sulfate (mg/L)	<0.1	56	1.9	.30	59	2.1	5.8	300	32.0	360	1,000	510	9.2
Silica (mg/L)	7.3	15	10	7.5	13	9.2	8.1	13	12	5.7	14	9.2	9.2
Solids, residue at 180°C dissolved (mg/L)	16	210	52	40	250	96	163	1,280	240	1,100	8,060	2,140	171
Solids, sum of constituents, dissolved (mg/L)	29	179	52	35	247	87	163	1,140	238	1,020	7,760	2,025	159
Barium (µg/L)	3	47	14	<2	36	5	12	65	18	17	100	34	6
Iron (µg/L)	4	7,100	22	<3	1,700	11	4	310	14	<3	370	78	18
Lithium (µg/L)	<4	<4	<4	<4	<4	<4	<4	170	22	220	4,100	740	11
Manganese (µg/L)	9	130	31	<1	1,400	11	<3	86	8	<1	110	10	5
Strontium (µg/L)	5	130	16	9	200	22	70	1,200	96	1,100	7,700	3,950	98

VOC's in concentrations less than the MCL's (table 7). Chlorinated organic compounds including 1,2-DCA, 1,1-DCE, and TCE also have been detected at several IRP sites located at AEDC. These sites include landfill #2 and leaching pit #2 (IRP site 1), the main testing area (IRP site 7), leaching pit #1 (IRP site 8), and the old fire training area (IRP site 10) (fig. 24).

GROUND-WATER FLOW TO THE J4 TEST CELL

Locally, ground water in the aquifers surrounding the J4 test cell flows to the cell from all directions because these aquifers are continuously drained through the network of six peripheral wells. Ground water drains by gravity through these wells into a sump at the bottom of the J4 test cell. The six wells extend from the top of rock (about 68 feet) to a depth of approximately 250 feet below land surface as open boreholes. The wells do not have casing that extends to land surface because they were installed during construction of the test cell when the regolith had been excavated, exposing the bedrock surface. The area around the test cell then was backfilled as the cell was constructed. Because of this type of construction, the wells are not in direct contact with the shallow aquifer. However, the shallow aquifer is dewatered through downward infiltration of water into the Manchester aquifer (fig. 25).

The discharge from the J4 test cell has been gaged by the USGS continuously since October 1990 (Haugh, 1996). Most of the discharge is ground water withdrawn from aquifers around the test cell, but some of this water is cooling water from testing activities at the test cell. However, the 1991 water year is the last year that a significant amount of testing was conducted. The average discharge for the last 4 years of record (1992-95), is representative of ground-water discharge into the test cell and is 105 gal/min (table 8). The higher discharge years (1992 and 1994) correspond to the years of higher precipitation and, therefore, to the years of higher ground-water recharge.

The six dewatering wells surrounding the J4 test cell are open to the Highland Rim aquifers and penetrate the Chattanooga Shale, thereby introducing water from the overlying Highland Rim aquifer system into the underlying upper Central Basin aquifer system before it drains to the sump at the bottom of the J4 test cell. However, the possibility that some water from the Highland Rim aquifers could move out into the upper Central Basin aquifer system, thereby cross-contaminating the deeper aquifers, is highly unlikely. Drilling records indicate that no zones of significant permeability exist in the upper Central Basin aquifer system within the study area. The four USGS wells completed in the upper Central Basin aquifer system in the study area all have yields of less than 1 gal/min. Therefore, the path of least resistance for water from the Highland Rim aquifers to leave the system is through the dewatering network at the J4 test cell rather than through the upper Central Basin aquifer system.

The presence of features with high permeability in the Manchester aquifer results in complex flow patterns in the Highland Rim aquifers near the J4 test cell. The dewatering stress propagates out horizontally through the aquifers along the pathways of highest permeability. These pathways include the chert-gravel zones in the regolith and fractures, joints, and bedding planes in the bedrock. Because the aquifers above the Chattanooga Shale are not separated by distinct confining units, the stress also propagates vertically, dewatering areas above and below these zones of high permeability. This vertical propagation accounts for the gradient reversal in water levels from well clusters noted in the water-level section of this report. In some well clusters affected by dewatering at J4, the lowest water level is in the Fort Payne aquifer, with a downward gradient from the Manchester aquifer to the Fort Payne aquifer, and a downward gradient from the shallow aquifer to the Manchester aquifer. In other well clusters affected by dewatering at J4, the lowest water level is in the Manchester aquifer, with an upward gradient from the Fort Payne aquifer to the Manchester aquifer, and a downward gradient from the shallow aquifer to the Manchester aquifer. This condition is believed to exist where zones of higher lateral hydraulic conductivity are present in the Manchester aquifer, relative to the overlying and underlying aquifers; therefore, this zone is preferentially dewatered (fig. 25). The left side of figure 25 shows this condition where the chert gravels of the upper part of the Manchester aquifer are in good hydraulic connection with the dewatering well and are preferentially dewatered causing an upward gradient from the Fort Payne aquifer.

Because of these pathways of high permeability, the depressions around the J4 test cell in each of the Highland Rim aquifers exhibit a large degree of

Table 7. Concentrations of chlorinated volatile organic compounds detected in ground-water samples collected from 35 wells located near the J4 test cell and from the J4 test cell

[µg/L, micrograms per liter; SH, shallow aquifer; MN, Manchester aquifer; FP, Fort Payne aquifer; UCB, upper Central Basin aquifer; values given as < (less than) indicate that the concentration was below the reporting level of the analytical method used and does not indicate the presence or absence of the consituent; --, sample not specific to single aquifer]

AEDC well number (fig.2)	Aquifer	Tetra-chloro-ethyl-ene total (µg/L)	Tri-chloro-ethyl-ene total (µg/L)	1,1,1-tri-chloro-ethane total (µg/L)	1,1,2-tri-chloro-ethane total (µg/L)	1,1-di-chloro-ethyl-ene total (µg/L)	Trans 1,2-di-chloro-ethene total (µg/L)	Cis-1,2-di-chloro-ethene water total (µg/L)	1,1-di-chloro-ethane total (µg/L)	1,2-di-chloro-ethane total (µg/L)	Tri-chloro-fluoro-methan e total (µg/L)
AEDC-30	SH	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-31	MN	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-64	MN	<0.2	15	19	<0.2	23	<0.2	0.5	2.1	<0.2	19
AEDC-83	SH	0.4	1.5	1.1	<0.2	29	<0.2	0.4	6.3	0.3	1.1
AEDC-154	MN	<0.2	4.8	0.8	<0.2	1.5	<0.2	0.4	1.9	<0.2	0.8
AEDC-155	FP	<0.2	1.7	0.3	<0.2	2.1	<0.2	<0.2	0.3	<0.2	0.3
AEDC-158	MN	0.3	0.5	0.2	<0.2	5.3	<0.2	<0.2	1.6	<0.2	0.2
AEDC-159	FP	0.7	580	<0.2	0.4	1.9	<0.2	18	0.9	<0.2	<0.2
AEDC-175	UCB	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-267	MN	<0.2	<0.2	1.5	<0.2	0.9	<0.2	<0.2	<0.2	<0.2	1.5
[1]AEDC-268	UCB	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
AEDC-269	MN	4.6	43	19	<0.2	25	<0.2	8.3	3.6	1.1	19
AEDC-270	FP	<0.2	2.0	<0.2	<0.2	0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-271	MN	0.5	17	1.8	<0.2	7.9	<0.2	3.1	3.3	<0.2	1.8
AEDC-272	MN	1.9	0.5	4.2	<0.2	22	<0.2	0.4	8.8	0.3	4.2
AEDC-273	FP	0.4	140	5.1	<0.2	52	<0.2	0.3	1.1	9.9	5.1
AEDC-274	MN	0.9	1,200	35	0.8	320	<0.2	0.3	5.3	45	35
AEDC-275	SH	<0.2	6.7	3.2	<0.2	5.2	4.5	<0.2	1.2	0.4	3.2
AEDC-276	MN	<0.2	<0.2	<0.2	<0.2	0.3	<0.2	<0.2	0.4	<0.2	<0.2
AEDC-277	UCB	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-278	MN	0.2	2.6	3.7	<0.2	12	<0.2	<0.2	1.7	<0.2	3.7
AEDC-279	MN	1.2	1.0	1.0	<0.2	2.7	<0.2	<0.2	0.4	<0.2	1.0
AEDC-280	SH	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-281	UCB	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	1.1	0.4	<0.2	<0.2
AEDC-282	FP	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-283	MN	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-284	SH	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-285	MN	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-286	MN	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-287	SH	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-288	FP	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-289	MN	<0.2	<0.2	<0.2	<0.2	0.2	<0.2	<0.2	0.4	<0.2	<0.2
AEDC-290	SH	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-292	MN	<0.2	0.3	<0.2	<0.2	0.7	<0.2	<0.2	<0.2	<0.2	<0.2
AEDC-293	SH	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
J4-test cell	--	48	240	27	0.2	17	<0.2	0.9	3.5	0.4	27

[1]Method reporting limits raised due to laboratory dilution of sample.

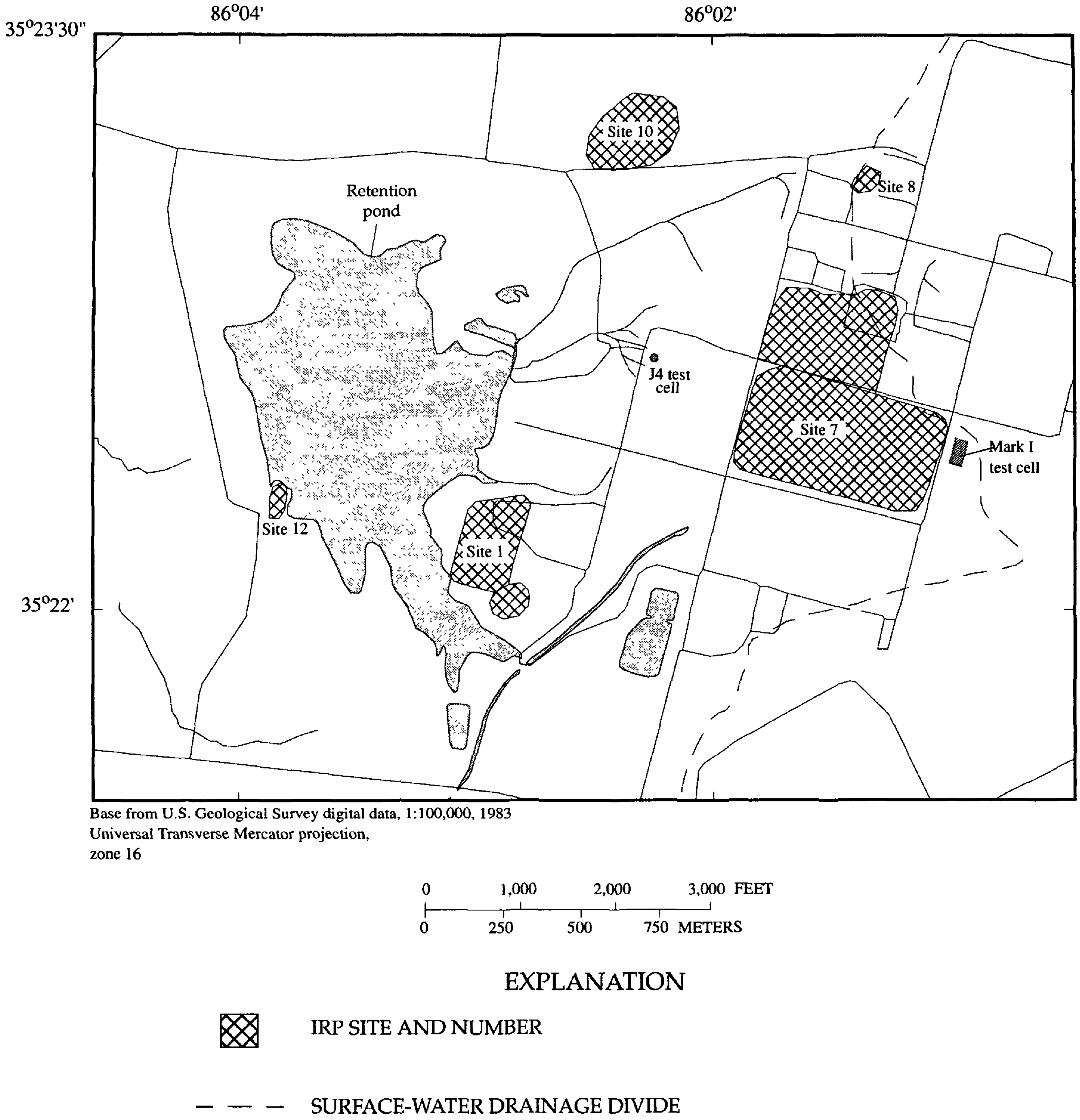


Figure 24. Installation Restoration Program (IRP) sites located near the J4 test cell at Arnold Engineering Development Center.

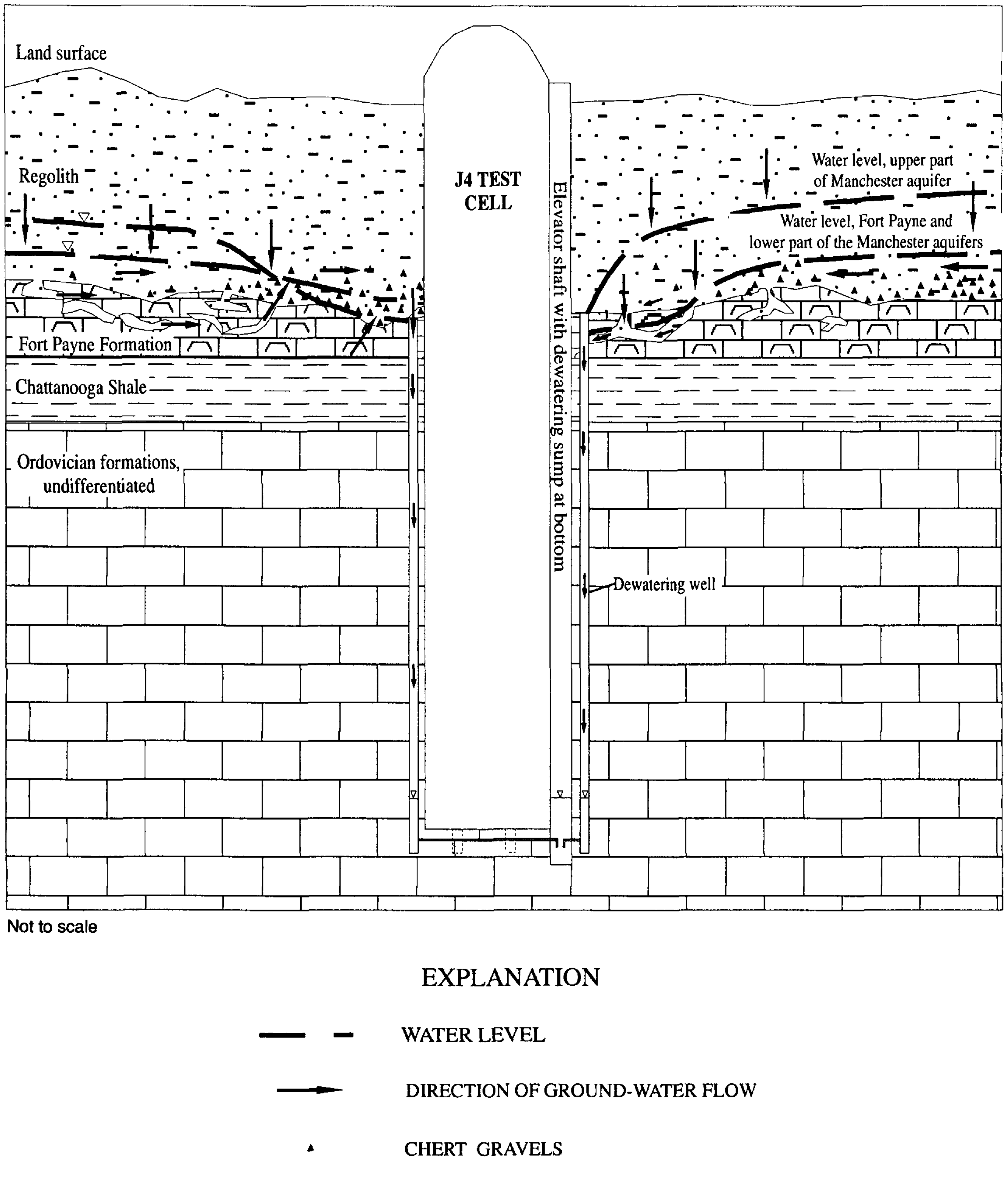


Figure 25. Conceptual cross-section showing ground-water flow to the J4 test cell at Arnold Engineering Development Center.

Table 8. Discharge data from the J4 test cell and precipitation data at Arnold Engineering Development Center for water years 1991 through 1995

[A water year begins October 1 and ends September 30]

Water year	Average discharge (gallons per minute)	Precipitation (inches)
1991	160	61.04
1992	117	64.12
1993	91.1	44.41
1994	115	63.35
1995	98.6	46.68

anisotropy (figs. 17, 18, and 19). The orientation of the anisotropy agrees well with the high conductivity orientations from the geophysical surveys and the lineation analysis. Some agreement also can be noted when comparing lineations mapped near the J4 test cell and the orientations of the depressions in the Fort Payne and the lower part of the Manchester aquifers (figs. 7 and 19).

Analysis of the chemistry of the water discharged from the J4 test cell suggests that most of the water is derived from the Manchester aquifer. Using the trilinear diagram plotting positions to compare water-quality types, the discharge water from J4 most resembles water from the Manchester aquifer (fig. 18). This result is consistent with data that show the Manchester aquifer is the most productive aquifer in the area and with regional water budget calculations that show that 78 percent of the ground water beneath AAFB flows through the Manchester aquifer and 9 percent flows through the Fort Payne aquifer (Haugh and Mahoney, 1994).

Based on the potentiometric surface maps for each aquifer, the area contributing ground water to the J4 test cell was estimated (figs. 17, 18, and 19). The size of the capture area is estimated to be 0.49 square mile in the shallow aquifer (fig. 17), 0.76 square mile in the upper part of the Manchester aquifer (fig. 18), and 0.84 square mile in the Fort Payne and the lower part of the Manchester aquifers, undifferentiated (fig. 19). To verify that these are reasonably sized areas, an estimated recharge rate was applied over the area, and the discharge to the J4 test cell was calculated. This analysis assumes that aerial recharge to the aquifers provides the only source of water discharged into the J4 test cell.

In a study by Hoos (1990), recharge rates for drainage basins across Tennessee were estimated using a hydrograph-separation technique (Rorabough, 1964; Daniel, 1976). Reported average annual recharge rates for drainage basins in the Highland Rim area ranged from 4.9 to 9.8 inches. In a regional ground-water model of the AAFB area, the average recharge rate applied was 8 inches per year (Haugh and Mahoney, 1994). For the analysis performed as part of the present study, a recharge rate of 8 inches per year is also assumed. Much of the capture area, however, is covered by impervious surfaces such as roofs of building, paved parking areas, and roads. Precipitation falling on these surfaces is conveyed to the surface-water-drainage system before it can infiltrate as ground-water recharge. Using maps and aerial photographs, the impervious area within the shallow aquifer capture area is estimated to be 40 percent. Therefore only 60 percent of the capture area is assumed to be available for infiltration of recharge.

Similarly, capture areas in the Manchester and Fort Payne aquifers that extend beyond the capture area of the shallow aquifer have been shown to have a lower recharge rate because only a percentage of the recharge entering the shallow aquifer infiltrates downward to reach the deeper aquifers. Percentages of the recharge to the shallow aquifer derived from the regional ground-water model (Haugh and Mahoney, 1994) were used for this analysis. The model shows that of the shallow recharge, 78 percent reaches the Manchester aquifer and 9 percent reaches the Fort Payne aquifer. Applying these effective-recharge rates to the capture areas results in an estimated flow to the J4 test cell of 111 gal/min. This compares favorably with the average measured flow of 105 gal/min for 1992-95.

The ground-water capture areas in each of the Highland Rim aquifers extend into all or parts of IRP sites 1, 7, and 10. At IRP site 1, the northern half of the site lies in the capture area of the shallow aquifer and the upper part of the Manchester aquifer. The capture area for the Fort Payne and the lower part of the Manchester aquifers, undifferentiated, extends further south encompassing nearly two-thirds of site 1.

At IRP site 7, all of the site except the northeastern part lies within the capture areas for the upper part of the Manchester aquifer and the Fort Payne and the lower part of the Manchester aquifers, undifferentiated. Most of the western and southern parts of site 7 also lie in the capture area for the shallow aquifer. Part of the eastern area of site 7 lies in the capture area of the Mark I test cell, and a part of the northeastern area of site 7 is outside the shallow capture area.

At IRP site 10, the capture areas of the upper part of the Manchester aquifer and the Fort Payne and the lower part of the Manchester aquifers, undifferentiated, encompass all except the northwestern edge of the site. The capture area for the shallow aquifer does not cover any of site 10, so ground water from the shallow aquifer that underlies site 10 and that moves horizontally before percolating downward to recharge the Manchester aquifer would not be captured by the dewatering system at the J4 test cell.

IRP site 8 lies on the surface-water divide. Potentiometric and water-quality data indicate that ground water from this site moves eastward down the side of the divide away from the J4 test cell. Therefore, ground water leaving this site would not be captured by the J4 test cell.

IRP site 12 is located on the southwestern edge of the retention reservoir. Ground water at this site is not effected by the dewatering at the J4 test cell.

All of the above interpretations are based on estimated capture areas derived from water-level data collected in July 1994. Even though the depressions around the J4 test cell are in equilibrium, the exact size and shape of the capture areas for each aquifer would show small variations in response to seasonal and yearly water-level fluctuations. Additionally, if these capture areas are used to assess which IRP sites possibly are contributing contaminants to the J4 dewatering system, they would only apply to contaminants that are dissolved in the ground water and, therefore, can move under the influence of the hydraulic gradient. In areas where ground-water contamination may exist as dense non-aqueous phase liquids (DNAPL's), its direction and rate of movement likely would be controlled more by structural features, such as the dip of the bedrock surface, the dip of the Chattanooga Shale, and fractures, joints, and bedding planes in the bedrock, than by the hydraulic gradient. Since the crest of an anticline in the Chattanooga Shale lies beneath the J4 test cell, the Chattanooga Shale dips away from the test cell in all directions (fig. 6). Similarly, with the exception of a local high-altitude area on the top of the bedrock surface directly west of the J4 test cell, the top of bedrock dips away from the test cell to the north-northeast and to the south-southwest (fig. 4). Upon reaching these surfaces, DNAPL's in ground water would move in a direction influenced by the local structure of these features.

CONCLUSIONS

The J4 test cell at the Arnold Engineering Development Center (AEDC) was constructed in the early 1960's to support the testing of rocket motors. The cell is approximately 100 feet in diameter, extends approximately 250 feet below land surface, and penetrates several aquifers. Ground water is pumped continuously from around the test cell to keep it structurally intact. Because of the test cell's depth, dewatering has depressed the water levels in the aquifers surrounding the site. The depressions that have developed exhibit anisotropy that is controlled by zones of high permeability in the aquifers. Additionally, contaminants—predominantly volatile organic compounds (VOC's)—are present in the ground-water discharge from the test cell and in ground water at several other nearby sites within the AEDC facility. The dewatering activities at J4 appear to be drawing these contaminants in from the nearby sites.

Contour maps of the potentiometric surfaces for the shallow, Manchester, and Fort Payne aquifers (collectively, part of the Highland Rim aquifer system) show anisotropic water-level depressions centered on the J4 test cell. This anisotropy is the result of zones of high permeability in the regolith and the bedrock. The presence of more permeable features in the Manchester aquifer results in complex flow patterns in the Highland Rim aquifer system near the J4 test cell. The occurrence, distribution, and orientation of these features effect the ground-water flow to the J4 test cell. Dewatering stress propagates out horizontally through the aquifers along the pathway of highest permeability. These pathways include the chert gravel zones in the regolith and fractures, joints, and bedding planes in the bedrock. Because the aquifers above the Chattanooga Shale are not separated by distinct confining units, the stress also propagates vertically, dewatering areas above and below these zones of high permeability. Because of these more permeable pathways, the depressions around the J4 test cell in each of the Highland Rim aquifers exhibit strong anisotropy.

In all the aquifers, the size and shape of the depressions are in equilibrium because ground-water withdrawal at the test cell has been continuous since the late 1960's. The average ground-water discharge from the dewatering system is 105 gal/min for 1992-95.

The ground-water capture areas in each of the Highland Rim aquifers extend into all or parts of IRP sites 1, 7, and 10. At IRP site 1, the northern half of the site lies in the capture area of the shallow and the upper part of the Manchester aquifers. The capture area for the Fort Payne and the lower part of the Manchester aquifers, undifferentiated, extends further south encompassing nearly two-thirds of site 1. At IRP site 7, all but the northeastern part of the site lies within the capture areas for the upper part of the Manchester aquifer and the Fort Payne and the lower part of the Manchester aquifers, undifferentiated. Most of the western and southern parts of site 7 also lie in the capture area for the shallow aquifer. Part of the eastern area of site 7 lies in the capture area of the Mark I test cell, and a part of the northeastern area of site 7 is outside the capture area for the shallow aquifer. At IRP site 10, the capture areas of the upper part of the Manchester aquifer and the Fort Payne and the lower part of the Manchester aquifers, undifferentiated, encompass all of the site except the northwestern edge. The capture area for the shallow aquifer does not cover any of site 10, so ground water from the shallow aquifer that underlies site 10 and that moves horizontally before percolating downward to recharge the upper part of the Manchester aquifer is not captured by the dewatering system at the J4 test cell. IRP sites 8 and 12 are outside the ground-water capture areas for the Highland Rim aquifers.

Even though the depressions around the J4 test cell are in equilibrium, the exact size and shape of the capture areas for each aquifer would show small variations in response to seasonal and yearly water-level fluctuations. Additionally, if these capture areas are used to assess which IRP sites are possibly contributing contaminants to the J4 dewatering system, they would only apply to contaminants that are dissolved in the ground water and, therefore, that can move under the influence of the hydraulic gradient. In areas where ground-water contamination may exist as dense non-aqueous phase liquids (DNAPL's), its direction and rate of movement likely would be controlled more by structural features, such as the dip of the bedrock surface, the dip of the Chattanooga Shale, and fractures, joints, and bedding planes in the bedrock, than by the hydraulic gradient.

Several wells in the J4 area produced water samples containing chlorinated organic compounds such as 1,2-dichloroethane (1,2-DCA), 1,1-dichloroethylene (1,1-DCE), and trichloroethylene (TCE) in concentrations that exceeded the Tennessee Department of Environment and Conservation Maximum Contaminant Levels (MCL's) for public water-supply systems. These wells are AEDC-64, -83, -159, -269, -271, -272, -273, -274, -275, and -278. The highest concentrations were detected in well AEDC-274 with 45 µg/L 1,2-DCA, 320 µg/L 1,1-DCE, and 1,200 µg/L TCE. These compounds are synthetic and do not occur naturally in the environment. A sample of ground-water discharge from the J4 test cell also contained concentrations of these compounds that exceeded MCL's. Additionally, several wells contained some of these VOC's in concentrations less than the MCL's. Chlorinated organic compounds including 1,2-DCA, 1,1-DCE, and TCE also have been detected at several IRP sites located at AEDC. These sites include landfill #2 and leaching pit #2 (IRP site 1), the main testing area (IRP site 7), leaching pit #1 (IRP site 8), and the old fire training area (IRP site 10).

The six dewatering wells surrounding the J4 test cell penetrate the Chattanooga Shale and are open to the Highland rim aquifer system, thereby introducing water from the overlying Highland rim aquifers into the underlying upper Central Basin aquifer system before it drains to the sump at the bottom of the J4 test cell. However, the possibility that some water from the Highland Rim aquifers could move out through the upper Central Basin aquifer system and cross-contaminate the deeper aquifers is highly unlikely. Drilling records indicate that no zones of significant permeability exist in the upper Central Basin aquifer system within the study area. The four USGS wells completed in the upper Central Basin aquifer system in the study area all have yields of less than 1 gal/min.

Therefore, the path of least resistance for water from the Highland Rim aquifers to leave the system is through the dewatering network at the J4 test cell rather than into the upper Central Basin aquifer system.

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