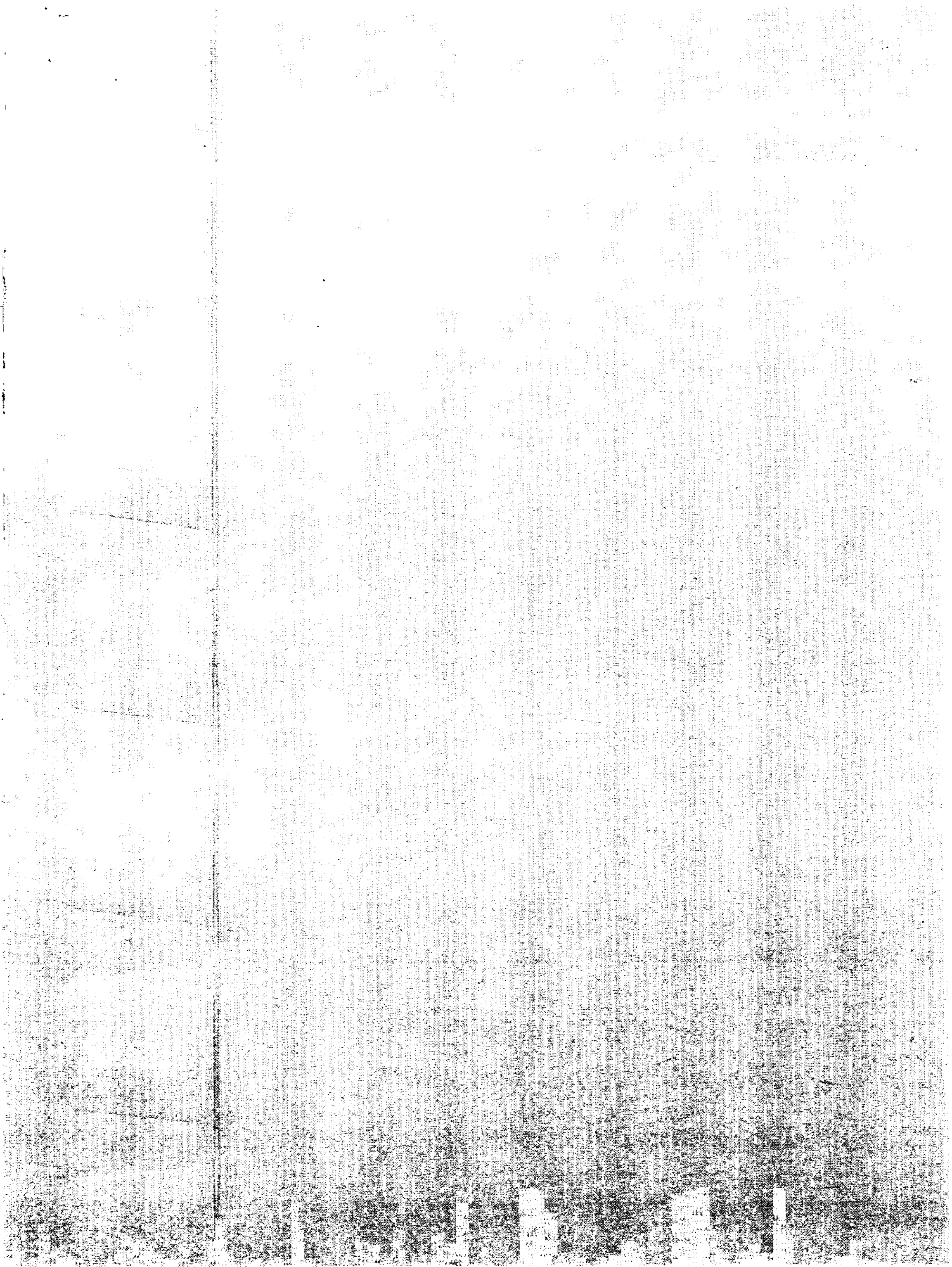
Tritium Migration From a Low-Level Radioactive-Waste Disposal Site Near Chicago, Illinois



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Tritium Migration From a Low-Level Radioactive-Waste Disposal Site Near Chicago, Illinois

By J.R. NICHOLAS and R.W. HEALY

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Tritium Migration From a Low-Level Radioactive-Waste Disposal Site Near Chicago, Illinois

By J.R. Nicholas *and* R.W. Healy

Abstract

This paper describes the results of a study to determine the geologic and hydrologic factors that control migration of tritium from a closed, low-level radioactive-waste disposal site. The disposal site, which operated from 1943 to mid-1949, contains waste generated by research activities at the world's first nuclear reactors. Tritium has migrated horizontally at least 1,300 feet northward in glacial drift and more than 650 feet in the underlying dolomite. Thin, gently sloping sand layers in an otherwise clayey glacial drift are major conduits for ground-water flow and tritium migration in a perched zone beneath the disposal site. Tritium concentrations in the drift beneath the disposal site exceed 100,000 nanocuries per liter. Regional horizontal joints in the dolomite are enlarged by solution and are the major conduits for ground-water flow and tritium migration in the dolomite. A weathered zone at the top of the dolomite also is a pathway for tritium migration. The maximum measured tritium concentration in the dolomite is 29.4 nanocuries per liter. Fluctuations of tritium concentration in the dolomite are the result of dilution by seasonal recharge from the drift.

INTRODUCTION

In 1943, the U.S. Army Corps of Engineers leased 1,025 acres from the Cook County (Ill.) Forest Preserve District to conduct nuclear research. Two nuclear reactors were built on the leased parcel of land, and low-level radioactive waste associated with the research was buried there. After the site was decommissioned and the land returned to the Forest Preserve District in 1956, Argonne National Laboratory (ANL) assumed responsibility for monitoring radionuclide activity at the forest preserve. In 1973, tritium was detected in water from a forest-preserve well located about 1,200 feet (ft) downgradient from the burial site. Since 1976, the U.S. Geological Survey, with the assistance of ANL, has conducted studies to determine the direction and rate of tritium migration in the subsurface and the location and concentration of tritium contamination in the forest preserve.

Purpose and Scope

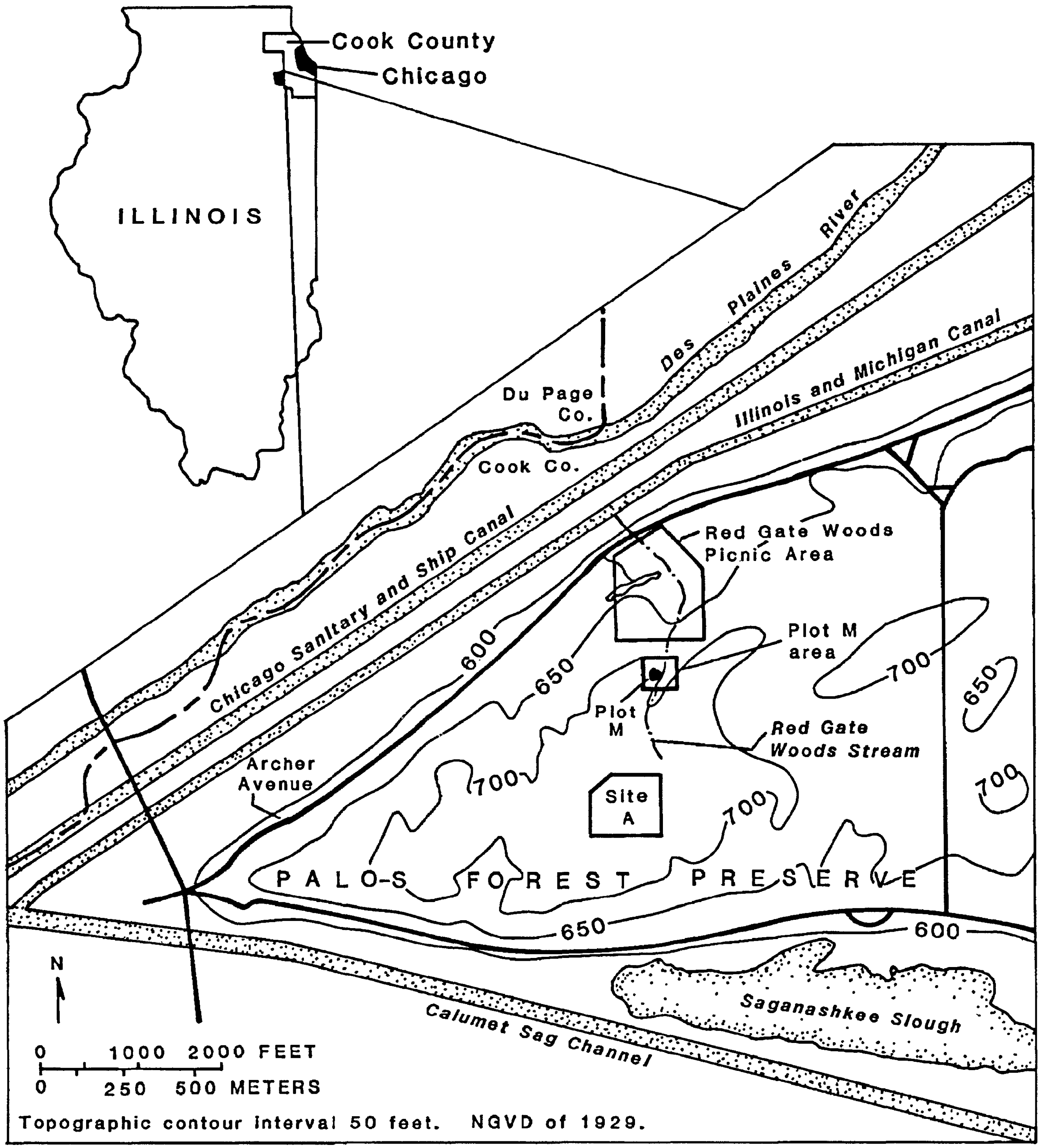
This paper describes the results of a study to determine the geologic and hydrologic factors that control tritium migration in the study area. Included are an explanation of the migration of tritium from the burial site to a forest-preserve well and the fluctuating tritium levels in that well. The scope of the paper includes discussion of ground-water flow and tritium migration in both glacial drift and dolomite; it also includes discussion of the role of streamflow and the source of tritium concentrations in surface water.

The scope of the work included drilling six wells in dolomite, collecting cores from glacial drift at five locations, and collecting leaves from 12 trees for tritium analysis. Ground-water levels were measured in 28 piezometers in glacial drift and 10 wells in dolomite, and more than 1,100 water samples for tritium analysis were collected from wells completed in glacial drift and dolomite and from a stream near the disposal site.

This investigation continues work reported by Olimpio (1984). Data collected from 1982 to 1985 necessitate refinement or changes of some of Olimpio's interpretations and conclusions.

Physical Setting

The study area consists of the burial site—designated Plot M—and the surrounding land. It is located near the Red Gate Woods picnic area of the Palos Forest Preserve in southwestern Cook County (fig. 1). For this paper, the study area is considered to be subdivided into two distinct areas (fig. 2): (1) the Plot M area, which was the focus of studies of the drift, and (2) the Red Gate Woods picnic area, which was the focus of studies of the dolomite. Plot M is constructed on a morainal upland, which is dissected by two valleys—the Des Plaines River valley to the north and the Sag valley to the south. Total relief in the area is about 200 ft. The upland is characterized by a rolling, knobby topography and poorly developed drainage. Streams are ephemeral and either drain



Base from U.S. Geological Survey
Sag Bridge 1:24,000, 1963

Figure 1. Location of study area in the Palos Forest Preserve.

internally to closed depressions or flow to one of the transmorainic valleys. The Red Gate Woods stream is an ephemeral stream that flows adjacent to Plot M and northward into the Des Plaines River valley. The transmorainic valleys are wide, flat features with low stream gradients in which three canals have been constructed. The Calumet Sag Channel was constructed in the mid-20th century in the Sag valley. The Illinois and Michigan

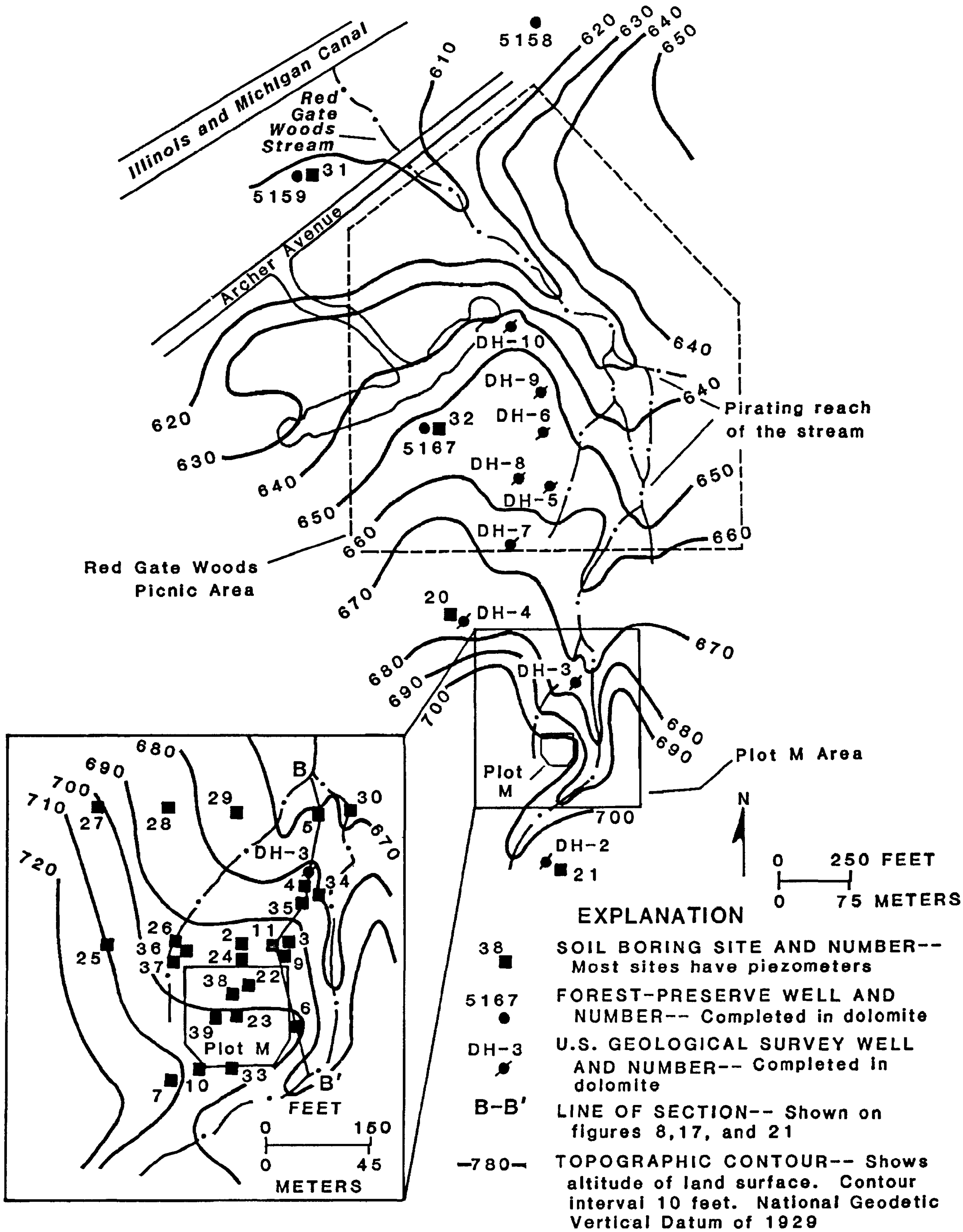


Figure 2. Locations of wells completed in dolomite and sites of soil borings in the study area.

Canal and the Chicago Sanitary and Ship Canal were constructed in the 19th century and are located south of and approximately parallel to the Des Plaines River. The canals join west of the study area, delineating a wedge-shaped upland area. Vegetation in the study area consists of mature deciduous forest, dominated by oak and hickory, and successional growth, dominated by hawthorne, in formerly cleared areas.

Site History

The world's first nuclear reactor, CP–1, was successfully operated at the University of Chicago in December 1942. Subsequently, for the purposes of safety and security, the reactor and associated research facilities were moved out of the city. In early 1943, the Manhattan Engineering District of the U.S. Army Corps of Engineers leased land for the nuclear research facility from the Cook County Forest Preserve District. CP–1 was dismantled, moved to the new location in the forest preserve (Site A, fig. 1), and rebuilt as CP–2. On May 15, 1944, CP–3, the world's first heavy-water cooled and moderated reactor, began operation at Site A. Both reactors remained in operation until 1954.

From early 1943 to mid-1949, low-level radioactive waste from operations at Site A and the University of Chicago was buried at Plot M (Golchert and Sedlet, 1978). Accurate descriptions of the amounts and types of waste and the method of burial are not available. Records show that waste was originally buried in 6-ft-deep trenches in the southern half of Plot M. In early 1948, waste in steel bins was buried in similar trenches in the northern half of Plot M. The bins were removed from the northern trenches in 1949 and taken to the present ANL site. Burial at Plot M was discontinued in June 1949, and the area was covered with soil and seeded.

The burial site was decommissioned in 1956 in order to return the land to forest-preserve use. Concrete sidewalls, 8 ft in depth, were poured around the perimeter of the site, and a 1-ft-thick concrete slab was placed over the entire area. The concrete structure resembles an inverted box measuring approximately 8 by 140 by 150 ft. The concrete was covered with about 2 ft of soil, and the area was seeded with grass.

ANL has maintained an environmental monitoring program at Plot M since 1954. The program includes analysis for radionuclides in samples of soil, glacial drift, surface water, and ground water. Sample-collection sites are shown in figure 2. Samples were collected primarily in the immediate vicinity of Plot M until 1973, when the sampling program was expanded to include ground water from forest-preserve wells completed in dolomite underlying the glacial drift (Golchert and Sedlet, 1978). In 1973, tritium was measured at a concentration of 11.9 nanocuries per liter (nCi/L) in water from well 5167 in the Red Gate Woods picnic area. This well is about 1,200 ft downgradient from Plot M. Since 1973, water has been collected regularly from well 5167. Tritium concentrations vary seasonally, ranging from background levels (0.2 nCi/L) in the summer to about 10 nCi/L in the winter.

In 1976, four test wells were drilled into the dolomite: DH–1, at Site A; DH–2, south of Plot M; DH–3, just north of Plot M; and DH–4, between Plot M and well 5167 (table 1, at end of report). Tritium concentrations in these wells are usually near background. The presence of tritium in well 5167 and the relative lack of tritium in wells DH–3 and DH–4 prompted a study of the potential pathways, directions, and rates of tritium migration in the forest preserve. The major focus of the study was tritium migration in the drift in the vicinity of Plot M. During the study, the drift in and around Plot M was cored continuously at 25 locations (fig. 2, inset) and piezometers were installed in most of the borings. Geologic and construction data for these borings are presented by Olimpio (1982). Cores of the drift were also retrieved next to wells DH–4, 5167, and 5159. In addition, ground-water samples were collected from drift piezometers and dolomite wells, and the samples were analyzed for tritium content.

Interpretation of subsurface data collected by the U.S. Geological Survey and ANL from 1976 through 1981 led to the following conclusions (Olimpio, 1984):

1. Plot M is the sole source of tritium entering the ground-water system.
2. The primary direction of tritium movement in the drift beneath Plot M is vertically downward.
3. Lines of equal concentration of tritium delineate a plume resembling a bull's-eye pattern, with the highest concentration at the center, about 50 ft below the surface of Plot M. The plume is moving deeper into the drift, with higher concentrations of tritium expected to reach the dolomite.
4. Tritium is present in the drift only in the area beneath and adjacent to Plot M; tritium is not moving to well 5167 through the drift and thereby bypassing wells DH–3 and DH–4. Rather, tritium enters the dolomite beneath Plot M and migrates from there to well 5167.

Acknowledgments

Technical support during this investigation from Jacob Sedlet, Norbert Golchert, Howard Svoboda, and other staff of ANL's Occupational Health and Safety Department (OHD) has been invaluable. With few exceptions, analyses for radionuclides, collection of water samples, and measurements of water levels were made by

OHD. The ongoing environmental monitoring program implemented by OHD in the 1950's provides an essential historical framework for interpretation of data. In addition, OHD serves as liaison between the U.S. Geological Survey and the Cook County Forest Preserve District. Water-level measurements in forest-preserve wells were made possible by the assistance of a Forest Preserve District pump-pulling crew composed of C. Bennett, O. Copperridge, H. Minter, and J. Balsamello.

GEOLOGY

Silurian System

Lithology

The uppermost bedrock unit in the study area is Silurian dolomite. The dolomite is part of the Racine Formation of the Niagaran Series. The rock is a light-gray, pure to silty, sometimes cherty, well-bedded dolomite. In the study area, the Racine Formation crops out along the northern bluffs of the Des Plaines River, on valley floors of large streams, and in quarries. Beneath the Racine Formation in the study area are the Sugar Run and Joliet Formations, also part of the Niagaran Series, and the Kankakee and Elwood Formations of the Alexandrian Series (Willman, 1973; Mikulic and others, 1985). These formations are typically well bedded, with lithologies ranging from pure dolomite to shaley dolomite. Some beds are cherty. Because the lithologies of these formations are similar, they are treated as a single unit, the Silurian dolomite, in this paper.

Bedrock Surface and Thickness

Most interpretations of the bedrock surface in the Chicago area are based on data from outcrops and borings. Maps show a gently rolling, dissected surface with a well-integrated drainage pattern (Horberg, 1950; Suter and others, 1959; Zeizel and others, 1962). Zeizel noted that the orientation of bedrock valleys in Du Page County are controlled by major joint sets.

Buschbach and Heim (1972) published a map of the bedrock surface based on data from outcrops, borings, and seismic refraction. Their map represents a new interpretation of the configuration of the bedrock surface in Cook County, east of the study area. The map shows a surface with numerous hills dissected by valleys that have steeply sloping sides. Many closed depressions were mapped, with depths ranging from 10 to 40 ft and areas ranging from less than a quarter of a square mile to more than 4 square miles (mi^2). Buschbach and Heim suggested these depressions may represent a karst topography.

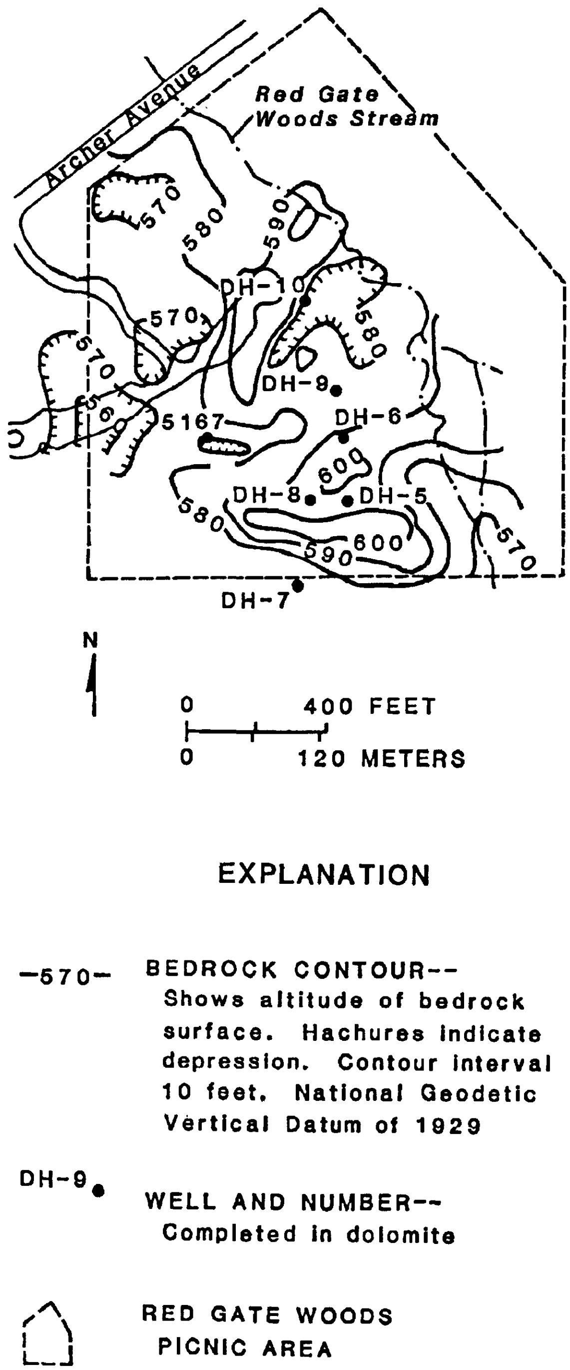


Figure 3. Configuration of the bedrock surface.

Preliminary interpretation of recently compiled seismic-refraction data indicates that the dolomite underlying the study area is karsted (Robert Gilkeson, Illinois State Geological Survey, personal commun., 1985). The data consist of 60 values for the altitude of the bedrock surface in the Red Gate Woods picnic area. Relief on the bedrock surface, based on the seismic data, is estimated to be greater than 40 ft, ranging from an altitude of about 560 ft to more than 600 ft above sea level (fig. 3).

The top of the dolomite is a weathered zone less than 5 ft thick. This zone has been reported by many drillers and construction engineers and has been noted in U.S. Geological Survey test wells.

The thickness of the Silurian dolomite varies in the study area because of relief on the Ordovician-Silurian unconformity and on the bedrock surface. Only one test well, DH–4, penetrates the entire thickness of the dolomite. In DH–4, the dolomite is 171 ft thick.

Structure and Jointing

The study area is located on the crest of the Kankakee arch (Willman, 1971). Silurian strata dip slightly to the east and southeast because of the eastward plunge of the arch. Tensile stress from subsidence of the Michigan basin and uplift of the Wisconsin and Kankakee arches caused jointing in the brittle dolomite (Foote, 1982).

Joints in the dolomite occur in three mutually orthogonal sets. Two of the sets are vertical and are caused by structural deformation, as noted above. The third set is horizontal and is caused by solution along bedding planes.

Evidence of vertical jointing in the study area was gathered from studies of outcrops, lineament mapping, and bedrock surface mapping. Orientations of 156 vertical joints were measured in two quarries and plotted on a rose diagram using one unit length per joint and grouping the joints into 5° sectors (fig. 4). Several investigators have mapped lineaments to locate joint sets, faults, and other linear structural features in the subsurface—for example, Trainer (1967), Siddique and Parizek (1971), and Sharpe and Parizek (1979). A total of 106 lineaments were mapped on aerial photographs of a 25-mi^2 area, with Plot M near the center. A rose diagram was constructed using one unit length per 1,000 ft of lineament length and grouping the lineaments into 5° sectors. Comparison of the rose diagrams shows that two sets of lineaments are analogous to the two sets of vertical joints; orientations of the two sets are approximately 40° and 130° azimuth. The third lineament set, oriented at about 20°, has no apparent analogy in joint sets. Other investigators have noted that frequency and aperture of vertical joints in the area decrease with depth below the bedrock surface—for example, Zeizel and others (1962) and Foote (1982). However, the presence of sinkholes suggests that some closely spaced groups of deeper vertical joints may be present in the study area. Also, one prominent lineament passes through the study area and coincides with the northernmost 2,000 ft of the Red Gate Woods stream valley; this lineament may reflect a set of vertical joints beneath part of the valley.

Horizontal joints along bedding planes are evident at outcrops and from interpretation of borehole geophys-

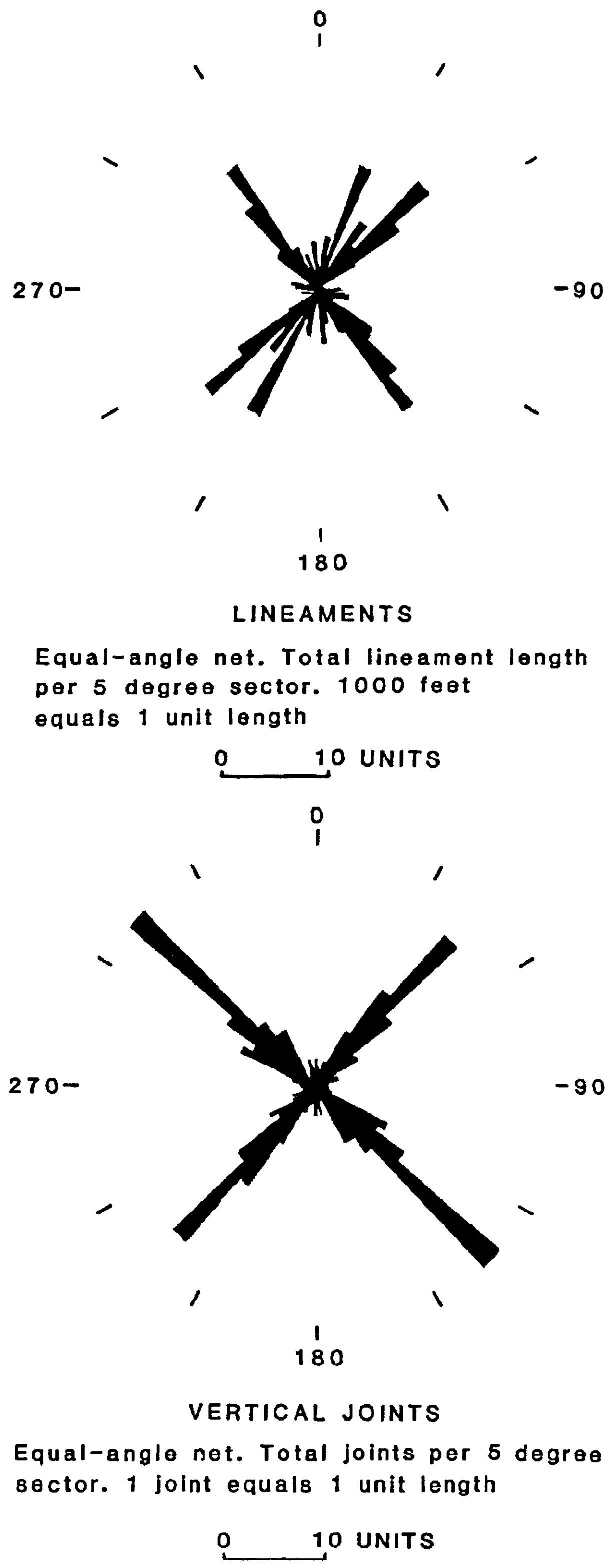


Figure 4. Lineament and vertical-joint orientations. (Orientations are in degrees azimuth; 0 degrees is true north.)

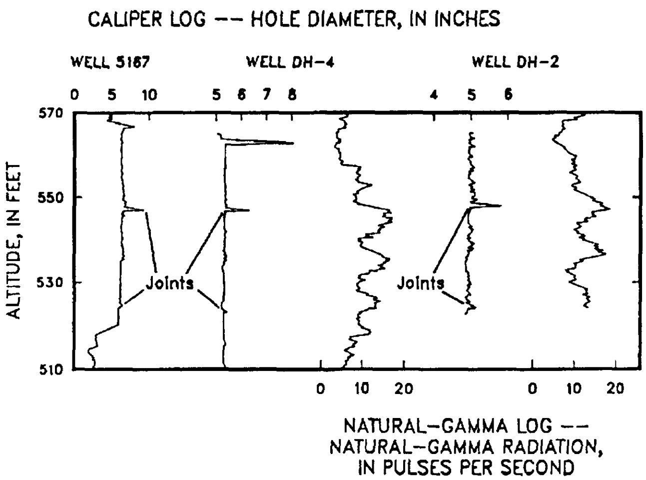


Figure 5. Borehole-geophysical logs for wells 5167, DH-4, and DH-2.

ical logs. Horizontal joints, hundreds of feet long, can be seen at outcrops along the northern side of the Des Plaines River valley. Many of these are weathered, and some are several inches wide. Acoustic and caliper logs of wells in the study area clearly show horizontal jointing. The correlation of joints and lithology between wells is excellent (fig. 5), and joints appear to be continuous for at least 1,600 ft.

The dolomite has been extensively weathered by solution. Zeizel and others (1962) report solution cavities tens of feet in dimension. In 1982, several hundred thousand gallons of water drained from a water-filled excavation in glacial drift at ANL in less than 2 days (d). The loss was attributed to drainage into a large solution cavity in the underlying dolomite (Marge Bynoe, Argonne National Laboratory, written commun., 1982). Drainage from the glacial drift into the solution cavity apparently transported glacial sediment from the bottom of the excavation into the cavity, resulting in formation of a subvertical, pipelike drain. Rock cores collected by the U.S. Army Corps of Engineers during construction of the Calumet Sag Channel show horizontal joints having apertures up to 2 ft. Evidence of sediment-filled horizontal joints has been observed both in the Corps of Engineers' cores and in the U.S. Geological Survey wells. The sediment recovered from joints ranges from clay- to sand-sized particles and appears to be of glacial origin.

In this paper, horizontal joints are classed as either subregional or regional. Joints that are located in bedrock highs and are truncated at the drift-dolomite contact are subregional joints. Subregional joints are commonly filled with glacial sediment. Joints that are areally extensive are regional joints. Only canals or sinkholes interrupt the continuity of regional joints. The major regional joints in the study area, as determined from interpretation of borehole geophysical logs, occur at altitudes of about 415, 440, 460, 525, 550, and 565 ft above sea level. The relation between subregional joints and regional joints is shown in figure 6.

Quaternary System

Unconsolidated deposits of Quaternary age cover the Silurian bedrock throughout the study area, except at steep bluffs or where removed by streams or man (Frye and Willman, 1960). Most deposits result from glaciation during the Wisconsinan Stage of the Pleistocene. A thin veneer of Holocene alluvium is present in parts of the Des Plaines River valley.

Two Wisconsinan tills—the Malden and overlying Wadsworth Till Members of the Wedron Formation—are present in the study area (Willman and Frye, 1970). Total thickness of tills in the study area ranges from less than 1 ft in the two major valleys to more than 170 ft near Site A. At Plot M, the drift is about 140 ft thick. The mineralogy, lithology, and stratigraphy of the two tills at Plot M are described in detail by Olimpio (1984). The outstanding lithologic feature of the Malden Till Member in the study area is that it is well sorted and appears to have been reworked by glacial meltwater (Bretz, 1955). The sandy silt and gravel of the Malden Till Member contrast sharply with the overlying Wadsworth Till Member. The Wadsworth Till Member is a dense, clayey silt that becomes progressively better sorted with depth. The upper 25 to 35 ft of the till contains numerous thin lenses and layers of sand and gravel.

Sand layers in the upper part of the Wadsworth Till Member are laterally continuous for at least 300 ft in the vicinity of Plot M. The sand layers are thin and range in thickness from less than 1 to about 6 inches (in). Figure 7 shows the configuration of the uppermost sand layer. This sand layer, like the rest of the drift, dips to the northwest. Sand-filled, subvertical fractures are present in the upper 10 to 15 ft of the Wadsworth Till Member.

A thin layer of drift composed chiefly of sand and gravel overlies the bedrock (Olimpio, 1984). This layer (unit 7 in Olimpio's classification) was found in only one boring, SB-36. However, SB-36 is the only boring that reached dolomite, and basal sand and gravel were found in wells DH-5 through DH-10, so it is reasonable to assume that this layer is present beneath most of the study area.

The Des Plaines River and Sag valleys were outlets for higher stages of the ancestral and modern Lake Michigan (Bretz, 1955). Meltwater from retreating glaciers scoured these transmorainic valleys down to bedrock, breaching the bedrock and topographic drainage divides. Deposits in the two valleys are markedly different. The Des Plaines River valley contains valley-train deposits of the Mackinaw Member of the Henry Forma-

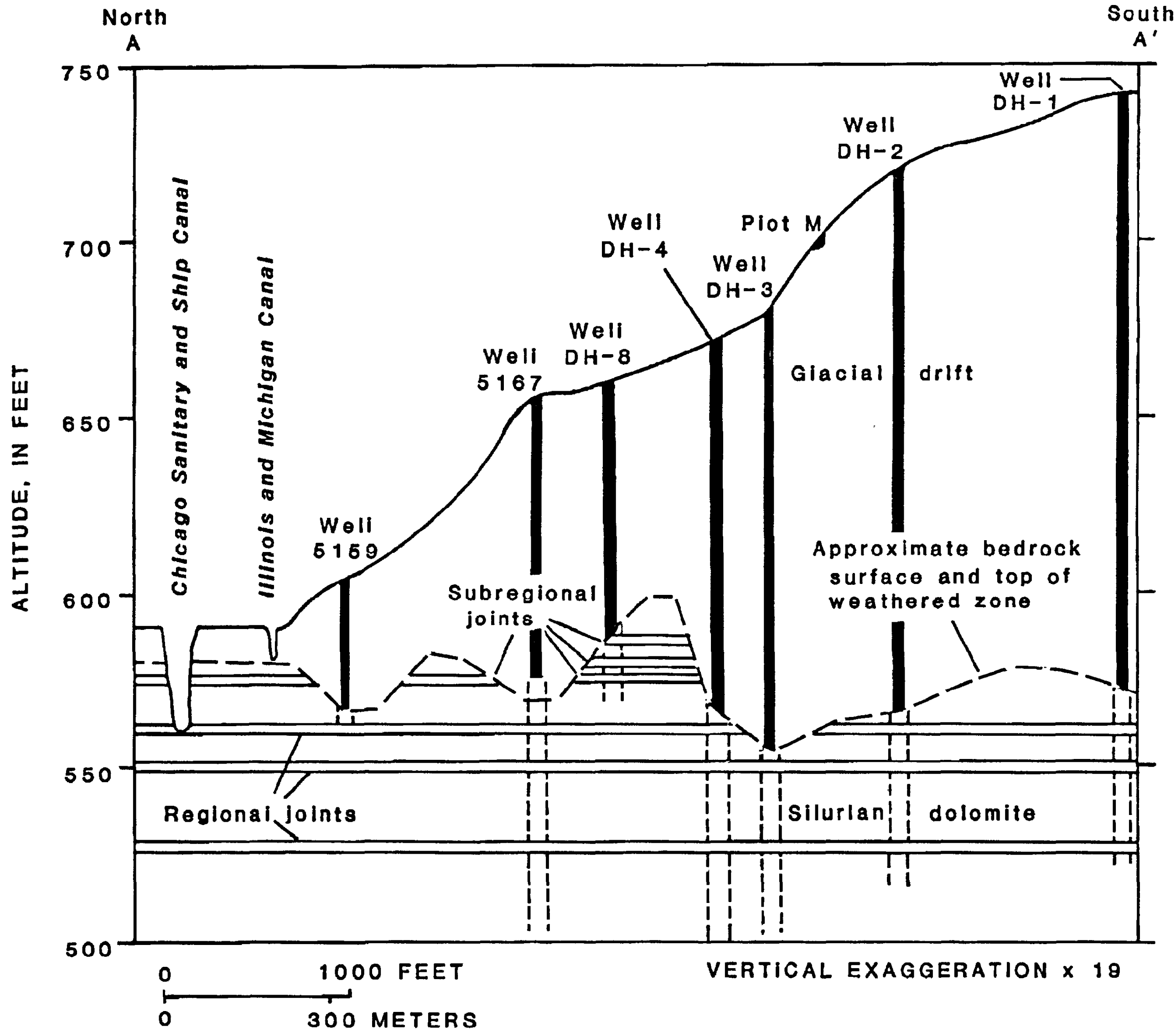


Figure 6. Generalized geologic section showing relation of subregional and regional horizontal joints. (See fig. 13 for trace of section.)

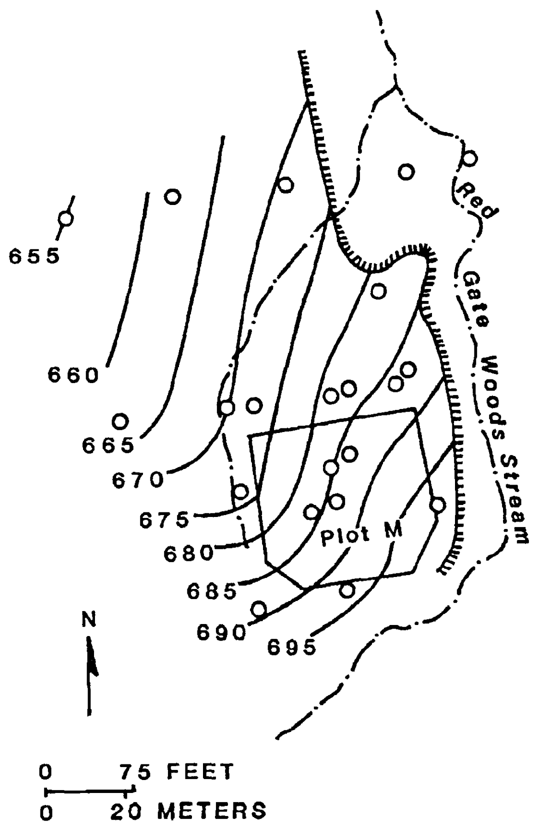
tion of the Wisconsinan Stage (Willman and Frye, 1970). The Mackinaw Member is outwash consisting mostly of sand and gravel, but several lag deposits of boulders are also present. The Sag valley, with its low gradient and no natural stream, contains thick deposits of Grayslake Peat.

HYDROLOGY

Surface Water

The Red Gate Woods stream is an ephemeral stream that flows from the upland near Site A, past Plot M, to discharge into the Illinois and Michigan Canal (fig. 1). The drainage area of the stream is about 0.21 mi^2. The part of the stream valley near Plot M is narrow and deeply incised. Downstream, the stream valley is much wider and the stream meanders across the valley floor. An unusual aspect of the stream in this reach is that, for a distance of about 400 ft, it has abandoned its natural channel. Erosion of wheel ruts in an old roadbed progressed to the point where the ruts pirated the stream (fig. 2). Where the current channel meets another tributary to the Red Gate Woods stream, a 10-ft-deep "canyon" has been eroded in the drift. Based on the amount of erosion seen in the canyon during this 3-year (yr) study, the piracy probably occurred in the last 10 yr.

The Red Gate Woods stream seldom flows other than in early spring. Streamflow results from snowmelt, precipitation, and ground-water discharge. During late spring and early summer, the thick forest vegetation



EXPLANATION

680 —— STRUCTURE CONTOUR--Shows altitude of uppermost sand layer. Contour interval 5 feet. National Geodetic Vertical Datum of 1929

SAND LAYER OUTCROP

O SOIL BORING

Figure 7. Configuration of the uppermost sand layer in the Plot M area.

intercepts or evapotranspires sufficient water to lower the water table in the drift to below the stream-channel bottom. Occasionally, the stream flows in late fall or early winter, before the soil freezes. Streamflow has been observed during relatively warm winters with periods of soil thawing, such as occurred in 1981–82 and 1982–83.

Near Plot M, the Red Gate Woods stream is a gaining stream. The major indicator of this is the consistent presence of tritium from the ground-water flow system beneath Plot M in the flowing stream. The relatively large relief in the Plot M area enhances ground-water discharge into the stream.

In its lower reaches, the Red Gate Woods stream is a losing stream. Except during periods of high flow, water seldom flows as far as Archer Avenue. A lower gradient and a cobbled and bouldered bottom in the last 2,000 ft of the stream valley facilitate loss of water to the drift. The loss is augmented by many debris jams. A large amount of the streamflow, even during relatively low flow, is lost overbank from pools above debris jams. In addition, the pools increase the loss by increasing the hydraulic gradient through the streambed. Water that is lost overbank is absorbed into the thick forest litter and soil.

Ground Water

Ground water in the drift and dolomite forms two interconnected flow systems in the study area. The flow system in the drift is controlled principally by topography. Topographic highs are usually areas of ground-water recharge, and topographic lows are usually areas of ground-water discharge. Ground water in the drift recharges the dolomite. The flow system in the dolomite is controlled by a natural discharge area—the Des Plaines River—and a manmade discharge area—the Calumet Sag Channel. Ground water flows through the dolomite primarily from the center of the forest preserve toward the valley discharge areas.

Glacial Drift

The hydrology of the glacial drift at Plot M has been described in detail by Olimpio (1984). Olimpio noted that the primary direction of flow in the drift was vertical but that sand layers in the upper part of the drift caused some horizontal flow. A zone in the middle of the drift was described as not yielding water to piezometers. Additional data collected during this study require that Olimpio's description be refined. In the following discussion, the drift is divided into three zones (fig. 8): an upper, perched zone; a middle, variably saturated zone; and a lower, fully saturated zone.

Ground-water levels in the upper, perched zone have changed as much as 25 ft in a water year (October 1 to September 30) and 32 ft since measurements began. Nine piezometers, SB–1 through SB–8 and SB–11a, are screened in the perched zone. Water levels in piezometer SB–6 fluctuate the most, about 20 to 25 ft in a year (fig. 9). Water levels in piezometer SB–5, which is topographically the lowest and near a discharge area, fluctuate the least—about 5 to 10 ft in a year. Ground-water levels are sometimes below the screened depth in piezometers

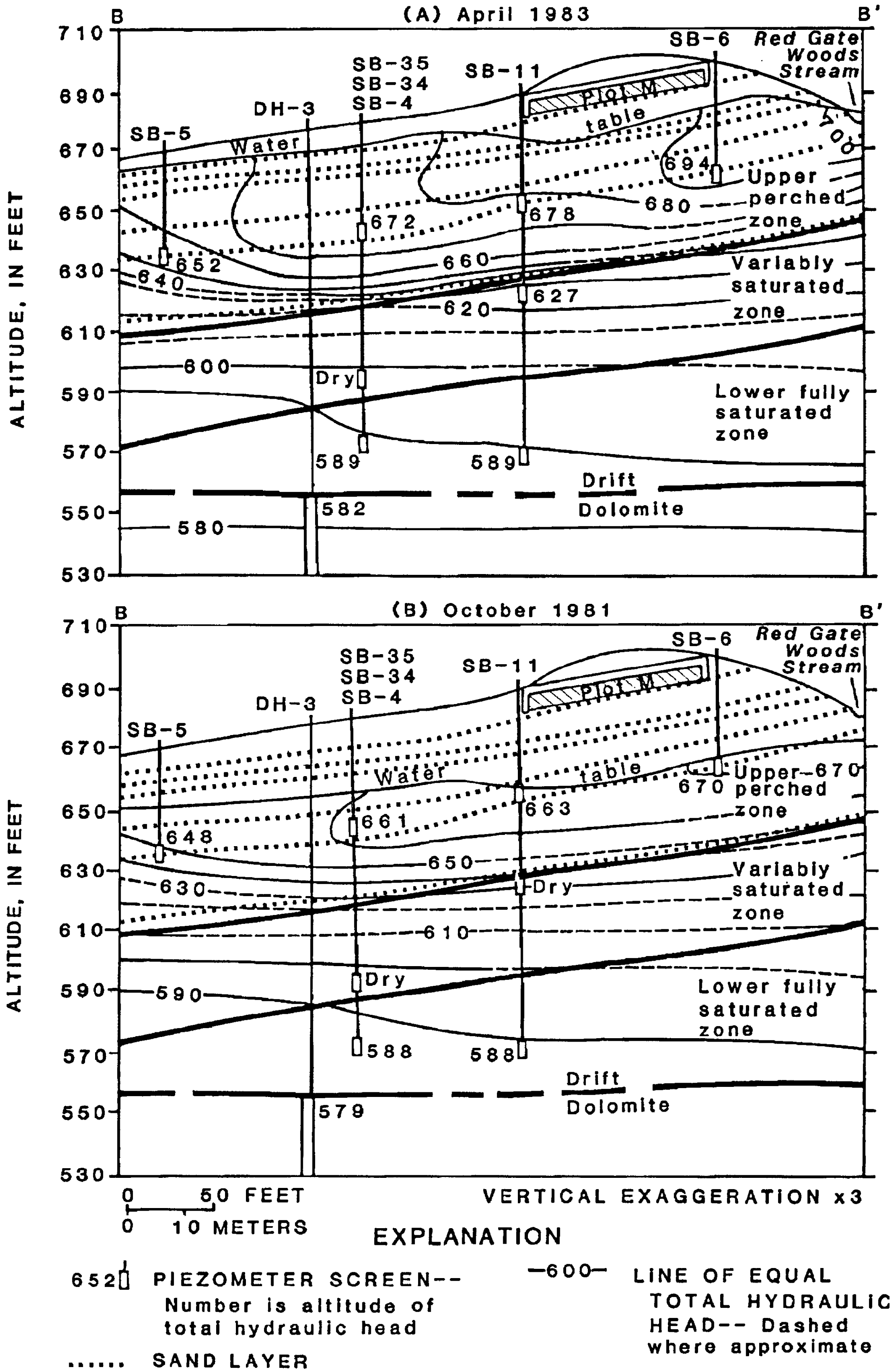


Figure 8. Vertical distribution of total hydraulic head in (A) April 1983 and (B) October 1981. (See fig. 2 for trace of section.)

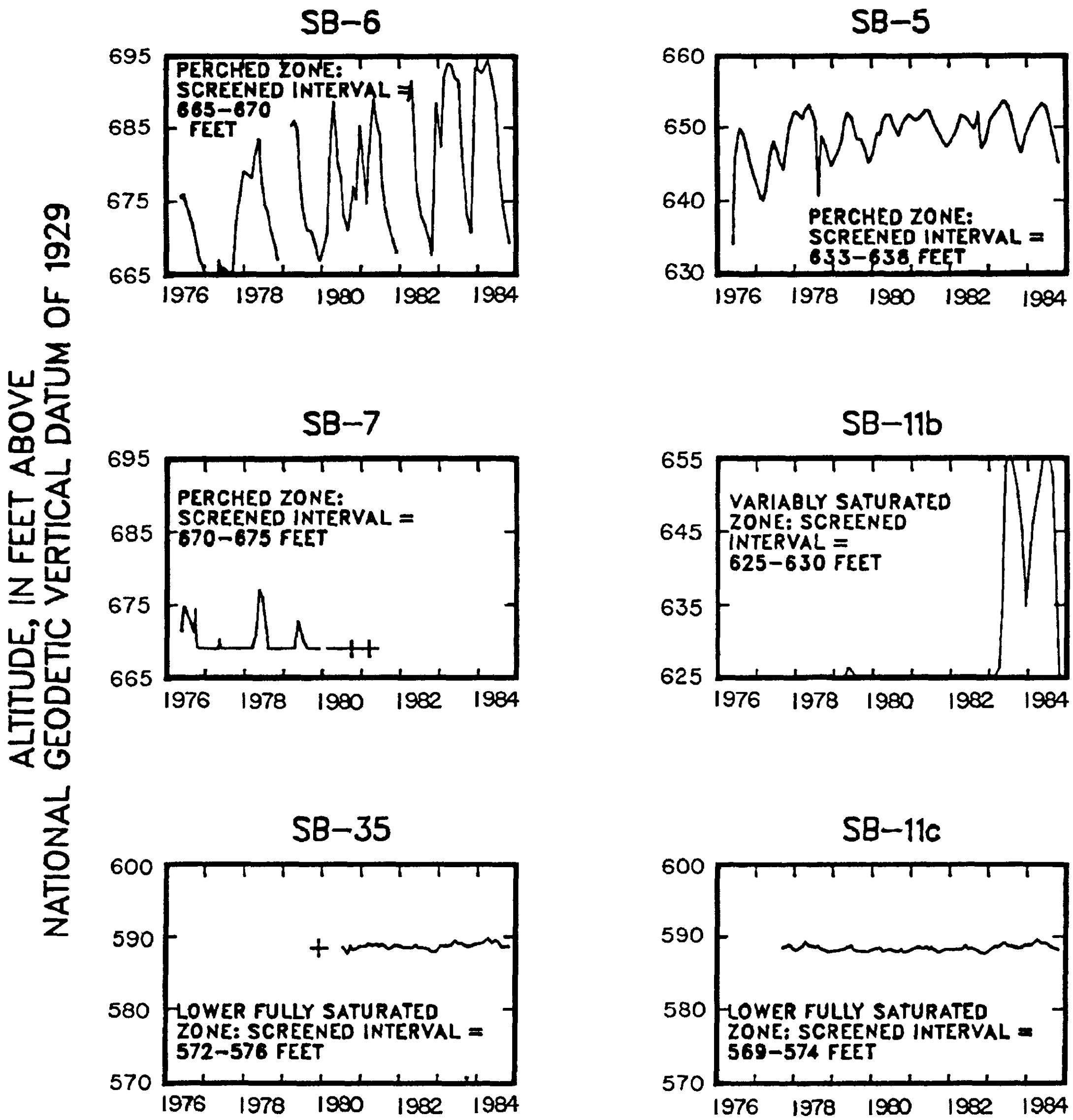


Figure 9. Water levels in piezometers SB-6, SB-5, SB-7, SB-11b, SB-35, and SB-11c, 1976-84.

SB-7 and SB-8. In the perched zone, only piezometers SB-11a and SB-4 have water levels that remain above the bottom of the screen.

Fluctuating water levels in the perched zone are caused by seasonal changes in the amount of recharge to the drift. The highest water levels are in April; these follow 2 to 3 months (mo) of heavy precipitation and snowmelt, before evapotranspiration begins to be significant. The lowest water levels are usually in the fall, before the first killing frost. The relatively large changes in water level occur because of a thick capillary fringe. The fringe is saturated but is under tension, and an increase in pressure head, resulting from a small increase in moisture content, can convert the capillary fringe to water-table conditions. This can result in a rapid and large increase in water level (O'Brien, 1982; Gillham, 1984). The exceptionally large fluctuations in piezometer SB-6 may be exaggerated by runoff from the concrete cap, which slopes slightly toward the east.

The perched zone is characterized by nearly horizontal ground-water flow in sand layers. Because the hydraulic conductivity of sand layers is greater than that of the surrounding clayey silt, flow lines refract when they cross from clayey silt to sand (fig. 10). Thus, although the hydraulic gradient has a strong vertical component, the sand layers result in ground-water flow having a strong horizontal component. Anisotropy of flow caused by alternating horizontal layers of different hydraulic conductivities results in a lower hydraulic conductivity in a direction normal to the layers and a higher hydraulic

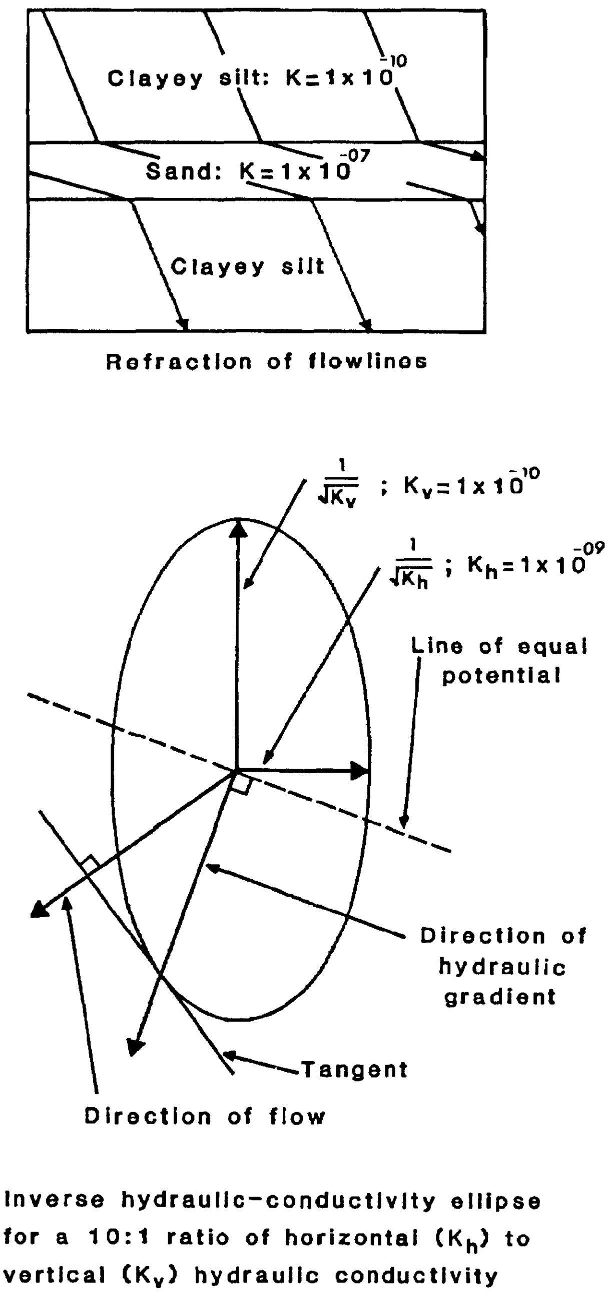


Figure 10. Flow-line refraction and inverse, hydraulic-conductivity ellipse.

conductivity in a direction parallel to the layers (Bear, 1979, p. 73).

The effect of layered heterogeneities on anisotropy of ground-water flow can be demonstrated by use of equivalent hydraulic conductivities (Todd, 1980, p. 79) and inverse hydraulic-conductivity ellipses (Freeze and Cherry, 1979, p. 178). Assuming a conservative hydraulic conductivity of 1×10^{-7} foot per second (ft/s) for silty sand and using a reported hydraulic conductivity value of 1×10^{-10} ft/s for the clayey till (Olimpio, 1984), equivalent hydraulic conductivities for the perched zone can be calculated using the following equations and assumptions (fig. 10):

$$Keq_h=\frac{\Sigma\, Kb}{\Sigma\, b}=\frac{(K_{sand}\, b_{sand})+(K_{till}\, b_{till})}{b_{sand}+b_{till}}$$

and

$$Keq_v=\frac{\Sigma\, b}{\Sigma \frac{b}{K}}=\frac{b_{sand}+b_{till}}{\frac{b_{sand}}{K_{sand}}+\frac{b_{till}}{K_{till}}}$$

where Keq_h is horizontal equivalent hydraulic conductivity, K is hydraulic conductivity, b is thickness, and Keq_v is vertical equivalent hydraulic conductivity. For the sand, b is assumed to equal 0.1 ft, and for the clayey till, to equal 10 ft. Thus,

$$Keq_h=\frac{(1\times10^{-7})(0.1)+(1\times10^{-10})(10)}{0.1+10}=1\times10^{-9} \text{ ft/s}$$

and

$$Keq_v=\frac{0.1+10}{\frac{0.1}{1\times10^{-7}}+\frac{10}{1\times10^{-10}}}=1\times10^{-10} \text{ ft/s}$$

Thus, the ratio of horizontal to vertical equivalent hydraulic conductivities is 10:1. This ratio can be used to construct an inverse hydraulic-conductivity ellipse which shows that the principal direction of flow is not necessarily the same as the direction of the hydraulic gradient. Figure 10 shows an ellipse constructed using the calculated equivalent hydraulic conductivities and an equipotential line inclined similarly to those in the perched zone. The ellipse clearly shows that for a 10:1 ratio of hydraulic conductivities and a gradient with a small horizontal component, the primary direction of ground-water flow is subhorizontal.

Ground-water-level contours for the perched zone (fig. 11) indicate that the concrete cap over Plot M reduces recharge to the perched zone beneath the cap. An increase in the spacing of equipotential lines beneath the cap indicates less recharge to the perched zone beneath and just downgradient from the cap than to the surrounding drift. Figure 11 also shows that ground water flows toward the Red Gate Woods stream and northward along the stream valley.

Between the perched zone and a lower fully saturated zone is a variably saturated zone about 35 ft thick (fig. 8). Thirteen piezometers are screened within this variably saturated zone. Water is occasionally detected in three of these piezometers, SB–11b, SB–27b, and

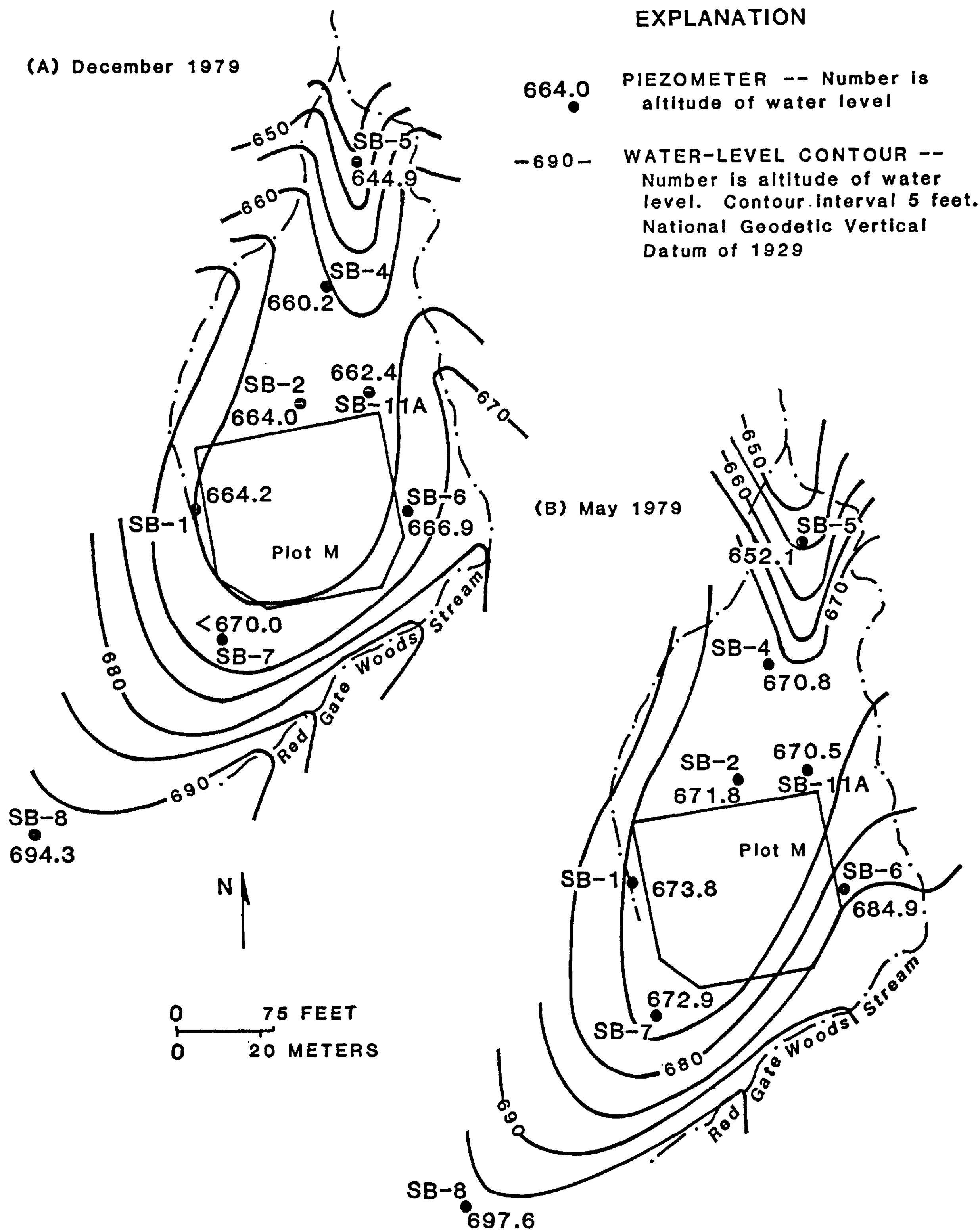


Figure 11. Water levels in piezometers screened in the perched zone at Plot M in (A) December 1979 and (B) May 1979.

SB–28b. The remaining 10 piezometers have been dry since installation.

In order for the variably saturated zone to be present, this zone must have a hydraulic conductivity significantly higher than that of the lower part of the perched zone. This would enable the variably saturated zone to drain more quickly than the material just above it and thus, at times, to be partially saturated. Such a phenomenon has been described in more detail by Foster and others (1984) for the Sheffield waste-disposal site in northwestern Illinois.

Hydraulic-conductivity measurements indicated that the hydraulic conductivity of the variably saturated zone is similar to that of the lower part of the perched zone. Values for hydraulic conductivity of the perched zone ranged from 1×10^{-8} to 1×10^{-10} ft/s, and for the variably saturated zone, from 1×10^{-9} to 1×10^{-10} ft/s (Olimpio, 1984). It is suggested here that this apparent similarity is misleading and is a function of the methods of measurement. Hydraulic conductivities for the perched zone were measured by field bailer tests and by laboratory permeameter and pressure-pulse decay tests on cores, whereas hydraulic conductivities of the variably saturated zone were measured using only the laboratory tests on cores. Core samples may not provide representative hydraulic-conductivity measurements because of the sample size, the method of collection, and the method of laboratory analysis. Core samples, because of their small size, are less likely to incorporate heterogeneities, such as thin sand layers or fractures. In fact, cores with sand layers and fractures, collected by the split-spoon method (used at Plot M), are usually not suitable for laboratory measurement of hydraulic conductivity. In addition, the split-spoon coring method compacts the sample. Laboratory measurements of hydraulic conductivity of the core samples may be several orders of magnitude less than field measurements in piezometers (Herzog and Morse, 1984).

Ground-water levels in the lower, fully saturated zone fluctuate over a relatively small range. A seasonal trend is not apparent from the 1- to 2-ft water-level changes that occur in the piezometers screened in this zone (fig. 9). The hydraulic gradient indicates that flow is downward toward the dolomite (fig. 8). However, the layer of sand and gravel just above the dolomite probably refracts flow, resulting in a horizontal component of flow.

Relatively few data are available for describing ground-water flow in the glacial drift north of Plot M. Flow directions, as inferred from topographic contours (fig. 2), are toward the Red Gate Woods stream valley and generally northward in the stream valley. The area where the Red Gate Woods stream loses water is probably an area of seasonal recharge to the drift (fig. 2, downstream from the 650-ft topographic contour).

Table 2. Pumping and tritium-concentration data from packer tests in wells 5167 and DH-4

[ft, feet; gal/min, gallons per minute; min, minutes; nCi/L, nanocuries per liter]

Altitude of: Upper packer (ft)	Lower packer (ft)	Pumping rate (gal/min)	Time of pumping (min)	Tritium concentration (nCi/L)
		Well 5167		
567	556	30	30	8.3
558	547	30	30	8.9
547	536	30	30	6.4
536	525	27	30	6.2
525	514	27	30	1.9
		Well DH-4		
567	556	26	12	0.22
556	545	30	30	.27
545	534	27	30	1.12
534	523	produced no water		--
523	512	10	30	<.2
512	501	produced no water		--
501	490	produced no water		--
490	479	produced no water		--

Dolomite

The dolomite has a primary porosity related to rock-matrix granularity and microscopic joints and a secondary porosity related to joints and cavities created and enlarged by solution. The rock-matrix porosity is relatively insignificant in terms of ground-water flow except as a storage reservoir. Most of the ground-water flow occurs in the enlarged joints, especially the horizontal joints. Studies of the Silurian dolomite in Door County, Wis. (Sherrill, 1978), and near Niagara Falls, N.Y. (Johnson, 1962), also have shown that horizontal joints are the major conduits for ground-water flow.

The weathered zone at the top of the dolomite is a pathway for ground-water flow. At wells DH–6 through DH–9, this zone was not cased or screened. Consequently, weathered dolomite and glacial material partially caved and bridged these holes (table 1). Because of these bridges, no quantitative information is available to describe the hydraulic characteristics of this zone. However, attempts to develop these wells indicated that the weathered contact zone has a large hydraulic conductivity.

The permeability of the rock matrix is relatively low. In 1980, 11-ft intervals were packed off and pumped in wells DH–4 and 5167 to sample for tritium. Intervals in DH–4 that did not yield any water or did so for only a few minutes are indicative of the low matrix permeability (table 2). None of these low-yield intervals coincided with horizontal joints detectable on geophysical logs.

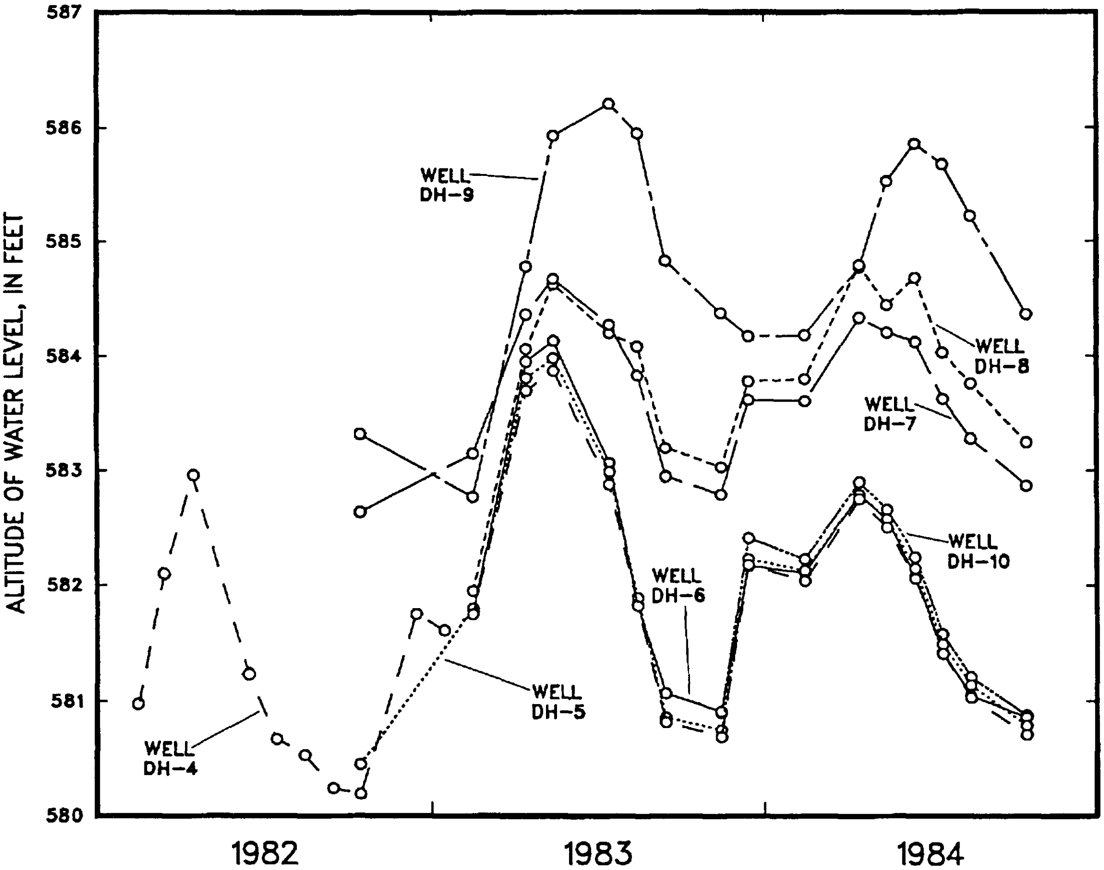


Figure 12. Water levels in wells DH–4 through DH–10, 1982–84.

Subregional horizontal joints in bedrock highs are hydraulically connected to the drift, as inferred from two observations: (1) these joints are physically connected to the drift along the edges of bedrock highs, and (2) ground-water levels in these joints are distinctly higher than those in regional joints. Wells DH–7 and DH–8 are open to only a subregional joint, and the water levels in these wells are about 2 ft higher than the water levels in wells open to regional joints (fig. 12). Also, water levels in wells open to subregional joints fluctuate less than those in wells open to regional joints. Higher water levels and muted fluctuations are attributable to the subregional joints' hydraulic connection to the glacial drift.

Horizontal joints below an altitiude of 570 ft above sea level form a regional ground-water flow system throughout the forest preserve. Although water-level data are a composite from more than one joint in most test wells, they indicate that the gradient between regional joints is small and slightly downward. Well DH–4 is open to all six of the major joints, and ground-water levels in DH–4 are 0.1 to 0.2 ft lower than those in DH–10, which is open to only the upper two major joints. The horizontal gradient within each joint cannot be calculated from composite data, but in the Red Gate Woods area, it is estimated to be about 1 ft per 1,600 ft. This estimate is based on composite water-level information from wells DH–1 through DH–4 and 5167.

The uppermost regional joints are highly conductive. During drilling of new test wells in 1985, drilling fluid was lost in the highest joint (altitude of about 565 ft) at a rate of approximately 30 gallons per minute (gal/min) (Allen Shapiro, U.S. Geological Survey, personal commun., 1985). While drilling with air through the horizontal joint at an altitude of 550 ft, air and water were observed escaping from a finished well more than 500 ft away.

Dissection of the regional flow system by the canals results in relatively short ground-water flow paths in the dolomite. The general flow system in the forest preserve is depicted in figure 13. The water-level map is not a true potentiometric map, because the water levels are a composite of the several potentiometric surfaces associated with different joints. Most flow paths from the center of the upland area to discharge areas are less than 1.5 miles (mi). Short flow paths and highly conductive regional joints result in a seasonal dilution of solutes. This dilution is depicted in figure 14, which shows that specific conductance in well 5167 is inversely related to

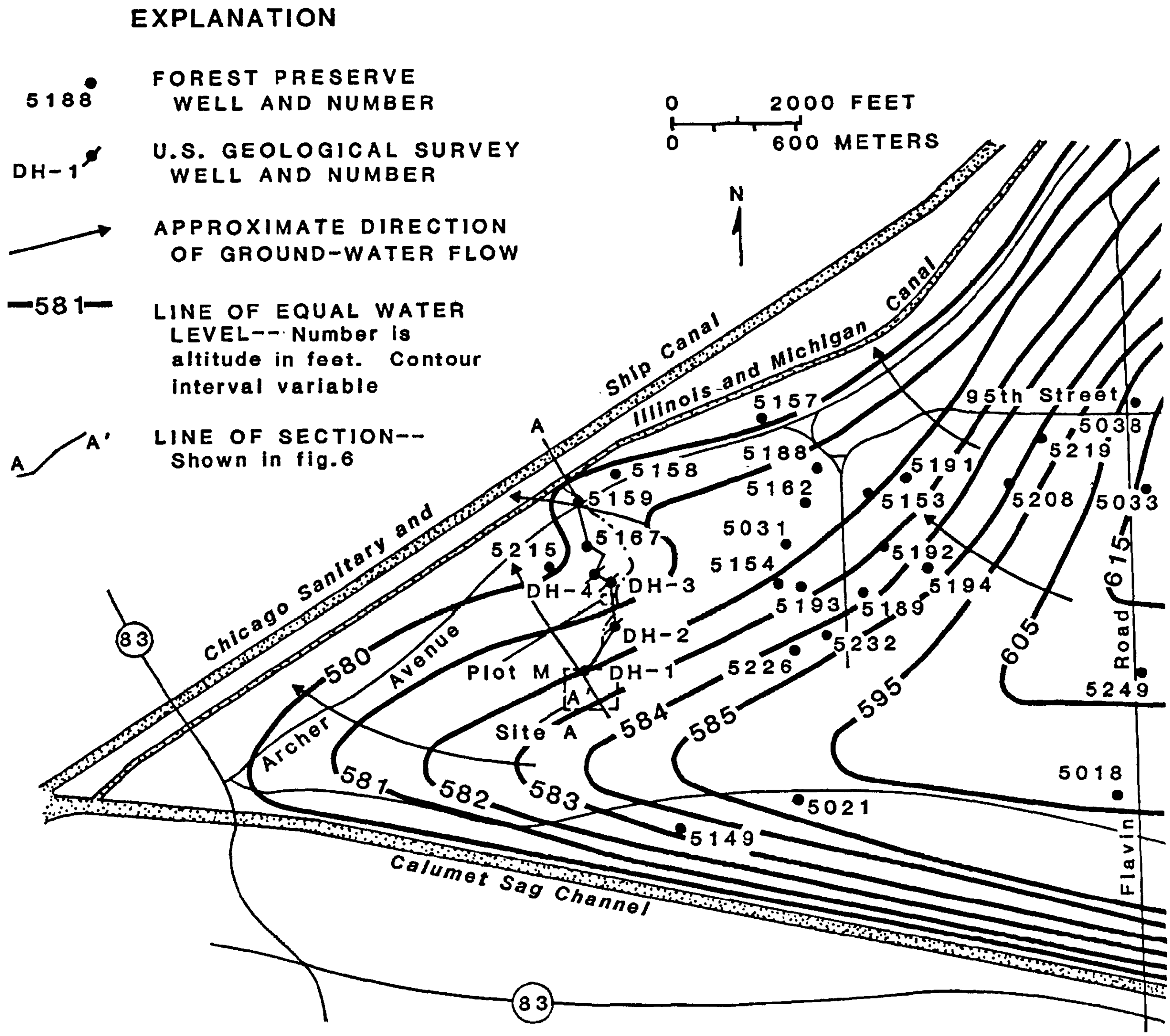


Figure 13. Water levels and approximate flow directions in the dolomite at Palos Forest Preserve in November 1983.

water levels in well DH–3. (Water levels could be measured in well 5167 only two times per year, but more samples were available from well 5167 for measurements of specific conductance.)

Vertical joints inferred from lineament mapping result in areal anisotropic transmissivity. Although the location and effect on flow of vertical joints in the study area are not known, it can be demonstrated that vertical joint sets do affect flow at nearby ANL (2 mi west of the study area). Aquifer-test data from a ground-water study at ANL (Knowles and others, 1963) can be interpreted using Papadopulos' (1965) solution for anisotropic transmissivity. If transmissivities calculated from the original test data are plotted in the unit-vector directions of the observation wells, then a transmissivity ellipse can be drawn through the data (fig. 15). At ANL, the solution for the transmissivity tensor yielded values of 0.11 and 0.067 foot squared per second (ft^2/s) along the principal directions of transmissivity. This results in an anisotropy of about 2 to 1. The orientation of the principal direction of transmissivity (the ξ axis) approximately bisects the angle made by the vertical joint sets in the area. The results from ANL suggest that, if vertical joint sets affect ground-water flow in the Red Gate Woods area, the resulting transmissivity tensor would be anisotropic, with the principal direction of transmissivity oriented along a north-south axis.

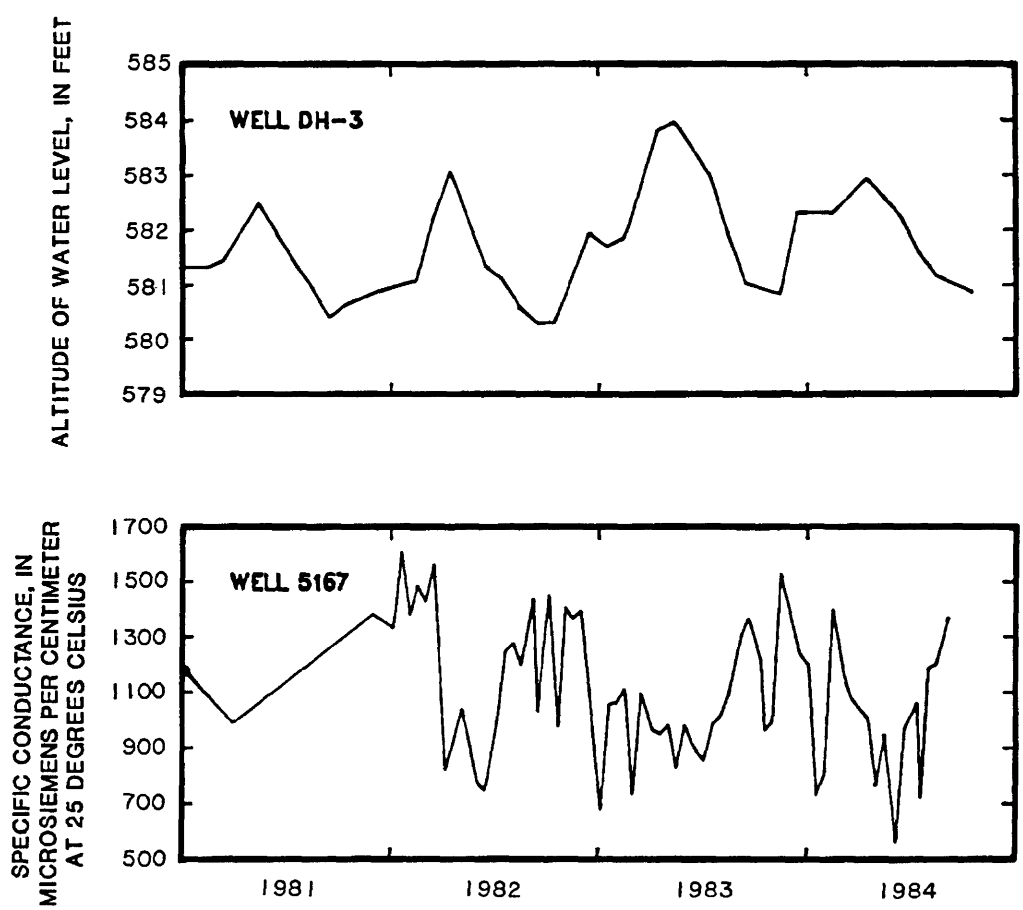


Figure 14. Relation of specific conductance in ground water sampled from well 5167 to altitude of water levels in well DH-3, 1981–84.

TRITIUM MIGRATION

Surface Water

Tritiated ground water has discharged from the glacial drift near Plot M into the Red Gate Woods stream since at least 1954 (Golchert and Sedlet, 1978). In 1976, ANL personnel began routine sampling of the stream at 13 locations, 9 of which are in the vicinity of Plot M (fig. 16). The same general trend of tritium concentration along the stream profile is apparent each year. Upstream from Plot M, concentrations of tritium in the stream are usually at background level (0.2 nCi/L). Concentrations increase as the stream flows adjacent to Plot M and then decrease downstream as a result of dilution. Concentrations above background level have been measured in samples downstream as far as the Illinois and Michigan Canal. The highest concentrations are in water from a small seep (location 6, fig. 16) in an abandoned meander. Concentrations measured at a sampling location in a given year may range over two orders of magnitude. No regular pattern of increase or decrease in tritium concentration over time is evident during the period 1976 through 1983 (fig. 16). However, concentrations during this period are about an order of magnitude less than those in 1954 (Golchert and Sedlet, 1978). Surface-water samples were not collected between 1954 and 1976.

In February 1983, ANL personnel collected samples at two locations between stations 2 and 3. Concentrations were 31.6 and 425 nCi/L (fig. 16). These data suggest that discharge of tritiated ground water into the stream occurs at small, localized areas, possibly where the stream bottom intercepts sand lenses in the drift.

Ground Water

Glacial Drift

Information on tritium in the glacial drift comes from two sources—water from piezometers and moisture in cores. Piezometers were sampled using a bailer. Core moisture was extracted using an oven and a cold trap. The tritium concentration in piezometer water is not necessarily similar to the tritium concentration in

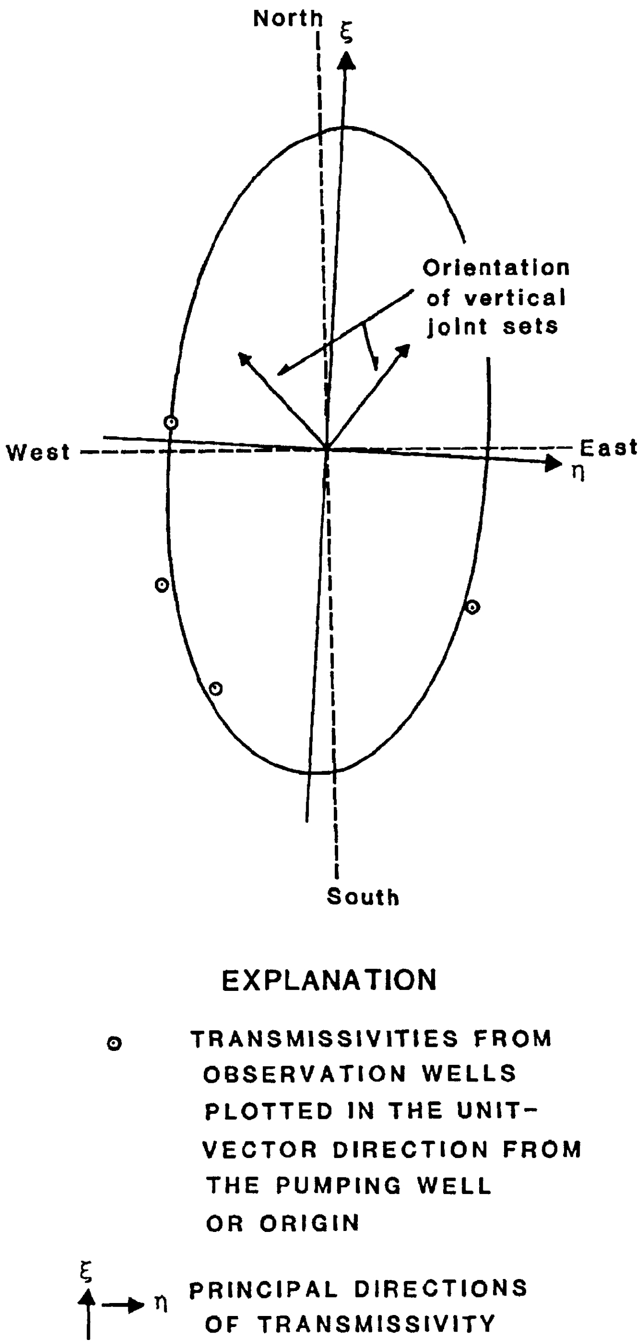


Figure 15. Transmissivity ellipse for the dolomite at Argonne National Laboratory.

moisture from a core retrieved from the same depth as the piezometer screen. The main reason for this is that samples from a piezometer come from the most permeable material with which the screen is in contact, whereas all of the pores are sampled when moisture is extracted from cores by drying. Thus, those pores through which little ground water flows and where tritium is not seasonally diluted by recharge (stagnant pores) contribute as much or more water to a core sample as do the well-connected pores. This introduces a sampling bias where the moisture extracted from an entire core is not representative of the ground water that actually flowed through the core. In the following discussion of the distribution of tritium in the glacial drift, core-moisture and piezometer-water data are considered separately.

Figure 17 shows a cross section of the tritium plume beneath Plot M made from core-moisture data. The highest concentrations, greater than 100,000 nCi/L, are in the center of the plume, about 30 to 70 ft beneath the cap. The concentration from the deepest core, near bedrock, was 1,500 nCi/L. Tritium has migrated mostly northward and downward (figs. 17, 18). Two northward-extending lobes are present: One, trending northwest, is influenced by the dip of the geologic materials (compare fig. 7), and the other, trending northeast, is controlled by the direction of ground-water flow (compare fig. 11).

Core-moisture data suggest that if the part of the tritium plume directly beneath Plot M is moving downward vertically, it is doing so very slowly. Olimpio (1984) concluded that the initial downward movement of tritium occurred before the cap was constructed in 1956. This conclusion is supported by other information: (1) the cap reduces recharge to the drift (compare fig. 11), and (2) comparison of peaks in tritium concentration in two sets of adjacent cores collected from beneath the cap in 1977 and 1982 indicates that little or no downward movement of the plume occurred in the interim (fig. 19).

Tritium concentrations vary seasonally in water from the perched-zone piezometers near Plot M. The variations result from dilution following seasonal recharge (fig. 20). The flow of nontritiated ground water upgradient from Plot M through the drift beneath Plot M dilutes the concentration of tritium in the sand layers. Tritium concentrations in many of these piezometers are lower than concentrations from cores, because the tritium concentration in stagnant pores is not readily diluted by the seasonal flux through connected pore spaces. Tritium concentrations increase when the flux of tritiated water becomes greater than that of nontritiated water.

Tritium concentrations in water from piezometers in the variably saturated zone (SB–11b and SB–28b) and the lower, fully saturated zone are similar to those in cores from the same depth. This indicates that minimal dilution of tritium occurs from seasonal recharge through these zones. Water moving nearly vertically through these zones probably is tritiated water rather than nontritiated water that might move horizontally through the plume from outside the Plot M area.

Figure 21 shows lines of equal tritium concentration in piezometer water. The two sampling dates correspond to low and high water levels measured in the shallow piezometers. Note that they show the same general pattern as figure 17, which was constructed from

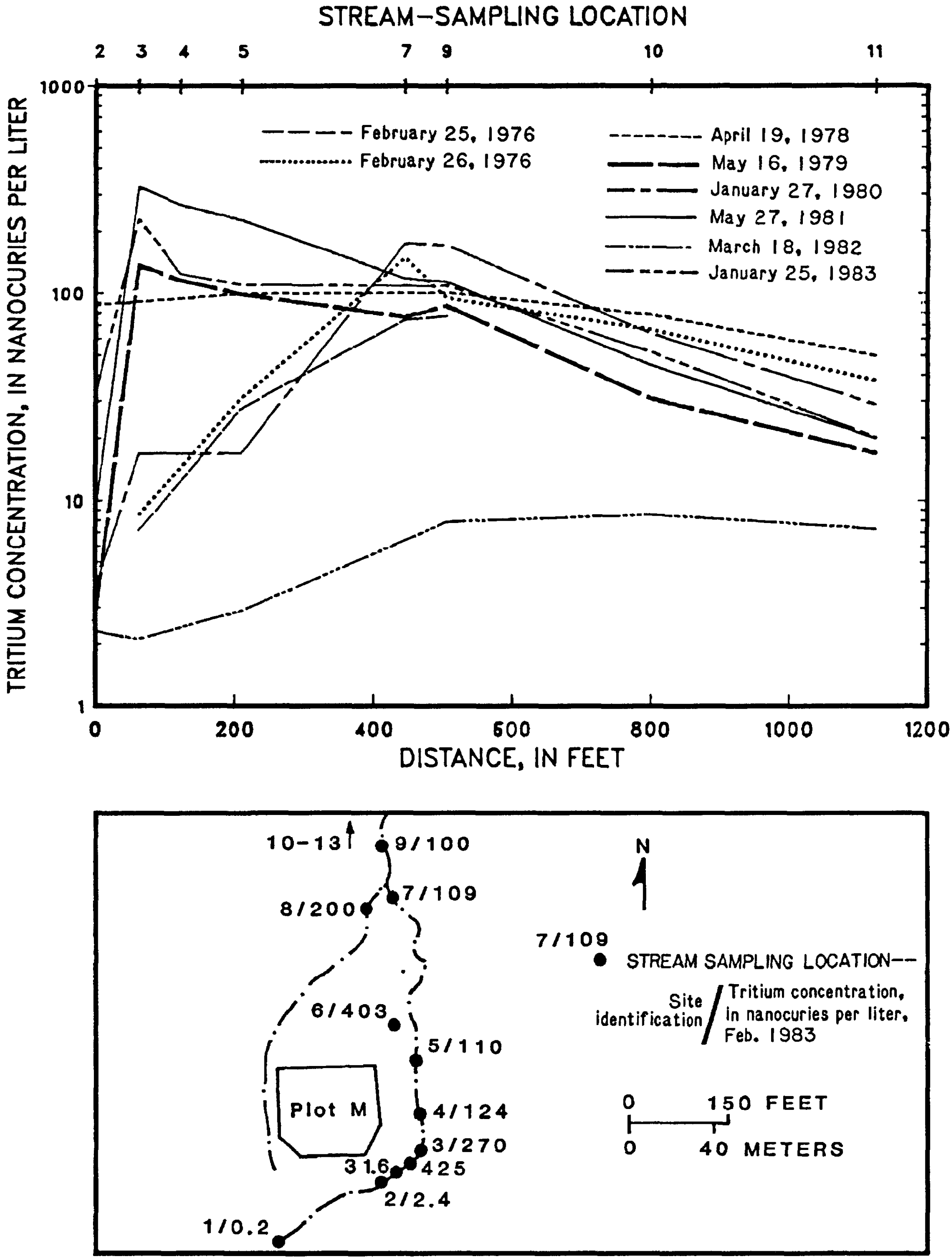


Figure 16. Tritium concentrations in the Red Gate Woods stream at various times during 1976 through 1983.

core-moisture data. However, dilution from ground water flowing horizontally through the plume is apparent in the perched zone.

Diffusion may be an important transport mechanism in the glacial drift in the Plot M area. Grisak and others (1980) demonstrate that diffusion into the clayey matrix in glacial till attenuates the concentration of conservative solutes. Diffusion into poorly connected pores may provide an additional explanation for the discrepancies between tritium concentrations in cores and tritium concentrations in piezometer water. Low hydraulic conductivities and ground-water velocities in much of the drift and sharp concentration gradients enhance the potential for diffusion, which may be more

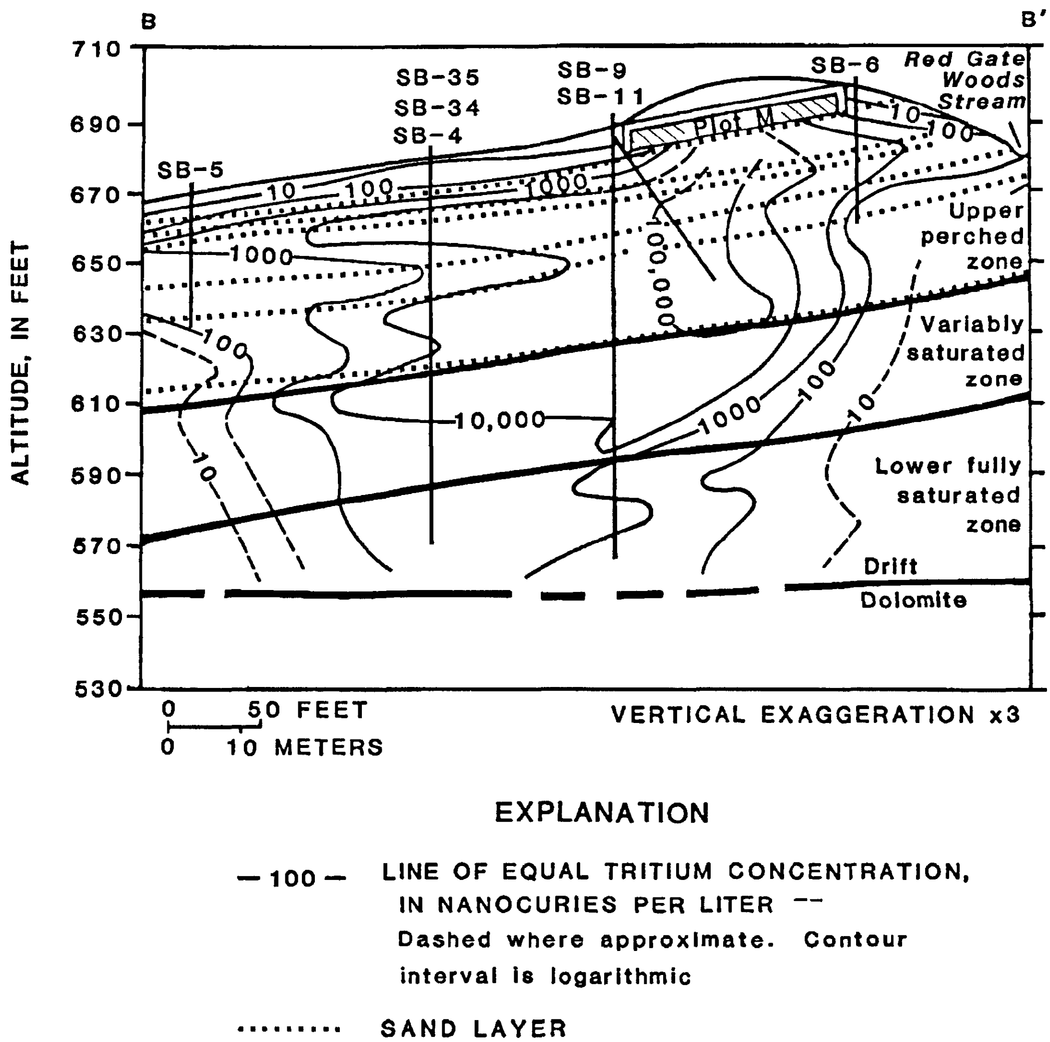


Figure 17. Vertical distribution of tritium concentrations in moisture from cores of the drift near Plot M. (See fig. 2 for trace of section.)

significant than advective-dispersive mechanisms in parts of the drift. Gillham and Cherry (1982) propose that, while solutes are transported by advection in more permeable heterogeneities, migration by diffusion occurs into adjacent heterogeneities of lower permeability. The result is a smoothing of concentration patterns. The pattern of tritium beneath Plot M may reflect such a conceptualization.

To determine the northward extent of tritium migration in the drift beneath the stream valley, tritium concentrations were measured in water extracted from leaves cut from 12 trees (fig. 22, table 3). Data from the leaf sampling indicated that tritium was present in the drift beneath the stream valley, but not alongside the pirating reach of the stream or north of tree I. Subsequent coring substantiated this finding. Cores of the drift were collected with a portable auger rig at five locations (C–1 through C–5, fig. 22). Tritium concentrations in moisture extracted from cores at these locations ranged from 0.5 to 91.5 nCi/L (table 4).

The results from the shallow coring suggest that tritium migrates nearly horizontally in the glacial drift beneath the stream valley from Plot M to at least C–5. Maximum tritium concentrations at C–1, C–2, and C–3 were about an order of magnitude higher than concentrations in the stream at those locations. At all coring locations, thin sand or sand and gravel layers were present and lithology correlated well between borings.

The tritium at C–1 and C–2 could be attributed to loss of tritiated water from streamflow in the 1950's, when concentrations in the stream were higher. However, two observations contradict this supposition: (1) stream loss has been observed downstream from C-1, especially downstream from C–5, yet tritium concentrations in C–5 are relatively low and no tritium was present in tree leaves north of tree I, and (2) tritium is present at

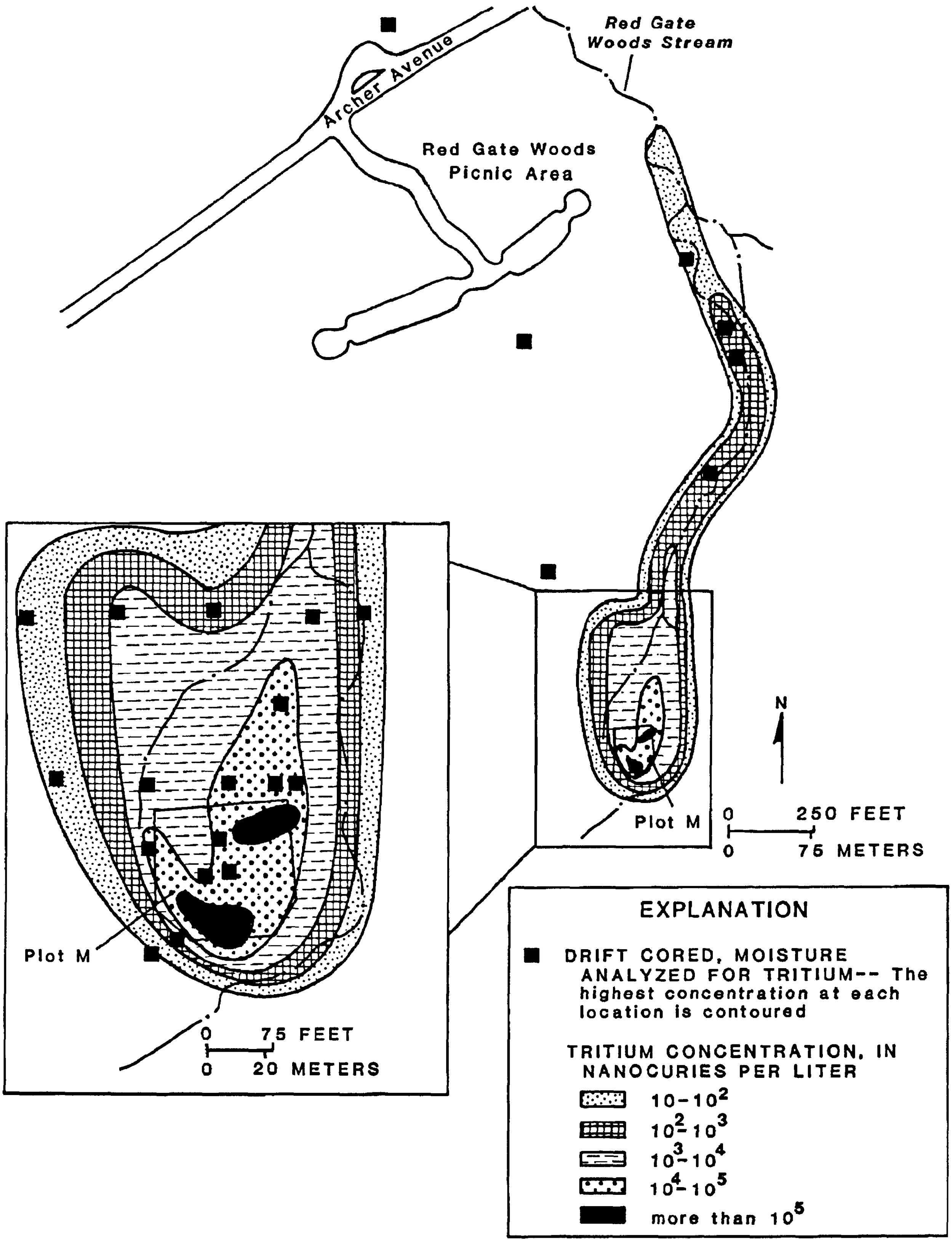


Figure 18. Areal distribution of tritium concentrations in moisture from cores of the drift in the study area.

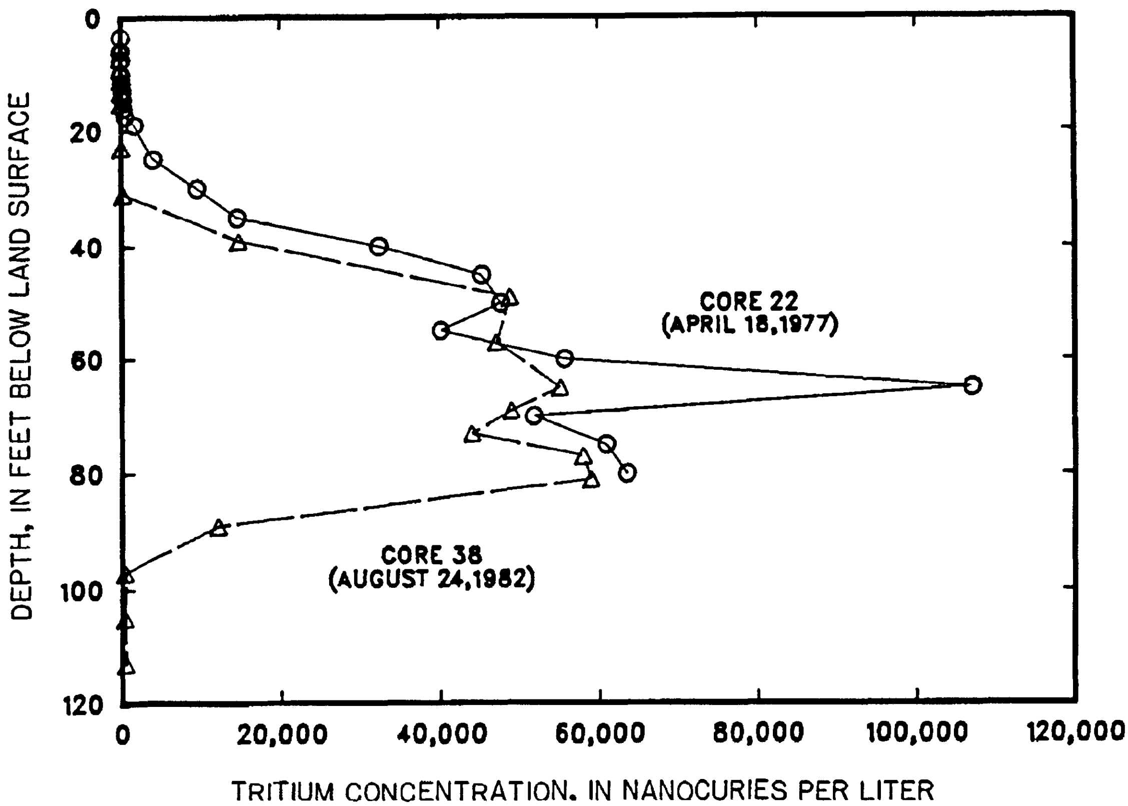


Figure 19. Tritium concentrations in moisture from two sets of cores beneath Plot M.

Table 3. Concentration of tritium in leaves collected from 12 trees on May 20, 1983
[nCi/L, nanocuries per liter]

Tree	Tree description[1]	Tritium concentration in leaves (nCi/L)
A	4-inch Red Oak	<0.2
B	3-inch Red Oak	<.2
C	4-inch Black Walnut	2.0
D	2-inch Red Oak	7.8
E	4-inch Red Oak	7.4
F	3-inch White Oak	<.2
G	2-inch Red Oak	<.2
H	2-inch Red Oak	<.2
I	10-inch Shagbark Hickory	1.0
J	6-inch Basswood	<.2
K	5-inch Black Cherry	<.2
L	3-inch Elm	<.2

[1] Figures are trunk diameter at a height of about 4 feet above ground.

C–3, yet no stream loss has been observed upstream from C–1.

Dolomite

Tritium enters the dolomite at two different areas, forming two distinct plumes (fig. 23). The first—the Plot M plume—contains relatively low concentrations of tritium. The source of tritium for this plume is in the drift beneath Plot M. The second—the Red Gate Woods plume—contains higher concentrations of tritium. The source of tritium for this plume is in the drift beneath the Red Gate Woods stream valley, east of DH–9.

Relatively low concentrations of tritium in the Plot M plume indicate that either (1) little tritium is entering the dolomite, or (2) higher concentrations of tritium are diluted shortly after entering the dolomite. The source for the Plot M plume is much larger than that for the Red Gate Woods plume, yet concentrations in the latter plume are higher. Relatively high flow rates in regional horizontal joints might dilute tritium as it enters the flow system in the dolomite. However, if dilution is reducing concentrations in the Plot M plume, it would be expected that dilution would do the same in the Red Gate Woods plume. The data do not support this. Rather, it appears

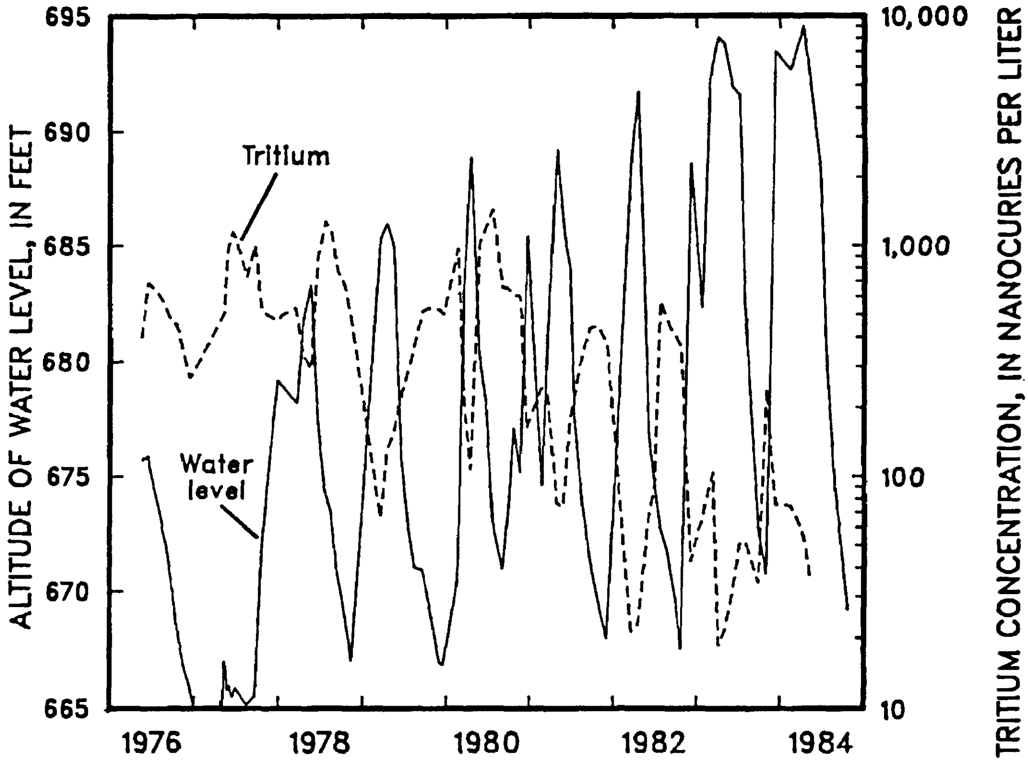


Figure 20. Relation of water level to tritium concentration in ground water sampled from piezometer SB-6, 1976–84.

Table 4. Tritium concentration of moisture extracted from cores retrieved from the Red Gate Woods stream valley

[nCi/L, nanocuries per liter]

Depth interval (feet)	Tritium concentration (nCi/L)
CORE 1	
3.0 – 4.5	16.0
4.5 – 6.0	13.0
6.0 – 7.5	11.6
9.0 – 10.5	10.5
10.5 – 12.0	20.3
12.0 – 13.5	33.5
13.5 – 15.0	60.1
15.0 – 16.5	60.2
16.5 – 19.0	91.5
CORE 2	
3.0 – 4.5	14.5
4.5 – 6.0	18.8
6.0 – 7.5	26.1
7.5 – 9.0	26.0
9.0 – 10.5	22.2
10.5 – 12.0	39.9
12.0 – 13.5	38.7
13.5 – 15.0	64.9
CORE 3	
3.0 – 4.5	23.5
4.5 – 6.0	54.5
6.0 – 7.5	75.3
7.5 – 9.0	84.7

Table 4. Tritium concentration of moisture extracted from cores retrieved from the Red Gate Woods stream valley—Continued

[nCi/L, nanocuries per liter]

Depth interval (feet)	Tritium concentration (nCi/L)
CORE 3	
9.0 – 10.5	65.8
10.5 – 12.0	73.8
12.0 – 13.5	55.0
13.5 – 15.0	66.4
15.0 – 16.5	47.8
16.5 – 18.0	50.3
CORE 4	
3.0 – 4.5	0.7
6.0 – 7.5	1.9
9.0 – 10.5	.5
12.0 – 13.5	1.7
15.0 – 16.5	7.5
18.0 – 19.5	5.5
21.0 – 22.5	6.8
24.0 – 25.5	5.7
CORE 5	
3.0 – 4.5	2.7
6.0 – 7.5	1.9
9.0 – 10.5	.8
12.0 – 13.5	.7
15.0 – 16.5	3.9

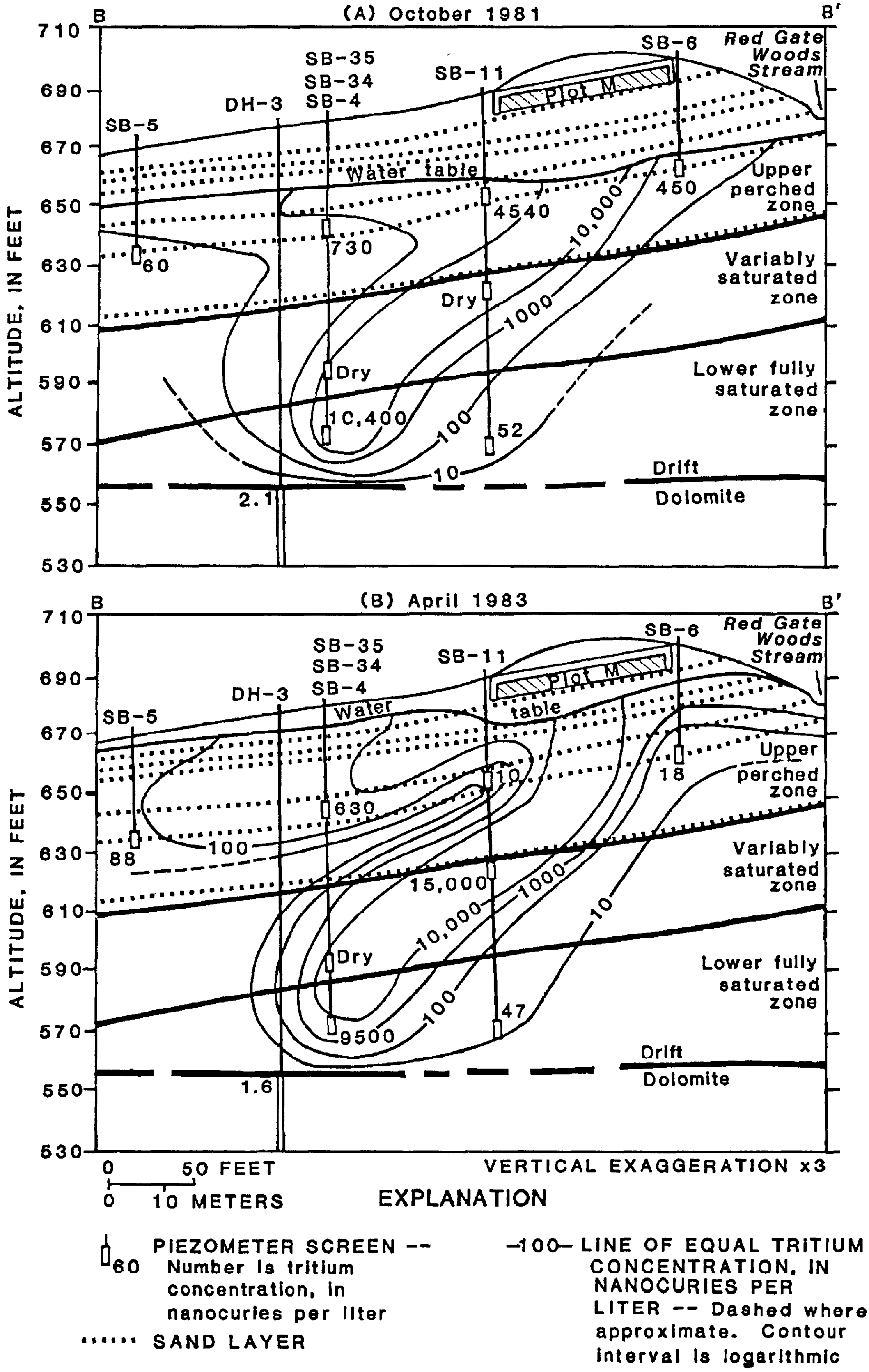


Figure 21. Vertical distribution of tritium concentrations in ground water sampled from piezometers near Plot M in (A) October 1981 and (B) April 1983. (See fig. 2 for trace of section.)

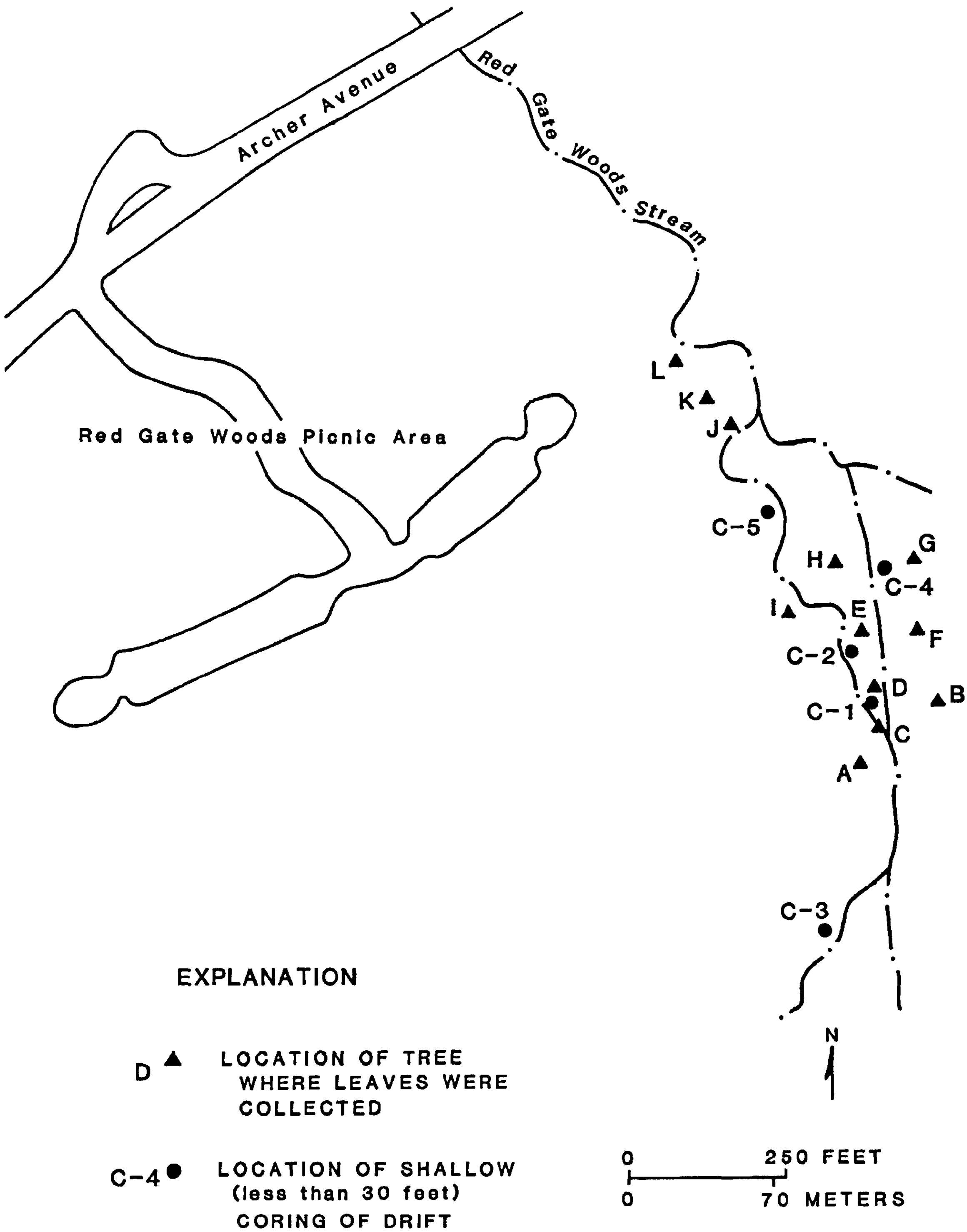


Figure 22. Locations of shallow coring in drift and trees where leaves were sampled.

that the basal layer of sand and gravel beneath Plot M refracts ground-water flow and minimizes the amount of tritium entering the dolomite there.

Measurements of tritium above background in DH–2, which is apparently upgradient from Plot M, warrant some discussion. Although concentrations in DH–2 usually are below background, concentrations as high as 0.98 nCi/L have been measured (table 5 (at end of report), Nov. 16, 1977). The following observations should be considered. First, measurement errors of ±0.1 nCi/L are associated with concentrations equal to or less than 1.0 nCi/L. Second, DH–2 is apparently upgradient from Plot M, but actual flow directions are unknown because of the lack of potentiometric data for individual horizontal joints and uncertainty as to the effect of vertical joints. Third, although 0.2 nCi/L is generally accepted as background, local background in the study area may be higher owing to emissions of tritiated vapor from CP–3 in the 1940's. Emissions from CP–3 would have caused local fallout of tritiated water (Norbert Golchert, Argonne National Laboratory, personal commun., 1985), with a resultant increase in tritiated water within the hydrologic system. Elevated concentrations of tritium in DH–2, and possibly DH–4, may be residual effects of this fallout.

The highest tritium concentrations in the Red Gate Woods plume are near the stream. Tritium from the drift beneath the stream valley apparently enters the dolomite east of DH–9, possibly because the bedrock high in the area (compare fig. 3) acts as a ground-water sink. Concentrations decrease to the west and north. No data are available for east of the stream. The fractured nature of the dolomite and the types of data available make quantitative description of tritium migration in the dolomite difficult. The effect of vertical joints on tritium migration is not considered since locations of these joints are unknown. These limitations should be considered as qualifying the following discussion.

The weathered contact zone at the bedrock surface is a conduit for tritium migration near the stream valley. Well DH–9 is open to the weathered zone and has the highest concentration of tritium in the Red Gate Woods plume. Wells DH–6, DH–7, and DH–8 are also open to the weathered zone, but water from these wells is seldom above background. The bedrock topography (fig. 3) may restrict ground-water movement toward these wells from the source area beneath the stream valley.

Elevated concentrations of tritium have not been detected in water from wells open to subregional joints (wells DH–5 through DH–8). This absence of tritium could be due to any of the following: (1) subregional joints are not zones of tritium transport, (2) wells open to subregional joints are not downgradient from the source of tritium, and (3) some of the wells are downgradient, but bridging of the wells prohibited representative sampling of water from subregional joints.

Regional horizontal joints at altitudes of 565 and 550 ft above sea level are major conduits for tritium migration in the Red Gate Woods plume. Wells DH–10 and 5167 are open to both of these joints and have the second and third highest concentrations of tritium in the plume. These joints are highly conductive, and results of sampling using packer apparatus in well 5167 show that tritium concentrations below these upper regional joints are low (table 1).

Tritium concentrations in well 5167 fluctuate seasonally (fig. 24). Fluctuations are similar to those for specific conductance (fig. 14) and potassium (Golchert and others, 1983). Comparison of precipitation records with tritium fluctuations shows there is a lag time of about 20 to 40 d between major periods of precipitation and decreases in tritium concentration in well 5167. The dilution phenomenon satisfactorily explains anomalous years in the tritium record. Figure 25 shows cumulative monthly precipitation, exclusive of the months June through September, and monthly average tritium concentrations in well 5167, for 1976 to early 1984. (Tritium concentrations are normalized for radioactive decay to January 1, 1976.) The summer months were excluded from the cumulative graph because during these months evapotranspiration is very high and recharge is near zero. In 1977, tritium concentrations did not decrease as in other years because precipitation was very low. In 1982, tritium decreased uncharacteristically in the winter following more than 12 in of rain in November and December, months of low evapotranspiration. The low peak in 1983 and continuing low concentrations in 1984 follow two unusually wet years. Tritium concentrations show little fluctuation in well DH–9. One explanation may be that because DH–9 is close to the source area (the tritium plume beneath the stream valley), there is little potential for dilution between the source and DH–9.

Normalizing tritium concentrations in well 5167 for radioactive decay (compare figs. 24 and 25) shows that seasonal normalized concentration maximums entering the well have been nearly constant from 1976 to early 1984. Variations in the concentration of tritium in well 5167 are caused by variations in recharge to the dolomite.

SUMMARY AND CONCLUSIONS

Tritium is migrating from Plot M, a low-level radioactive-waste disposal site located in the Palos Forest Preserve in southwestern Cook County, Ill. Low-level waste from operations at the world's first nuclear reactors was buried at Plot M from 1943 through mid-1949. In 1973, tritium was detected in water from well 5167, a forest-preserve well located 1,200 ft downgradient from Plot M.

Plot M is constructed in glacial drift that is 140 ft thick and overlies Silurian dolomite. Data from test drilling in the drift and dolomite, tritium analyses of samples of ground water and surface water, and water-level measurements were used to determine the geologic and hydrologic factors that control tritium migration.

Ground-water flow in the drift is anisotropic. Thin, gently sloping sand layers in a perched zone refract flow, resulting in mostly horizontal movement of water and tritium in the upper 40 ft of drift.

Tritium concentrations in moisture extracted from drift cores are not representative of the concentrations in

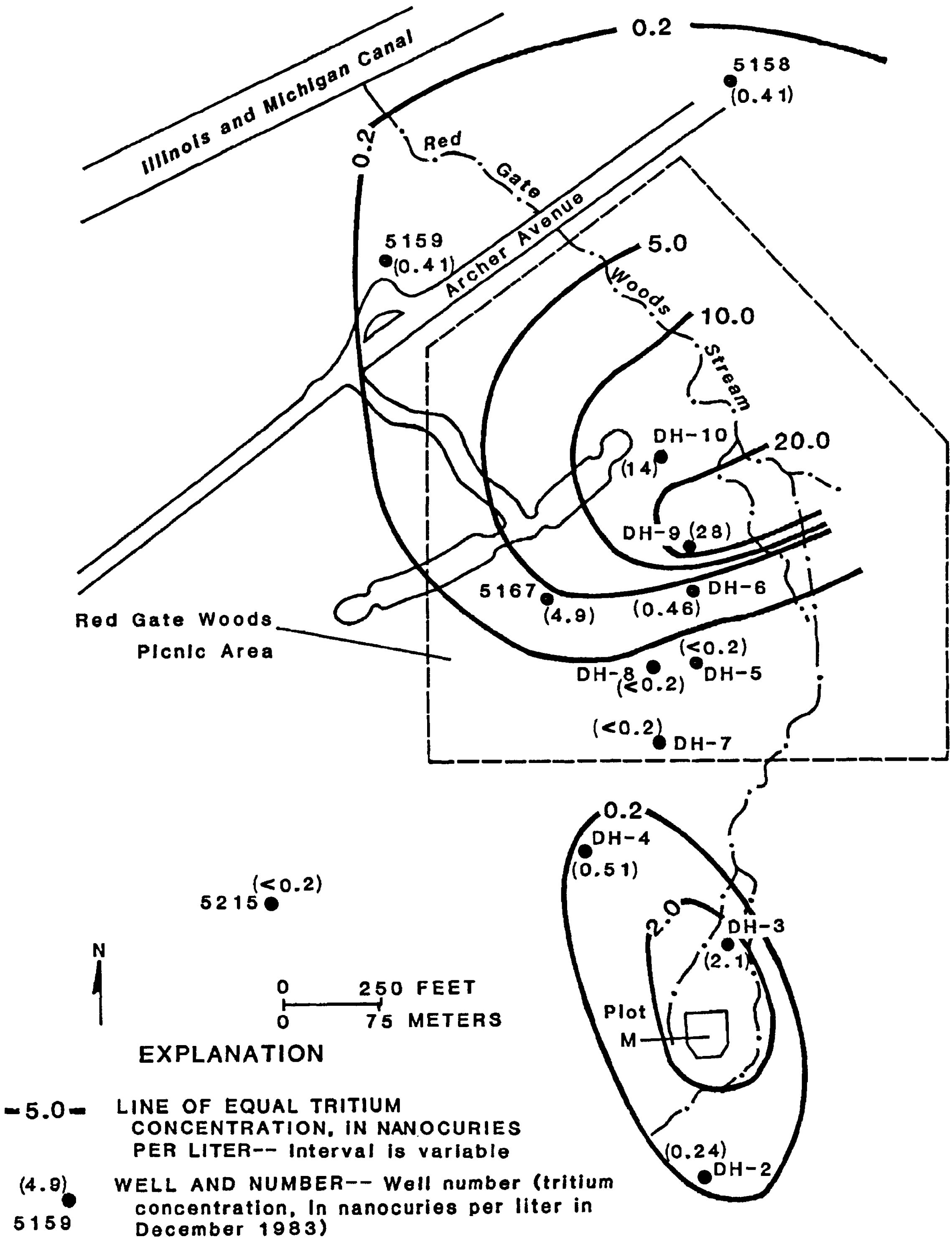


Figure 23. Areal distribution of tritium concentrations in ground water sampled in December 1983 from wells completed in dolomite.

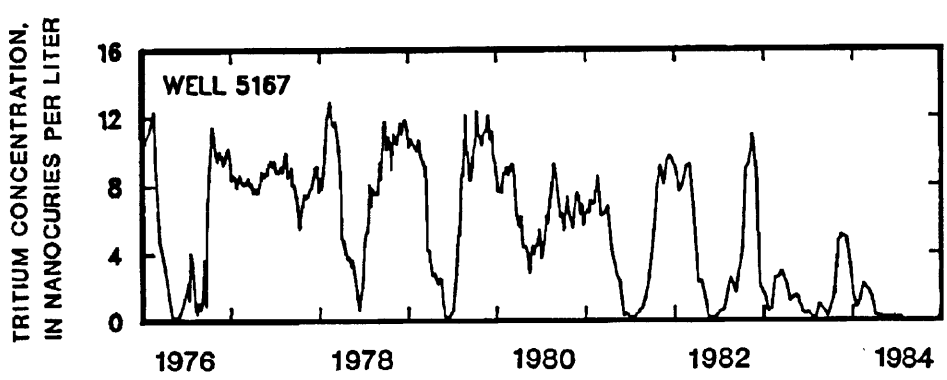


Figure 24. Tritium concentrations in ground water sampled from well 5167, 1976–84.

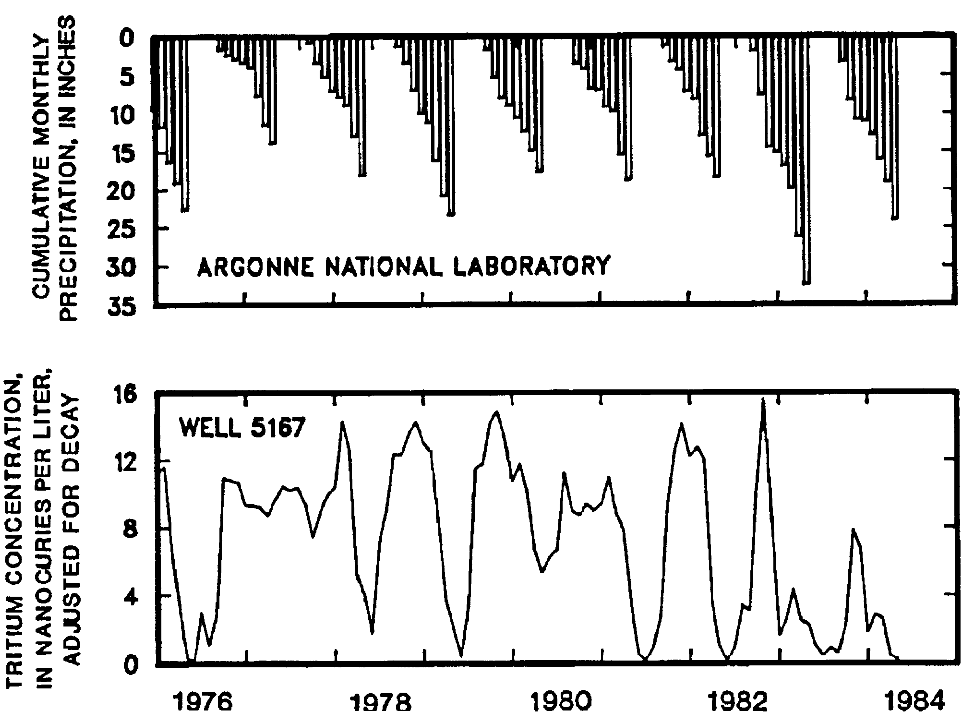


Figure 25. Relation of monthly average tritium concentration in ground water sampled from well 5167 to cumulative monthly precipitation at Argonne National Laboratory, 1976–84.

ground water that moves from Plot M in sand layers. Samples bailed from piezometers are representative of water moving through the most permeable zones in contact with the screen, whereas samples extracted from cores include water from pores that are poorly connected to the flow system.

Tritium enters the dolomite beneath Plot M and in the Red Gate Woods area beneath the stream valley. The plume beneath Plot M has tritium concentrations about an order of magnitude lower than those in the plume in the Red Gate Woods area.

Tritium migration in the dolomite is primarily through horizontal joints enlarged by solution. Interpretation of data from packer tests and borehole geophysical logs indicates that the uppermost regional joints are the major conduits for tritium migration. A weathered zone at the top of the dolomite also is believed to be a pathway for tritium migration. The effect of vertical joints on tritium migration is not well understood.

Seasonal fluctuations in tritium concentration in well 5167 are caused by variable rates of recharge to the dolomite. Recharge from snowmelt and precipitation in the spring causes a general dilution of solutes in the ground water throughout the forest preserve and of tritium in well 5167. The steady decrease in seasonal tritium concentration maximums from 1973 to early 1984 is attributed solely to radioactive decay.

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TABLES 1 AND 5

Table 1. Site and well-construction data for wells completed in dolomite

DH-1 Completed September 17, 1976

Diameter: 5 inches
Type of casing: 5-inch black steel

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		741.80
Measuring point:		743.47
Bottom of hole:	215	527
Bedrock surface:	170	572
Bottom of casing:	175	567
Bottom of well: (after bridging)	215	527

DH-2 Completed September 20, 1976

Diameter: 5 inches
Type of casing: 5-inch black steel

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		719.56
Measuring point:		721.21
Bottom of hole:	201	519
Bedrock surface:	152	568
Bottom of casing:	160	560
Bottom of well: (after bridging)	201	519

DH-3 Completed September 23, 1976

Diameter: 5 inches
Type of casing: 5-inch black steel

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		678.07
Measuring point:		679.52
Bottom of hole:	173	505
Bedrock surface:	122	556
Bottom of casing:	128	550
Bottom of well: (after bridging)	173	505

DH-4 Completed September 28, 1976

Diameter: 5 inches
Type of casing: 5-inch black steel

	Depth below land surface datum (feet)	Altitude[1] (feet)
Land surface datum:		673.76
Measuring point:		674.57
Bottom of hole:	280	394
Bedrock surface:	109	565
Bottom of casing:	116	558
Bottom of well: (after bridging)	280	394

DH-5 Completed August 6, 1982

Diameter: 6 inches
Type of casing: 6-inch PVC

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		659.46
Measuring point:		659.64
Bottom of hole:	102	557
Bedrock surface:	74	585
Bottom of casing:	84	575
Bottom of well: (after bridging)	101	558

DH-6 Completed August 2, 1982

Diameter: 6 inches
Type of casing: 6-inch PVC

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		654.72
Measuring point:		656.50
Bottom of hole:	97	558
Bedrock surface:	72	583
Bottom of casing:	72	583
Bottom of well: (after bridging)	83	572

DH-7 Completed August 12, 1982

Diameter: 6 inches
Type of casing: 6-inch PVC

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		665.38
Measuring point:		665.62
Bottom of hole:	98	567
Bedrock surface:	78	587
Bottom of casing:	78	587
Bottom of well: (after bridging)	87	578

DH-8 Completed August 25, 1982

Diameter: 6 inches
Type of casing: 6-inch PVC

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		658.12
Measuring point:		658.18
Bottom of hole:	92	566
Bedrock surface:	72	586
Bottom of casing:	72	586
Bottom of well: (after bridging)	88	570

Table 1. Site and well-construction data for wells completed in dolomite—Continued

DH-9 Completed August 28, 1982

Diameter: 6 inches
Type of casing: 6-inch PVC

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		655.53
Measuring point:		656.31
Bottom of hole:	87	569
Bedrock surface:	75	581
Bottom of casing:	75	581
Bottom of well: (after bridging)	78	578

DH-10 Completed September 28, 1983

Diameter: 5 inches
Type of casing: 5-inch PVC

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		644.86
Measuring point:		646.14
Bottom of hole:	100	545
Bedrock surface:	80	565
Bottom of casing:	80	565
Bottom of well: (after bridging)	100	545

5167 Completion date unknown; estimated early 1900's

Diameter: 6 inches
Type of casing: 6-inch steel

	Depth below land-surface datum (feet)	Altitude[1] (feet)
Land surface datum:		651.57
Measuring point:		651.67
Bottom of hole:	147	505
Bedrock surface:	85	567
Bottom of casing:	75	577
Bottom of well: (after bridging)	147	505

[1]Above sea level.

Table 5. Tritium concentrations in water from wells completed in dolomite

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
11-13-73	11.9	1.3	---	---	---	---	---	---	---	---	---	---	---
12-27-73	11.2	5.2	0.24	---	---	---	---	---	---	---	---	---	---
05-23-74	4.7	8.5	.68	---	---	---	---	---	---	---	---	---	---
07-29-74	.49	---	---	---	---	---	---	---	---	---	---	---	---
10-09-74	8.8	.65	.43	---	---	---	---	---	---	---	---	---	---
11-06-74	11.3	.92	.27	---	---	---	---	---	---	---	---	---	---
12-04-74	10.1	.54	.27	---	---	---	---	---	---	---	---	---	---
01-08-75	10.0	<.2	.21	---	---	---	---	---	---	---	---	---	---
02-05-75	8.8	3.2	<.2	---	---	---	---	---	---	---	---	---	---
03-05-75	11.4	.72	<.2	---	---	---	---	---	---	---	---	---	---
04-02-75	7.8	3.5	<.2	---	---	---	---	---	---	---	---	---	---
05-07-75	2.8	4.5	.27	---	---	---	---	---	---	---	---	---	---
06-04-75	.23	2.8	.45	---	---	---	---	---	---	---	---	---	---
07-02-75	.21	1.9	.24	---	---	---	---	---	---	---	---	---	---
08-06-75	1.8	.83	.48	---	---	---	---	---	---	---	---	---	---
09-03-75	4.7	.54	.37	---	---	---	---	---	---	---	---	---	---
10-01-75	11.5	.58	.26	---	---	---	---	---	---	---	---	---	---
11-05-75	14.1	.40	<.2	---	---	---	---	---	---	---	---	---	---
12-03-75	12.7	<.2	<.2	---	---	---	---	---	---	---	---	---	---
12-16-75	13.2	---	---	---	---	---	---	---	---	---	---	---	---
01-14-76	10.5	2.9	<.2	---	---	---	---	---	---	---	---	---	---
02-04-76	11.3	1.4	<.2	---	---	---	---	---	---	---	---	---	---
02-19-76	12.4	.55	---	---	---	---	---	---	---	---	---	---	---
02-26-76	9.4	1.3	<.2	---	---	---	---	---	---	---	---	---	---
03-03-76	7.9	1.5	<.2	---	---	---	---	---	---	---	---	---	---
03-15-76	4.7	3.8	.22	---	---	---	---	---	---	---	---	---	---
04-07-76	3.0	4.4	<.2	---	---	---	---	---	---	---	---	---	---
05-05-76	.23	4.1	.24	---	---	---	---	---	---	---	---	---	---
06-01-76	<.2	2.6	<.2	---	---	---	---	---	---	---	---	---	---
07-07-76	2.3	1.5	.25	---	---	---	---	---	---	---	---	---	---
07-14-76	1.2	1.3	---	---	---	---	---	---	---	---	---	---	---
07-21-76	4.1	1.2	---	---	---	---	---	---	---	---	---	---	---
07-28-76	3.3	1.2	---	---	---	---	---	---	---	---	---	---	---
08-04-76	2.0	1.2	<.2	---	---	---	---	---	---	---	---	---	---
08-10-76	.65	1.1	---	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
08-18-76	0.41	1.0	---	---	---	---	---	---	---	---	---	---	---
08-24-76	1.1	1.5	---	---	---	---	---	---	---	---	---	---	---
09-01-76	.70	1.5	<.2	---	---	---	---	---	---	---	---	---	---
09-08-76	1.2	1.0	---	---	---	---	---	---	---	---	---	---	---
09-15-76	3.7	2.4	---	---	---	---	---	---	---	---	---	---	---
09-24-76	.86	.97	---	---	---	---	---	---	---	---	---	---	---
09-29-76	6.9	.98	---	---	---	---	---	---	---	---	---	---	---
10-06-76	8.3	2.4	---	---	---	---	---	---	---	---	---	---	---
10-20-76	11.5	3.0	---	---	---	---	---	---	---	---	---	---	---
10-27-76	---	2.8	---	---	---	---	---	---	---	---	---	---	---
11-03-76	9.7	2.6	<.2	---	---	---	---	---	---	---	---	---	---
11-10-76	9.4	3.2	---	---	---	---	---	---	---	---	---	---	---
11-17-76	10.0	2.7	---	0.46	0.35	4.0	<0.2	---	---	---	---	---	---
11-24-76	9.7	2.3	---	---	---	---	---	---	---	---	---	---	---
12-01-76	9.2	1.9	.26	---	---	---	---	---	---	---	---	---	---
12-08-76	9.4	2.8	---	---	---	---	---	---	---	---	---	---	---
12-16-76	9.9	3.7	---	.36	.30	4.4	.40	---	---	---	---	---	---
12-22-76	10.1	2.7	---	---	---	---	---	---	---	---	---	---	---
12-29-76	9.6	2.2	---	---	---	---	---	---	---	---	---	---	---
01-05-77	8.3	2.2	.24	---	---	---	---	---	---	---	---	---	---
01-12-77	8.6	2.2	---	---	---	---	---	---	---	---	---	---	---
01-19-77	8.5	1.6	---	.26	<.2	4.2	<.2	---	---	---	---	---	---
01-26-77	7.9	1.7	---	---	---	---	---	---	---	---	---	---	---
02-02-77	8.3	1.3	---	---	---	---	---	---	---	---	---	---	---
02-15-77	---	---	---	<.2	<.2	4.2	.25	---	---	---	---	---	---
02-16-77	8.2	1.7	---	---	---	---	---	---	---	---	---	---	---
02-23-77	8.1	2.2	---	---	---	---	---	---	---	---	---	---	---
02-30-77	8.1	1.9	<.2	---	---	---	---	---	---	---	---	---	---
03-08-77	8.2	1.6	---	---	---	---	---	---	---	---	---	---	---
03-16-77	8.4	2.3	---	---	---	---	---	---	---	---	---	---	---
03-17-77	---	---	---	.40	<.2	4.0	.26	---	---	---	---	---	---
03-23-77	8.0	2.4	---	---	---	---	---	---	---	---	---	---	---
03-30-77	8.1	4.0	---	---	---	---	---	---	---	---	---	---	---
04-06-77	7.6	4.1	.35	---	---	---	---	---	---	---	---	---	---
04-14-77	7.8	5.0	---	.42	.31	3.8	.21	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
04-20-77	7.6	5.9	---	---	---	---	---	---	---	---	---	---	---
04-27-77	7.7	5.4	---	0.31	0.24	3.9	<0.2	---	---	---	---	---	---
05-04-77	8.2	4.0	<0.2	---	---	---	---	---	---	---	---	---	---
05-11-77	8.8	3.0	---	.48	<.2	4.2	.23	---	---	---	---	---	---
05-17-77	---	---	---	.44	<.2	3.7	.38	---	---	---	---	---	---
05-18-77	8.5	1.8	---	---	---	---	---	---	---	---	---	---	---
05-25-77	8.7	1.6	---	---	---	---	---	---	---	---	---	---	---
06-01-77	8.7	1.3	<.2	<.2	<.2	3.7	<.2	---	---	---	---	---	---
06-08-77	9.3	1.2	---	---	---	---	---	---	---	---	---	---	---
06-15-77	9.4	1.2	---	.22	<.2	3.7	<.2	---	---	---	---	---	---
06-22-77	9.1	.88	---	---	---	---	---	---	---	---	---	---	---
06-29-77	9.4	.66	---	<.2	<.2	3.8	<.2	---	---	---	---	---	---
07-06-77	8.8	.91	<.2	---	---	---	---	---	---	---	---	---	---
07-13-77	8.8	1.1	---	<.2	<.2	3.5	<.2	---	---	---	---	---	---
07-20-77	8.8	.81	---	---	---	---	---	---	---	---	---	---	---
07-27-77	9.1	.74	---	---	---	---	---	---	---	---	---	---	---
08-03-77	8.8	.63	<.2	---	---	---	---	---	---	---	---	---	---
08-10-77	9.3	.38	---	---	---	---	---	---	---	---	---	---	---
08-17-77	9.9	1.2	---	<.2	<.2	2.8	<.2	---	---	---	---	---	---
08-24-77	8.4	1.4	---	---	---	---	---	---	---	---	---	---	---
08-31-77	8.7	1.3	---	---	---	---	---	---	---	---	---	---	---
09-09-77	9.0	2.4	<.2	---	---	---	---	---	---	---	---	---	---
09-14-77	8.0	3.1	---	---	---	---	---	---	---	---	---	---	---
09-21-77	8.0	3.1	---	<.2	.24	3.0	.29	---	---	---	---	---	---
09-28-77	7.4	7.4	---	---	---	---	---	---	---	---	---	---	---
10-05-77	6.8	2.5	---	---	---	---	---	---	---	---	---	---	---
10-12-77	5.5	1.9	<.2	---	---	---	---	---	---	---	---	---	---
10-19-77	6.0	1.6	---	<.2	<.2	2.1	<.2	---	---	---	---	---	---
10-26-77	6.9	1.4	---	---	---	---	---	---	---	---	---	---	---
11-02-77	7.5	1.3	<.2	---	---	---	---	---	---	---	---	---	---
11-09-77	7.3	1.8	---	---	---	---	---	---	---	---	---	---	---
11-16-77	7.5	1.5	---	.55	.98	2.6	.44	---	---	---	---	---	---
11-23-77	7.8	1.2	---	---	---	---	---	---	---	---	---	---	---
11-30-77	7.9	1.4	---	---	---	---	---	---	---	---	---	---	---
12-07-77	8.4	1.7	.42	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
12-14-77	9.0	1.7	---	---	---	---	---	---	---	---	---	---	---
12-21-77	9.1	1.5	---	---	---	---	---	---	---	---	---	---	---
12-28-77	7.6	1.4	---	---	---	---	---	---	---	---	---	---	---
12-29-77	---	---	---	1.5	<0.2	2.2	<0.2	---	---	---	---	---	---
01-04-78	8.5	1.8	<0.2	---	---	---	---	---	---	---	---	---	---
01-11-78	7.8	1.7	---	---	---	---	---	---	---	---	---	---	---
01-18-78	8.7	1.9	---	.35	.76	2.1	.24	---	---	---	---	---	---
01-25-78	10.1	1.3	---	---	---	---	---	---	---	---	---	---	---
02-01-78	12.0	2.0	<.2	---	---	---	---	---	---	---	---	---	---
02-08-78	12.2	2.1	---	---	---	---	---	---	---	---	---	---	---
02-15-78	12.9	2.3	---	---	---	---	---	---	---	---	---	---	---
02-22-78	11.6	1.7	---	---	---	---	---	---	---	---	---	---	---
03-01-78	11.5	1.4	---	---	---	---	---	---	---	---	---	---	---
03-08-78	11.7	.9	---	---	---	---	---	---	---	---	---	---	---
03-15-78	11.0	.7	---	---	---	---	---	---	---	---	---	---	---
03-20-78	---	---	---	.29	<.2	2.1	<.2	---	---	---	---	---	---
03-22-78	10.0	.5	---	---	---	---	---	---	---	---	---	---	---
03-29-78	8.8	.4	---	---	---	---	---	---	---	---	---	---	---
04-05-78	4.8	1.4	<.2	---	---	---	---	---	---	---	---	---	---
04-12-78	4.7	2.3	---	---	---	---	---	---	---	---	---	---	---
04-19-78	4.0	2.0	---	.21	<.2	4.2	<.2	---	---	---	---	---	---
04-26-78	3.6	3.7	---	---	---	---	---	---	---	---	---	---	---
05-03-78	3.8	2.9	---	---	---	---	---	---	---	---	---	---	---
05-10-78	3.2	2.9	---	---	---	---	---	---	---	---	---	---	---
05-17-78	3.7	2.2	---	---	---	---	---	---	---	---	---	---	---
05-22-77	---	---	---	<.2	<.2	2.1	.21	---	---	---	---	---	---
05-24-78	2.8	2.2	---	---	---	---	---	---	---	---	---	---	---
06-06-78	1.3	---	<.2	---	---	---	---	---	---	---	---	---	---
06-14-78	.6	1.1	---	---	---	---	---	---	---	---	---	---	---
06-21-78	1.6	.9	---	<.2	.24	2.1	.22	---	---	---	---	---	---
06-28-78	2.1	.9	---	---	---	---	---	---	---	---	---	---	---
07-05-78	4.6	.8	.23	---	---	---	---	---	---	---	---	---	---
07-12-78	5.2	.7	---	---	---	---	---	---	---	---	---	---	---
07-19-78	5.3	.7	---	.21	<.2	2.2	.24	---	---	---	---	---	---
07-26-78	8.1	.6	---	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
08-02-78	6.7	0.7	0.22	---	---	---	---	---	---	---	---	---	---
08-09-78	7.9	.8	---	---	---	---	---	---	---	---	---	---	---
08-16-78	7.5	.8	---	0.21	0.21	2.2	<0.2	---	---	---	---	---	---
08-30-78	7.5	.7	---	---	---	---	---	---	---	---	---	---	---
09-06-78	9.4	.4	<.2	---	---	---	---	---	---	---	---	---	---
09-13-78	8.3	.6	---	---	---	---	---	---	---	---	---	---	---
09-20-78	11.0	.6	---	.22	.20	<.2	<.2	---	---	---	---	---	---
09-27-78	11.8	.9	---	---	---	---	---	---	---	---	---	---	---
10-04-78	10.0	.6	.23	---	---	---	---	---	---	---	---	---	---
10-11-78	10.9	.6	---	---	---	---	---	---	---	---	---	---	---
10-18-78	10.3	.5	---	.29	.25	.26	<.2	---	---	---	---	---	---
10-25-78	8.9	.3	---	---	---	---	---	---	---	---	---	---	---
11-01-78	11.1	.4	---	---	---	---	---	---	---	---	---	---	---
11-08-78	10.8	.4	---	---	---	---	---	---	---	---	---	---	---
11-15-78	10.4	.4	---	.21	.25	.34	<.2	---	---	---	---	---	---
11-29-78	11.7	.3	---	---	---	---	---	---	---	---	---	---	---
12-06-78	11.0	.6	---	---	---	---	---	---	---	---	---	---	---
12-13-78	11.7	.3	---	---	---	---	---	---	---	---	---	---	---
12-20-78	11.8	.5	---	.23	.22	.30	<.2	---	---	---	---	---	---
12-27-78	11.3	.5	---	---	---	---	---	---	---	---	---	---	---
01-03-79	10.2	.5	---	---	---	---	---	---	---	---	---	---	---
01-10-79	10.7	.3	<.2	---	---	---	---	---	---	---	---	---	---
02-07-79	10.0	.2	<.2	---	---	---	---	---	---	---	---	---	---
02-14-79	10.6	.6	---	---	---	---	---	---	---	---	---	---	---
02-21-79	9.7	.7	---	---	---	---	---	---	---	---	---	---	---
02-28-79	9.5	1.2	---	---	---	---	---	---	---	---	---	---	---
03-07-79	9.2	1.3	<.2	---	---	---	---	---	---	---	---	---	---
03-14-79	9.0	1.8	---	---	---	---	---	---	---	---	---	---	---
03-21-79	4.1	2.3	---	.23	<.2	.76	<.2	---	---	---	---	---	---
03-28-79	4.1	2.5	---	---	---	---	---	---	---	---	---	---	---
04-04-79	3.1	2.6	<.2	---	---	---	---	---	---	---	---	---	---
04-11-79	2.7	2.6	---	---	---	---	---	---	---	---	---	---	---
04-18-79	2.8	2.8	---	.22	<.2	.59	<.2	---	---	---	---	---	---
04-25-79	---	2.6	---	---	---	---	---	---	---	---	---	---	---
05-02-79	2.2	2.4	<.2	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
05-09-79	2.5	2.8	---	---	---	---	---	---	---	---	---	---	---
05-16-79	2.4	2.5	---	<0.2	<0.2	0.86	1.0	---	---	---	---	---	---
05-23-79	1.0	2.2	---	---	---	---	---	---	---	---	---	---	---
05-30-79	.3	1.8	---	---	---	---	---	---	---	---	---	---	---
06-06-79	<.2	1.7	0.25	---	---	---	---	---	---	---	---	---	---
06-13-79	<.2	1.5	---	---	---	---	---	---	---	---	---	---	---
06-20-79	.3	.8	---	---	---	---	---	---	---	---	---	---	---
06-21-79	---	---	---	<.2	<.2	.77	<.2	---	---	---	---	---	---
06-27-79	.5	.8	---	---	---	---	---	---	---	---	---	---	---
07-03-79	.6	.7	.35	---	---	---	---	---	---	---	---	---	---
07-11-79	1.7	.8	---	---	---	---	---	---	---	---	---	---	---
07-18-79	2.9	.8	---	<.2	<.2	.81	<.2	---	---	---	---	---	---
07-25-79	5.1	.6	---	---	---	---	---	---	---	---	---	---	---
08-01-79	5.1	.5	<.2	---	---	---	---	---	---	---	---	---	---
08-08-79	8.7	.5	---	---	---	---	---	---	---	---	---	---	---
08-15-79	8.6	.4	---	<.2	<.2	.90	<.2	---	---	---	---	---	---
08-22-79	12.2	.5	---	---	---	---	---	---	---	---	---	---	---
08-29-79	10.2	.4	---	---	---	---	---	---	---	---	---	---	---
09-05-79	9.3	.3	<.2	---	---	---	---	---	---	---	---	---	---
09-12-79	8.2	.4	---	---	---	---	---	---	---	---	---	---	---
09-19-79	8.9	.6	---	.21	.40	1.08	.27	---	---	---	---	---	---
09-26-79	10.0	.5	---	---	---	---	---	---	---	---	---	---	---
10-03-79	10.5	.5	---	---	---	---	---	---	---	---	---	---	---
10-10-79	12.4	.5	---	---	---	---	---	---	---	---	---	---	---
10-17-79	10.8	.5	---	.25	.25	1.23	<.2	---	---	---	---	---	---
10-24-79	10.8	.4	---	---	---	---	---	---	---	---	---	---	---
10-31-79	10.3	.4	---	---	---	---	---	---	---	---	---	---	---
11-07-79	11.0	.4	<.2	---	---	---	---	---	---	---	---	---	---
11-14-79	11.2	.5	---	---	---	---	---	---	---	---	---	---	---
11-21-79	11.2	.4	---	---	---	---	---	---	---	---	---	---	---
11-28-79	12.1	.4	---	---	---	---	---	---	---	---	---	---	---
12-05-79	10.6	.3	<.2	---	---	---	---	---	---	---	---	---	---
12-12-79	11.2	.4	---	---	---	---	---	---	---	---	---	---	---
12-19-79	9.6	.6	---	<.2	.29	1.17	<.2	---	---	---	---	---	---
12-26-79	9.3	.8	---	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
01-02-80	8.7	1.3	---	---	---	---	---	---	---	---	---	---	---
01-09-80	7.6	1.6	---	---	---	---	---	---	---	---	---	---	---
01-16-80	7.8	2.0	<0.2	---	---	---	---	---	---	---	---	---	---
01-23-80	7.6	1.6	---	---	---	---	---	---	---	---	---	---	---
01-30-80	8.8	1.6	---	---	---	---	---	---	---	---	---	---	---
02-06-80	8.7	1.2	<.2	---	---	---	---	---	---	---	---	---	---
02-13-80	9.0	1.3	---	---	---	---	---	---	---	---	---	---	---
02-20-80	8.6	1.3	---	<0.2	0.24	1.12	<0.2	---	---	---	---	---	---
02-27-80	9.0	1.3	---	---	---	---	---	---	---	---	---	---	---
03-05-80	9.2	.9	---	---	---	---	---	---	---	---	---	---	---
03-12-80	8.7	1.2	---	---	---	---	---	---	---	---	---	---	---
03-19-80	6.8	1.4	---	<.2	.23	1.01	<.2	---	---	---	---	---	---
03-26-80	6.0	1.3	---	---	---	---	---	---	---	---	---	---	---
04-02-80	5.6	1.3	<.2	---	---	---	---	---	---	---	---	---	---
04-09-80	6.2	1.4	---	---	---	---	---	---	---	---	---	---	---
04-16-80	4.3	1.5	---	---	---	---	---	---	---	---	---	---	---
04-17-80	---	---	---	<.2	<.2	1.08	<.2	---	---	---	---	---	---
04-23-80	4.4	1.8	---	---	---	---	---	---	---	---	---	---	---
04-30-80	4.4	1.8	---	---	---	---	---	---	---	---	---	---	---
05-07-80	4.0	1.6	---	---	---	---	---	---	---	---	---	---	---
05-14-80	2.8	1.5	---	---	---	---	---	---	---	---	---	---	---
05-21-80	---	---	---	.24	<.2	1.08	<.2	---	---	---	---	---	---
05-24-80	4.4	1.6	---	---	---	---	---	---	---	---	---	---	---
05-28-80	4.5	1.2	---	---	---	---	---	---	---	---	---	---	---
06-04-80	3.9	1.2	---	---	---	---	---	---	---	---	---	---	---
06-11-80	4.6	1.4	---	---	---	---	---	---	---	---	---	---	---
06-18-80	4.5	1.5	---	---	---	---	---	---	---	---	---	---	---
06-24-80	---	---	---	.39	.42	1.19	<.2	---	---	---	---	---	---
06-25-80	5.5	1.4	---	---	---	---	---	---	---	---	---	---	---
07-02-80	3.7	1.2	---	---	---	---	---	---	---	---	---	---	---
07-09-80	4.2	1.1	---	---	---	---	---	---	---	---	---	---	---
07-16-80	4.8	1.2	---	---	---	---	---	---	---	---	---	---	---
07-23-80	6.3	.8	---	---	---	---	---	---	---	---	---	---	---
07-24-80	---	---	---	.24	.42	1.07	<.2	---	---	---	---	---	---
07-30-80	5.7	.9	---	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
08-06-80	7.1	0.8	---	---	---	---	---	---	---	---	---	---	---
08-13-80	7.8	.6	---	---	---	---	---	---	---	---	---	---	---
08-20-80	9.3	.7	---	---	---	---	---	---	---	---	---	---	---
08-27-80	8.9	.5	---	---	---	---	---	---	---	---	---	---	---
09-03-80	---	.5	---	---	---	---	---	---	---	---	---	---	---
09-05-80	---	---	---	<0.2	0.24	1.13	<0.2	---	---	---	---	---	---
09-10-80	7.1	.5	---	---	---	---	---	---	---	---	---	---	---
09-17-80	6.1	.6	---	---	---	---	---	---	---	---	---	---	---
09-24-80	6.4	.7	---	---	---	---	---	---	---	---	---	---	---
10-01-80	5.3	.9	---	---	---	---	---	---	---	---	---	---	---
10-02-80	---	---	---	.32	.40	1.20	.24	---	---	---	---	---	---
10-08-80	6.5	1.0	---	---	---	---	---	---	---	---	---	---	---
10-15-80	7.4	.9	---	---	---	---	---	---	---	---	---	---	---
10-22-80	6.3	.9	---	---	---	---	---	---	---	---	---	---	---
10-23-80	---	---	---	.25	.21	.99	.20	---	---	---	---	---	---
10-29-80	6.0	1.0	---	---	---	---	---	---	---	---	---	---	---
11-05-80	5.5	1.0	---	---	---	---	---	---	---	---	---	---	---
11-12-80	6.4	.9	---	---	---	---	---	---	---	---	---	---	---
11-19-80	7.4	1.1	---	---	---	---	---	---	---	---	---	---	---
11-20-80	---	---	---	.25	.55	1.27	<.2	---	---	---	---	---	---
11-26-80	7.6	1.0	---	---	---	---	---	---	---	---	---	---	---
12-03-80	7.3	.9	---	---	---	---	---	---	---	---	---	---	---
12-10-80	6.3	.8	---	---	---	---	---	---	---	---	---	---	---
12-17-80	6.9	.7	---	---	---	---	---	---	---	---	---	---	---
12-18-80	---	---	---	<.2	.31	1.09	.33	---	---	---	---	---	---
12-22-80	5.6	.9	---	---	---	---	---	---	---	---	---	---	---
12-30-80	6.3	.9	---	---	---	---	---	---	---	---	---	---	---
01-07-81	6.5	1.3	<.2	---	---	---	---	---	---	---	---	---	---
01-14-81	6.4	1.4	---	---	---	---	---	---	---	---	---	---	---
01-21-81	7.1	1.3	---	---	---	---	---	---	---	---	---	---	---
01-28-81	6.9	1.3	---	---	---	---	---	---	---	---	---	---	---
02-04-81	7.0	1.2	<.2	---	---	---	---	---	---	---	---	---	---
02-18-81	8.6	1.1	---	---	---	---	---	---	---	---	---	---	---
02-20-81	---	---	---	<.2	<.2	1.18	.35	---	---	---	---	---	---
03-04-81	6.2	.9	<.2	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
03-18-81	6.4	0.9	---	<0.2	0.22	1.20	<0.2	---	---	---	---	---	---
04-01-81	6.8	1.1	<0.2	---	---	---	---	---	---	---	---	---	---
04-15-81	4.2	1.1	---	---	---	---	---	---	---	---	---	---	---
05-01-81	---	---	---	.28	.23	1.20	<.2	---	---	---	---	---	---
05-06-81	2.7	2.0	<.2	---	---	---	---	---	---	---	---	---	---
05-20-81	2.3	2.2	---	---	---	---	---	---	---	---	---	---	---
05-27-81	---	---	---	.25	---	---	<.2	---	---	---	---	---	---
06-03-81	.2	2.0	<.2	---	---	---	---	---	---	---	---	---	---
06-17-81	.5	1.4	---	---	---	---	---	---	---	---	---	---	---
06-26-81	---	---	---	.30	<.2	1.40	<.2	---	---	---	---	---	---
07-01-81	<.2	1.3	<.2	---	---	---	---	---	---	---	---	---	---
07-15-81	<.2	1.0	---	---	---	---	---	---	---	---	---	---	---
07-16-81	---	---	---	<.2	<.2	1.24	<.2	---	---	---	---	---	---
08-05-81	.5	.7	<.2	---	---	---	---	---	---	---	---	---	---
08-19-81	.7	.6	---	---	---	---	---	---	---	---	---	---	---
08-20-81	---	---	---	<.2	<.2	1.18	<.2	---	---	---	---	---	---
09-02-81	1.4	.6	<.2	---	---	---	---	---	---	---	---	---	---
09-16-81	2.4	.5	---	---	---	---	---	---	---	---	---	---	---
09-23-81	---	---	---	.25	<.2	1.20	<.2	---	---	---	---	---	---
10-07-81	5.2	.5	<.2	---	---	---	---	---	---	---	---	---	---
10-21-81	7.8	.4	---	---	---	---	---	---	---	---	---	---	---
10-27-81	---	---	---	<.2	<.2	1.33	<.2	---	---	---	---	---	---
11-04-81	9.2	.4	<.2	---	---	---	---	---	---	---	---	---	---
11-18-81	8.0	.4	---	---	---	---	---	---	---	---	---	---	---
12-02-81	9.5	.4	<.2	---	---	---	---	---	---	---	---	---	
12-03-81	---	---	---	.25	.22	1.36	<.2	---	---	---	---	---	---
12-16-81	9.7	5.2	---	---	---	---	---	---	---	---	---	---	---
01-06-82	8.9	.4	<.2	---	---	---	---	---	---	---	---	---	---
01-20-82	7.6	.3	---	---	---	---	---	---	---	---	---	---	---
02-03-82	8.1	.4	<.2	<.2	<.2	1.30	<.2	---	---	---	---	---	---
02-17-82	9.1	.4	---	---	---	---	---	---	---	---	---	---	---
03-03-82	9.2	.3	<.2	---	---	---	---	---	---	---	---	---	---
03-17-82	6.9	.4	---	---	---	---	---	---	---	---	---	---	---
03-18-82	---	---	---	.21	<.2	1.61	<.2	---	---	---	---	---	---
04-07-82	2.2	2.0	<.2	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
04-21-82	2.4	3.2	---	<0.2	<0.2	1.39	<0.2	---	---	---	---	---	---
05-05-82	1.2	2.2	<0.2	---	---	---	---	---	---	---	---	---	---
05-19-82	.2	1.8	---	---	---	---	---	---	---	---	---	---	---
06-02-82	.1	1.2	<.2	---	---	---	---	---	---	---	---	---	---
06-07-82	---	---	---	.23	<.2	1.58	1.58	---	---	---	---	---	---
06-16-82	.2	1.1	---	---	---	---	---	---	---	---	---	---	---
07-01-82	---	---	---	.28	.64	1.39	.24	---	---	---	---	---	---
07-07-82	.6	.7	<.2	---	---	---	---	---	---	---	---	---	---
07-21-82	.6	.6	---	---	---	---	---	---	---	---	---	---	---
07-26-82	---	---	---	---	---	---	---	---	---	0.22	---	---	---
07-27-82	---	---	---	<.2	<.2	1.42	<.2	---	---	---	---	---	---
08-04-82	1.8	.6	.27	---	---	---	---	---	---	---	---	---	---
08-18-82	2.6	.7	---	---	---	---	---	0.18	---	---	---	---	---
08-25-82	---	---	---	<.2	.22	1.54	.29	---	---	---	---	---	---
09-08-82	1.6	.5	<.2	---	---	---	---	---	---	---	---	---	---
09-15-82	2.5	.6	---	---	---	---	---	---	---	---	---	---	---
09-30-82	---	---	---	<.2	<.2	1.50	<.2	---	---	---	---	---	---
10-06-82	4.1	.6	<.2	---	---	---	---	---	---	---	---	---	---
10-13-82	---	---	---	---	---	---	---	<.2	<0.2	<.2	<0.2	10.2	---
10-20-82	9.0	.5	---	---	---	---	---	---	---	---	---	---	---
10-26-82	---	---	---	<.2	<.2	1.48	<.2	---	---	---	---	---	---
11-03-82	9.3	.6	<.2	---	---	---	---	---	---	---	---	---	---
11-17-82	11.0	.6	---	---	---	---	---	---	---	---	---	---	---
12-01-82	8.8	.4	<.2	---	---	---	---	---	---	---	---	---	---
12-07-82	---	---	---	.23	<.2	1.59	<.2	---	---	---	---	---	---
12-15-82	2.1	.4	---	---	---	---	---	---	---	---	---	---	---
12-16-82	---	---	---	---	---	---	---	<.2	.3	<.2	<.2	---	---
01-06-83	1.5	1.5	.22	---	---	---	---	---	---	---	---	---	---
01-19-83	.5	1.5	---	---	---	---	---	---	---	---	---	---	---
01-24-83	---	---	---	.21	<.2	1.49	<.2	---	---	---	---	---	---
02-02-83	.7	1.5	---	---	---	---	---	---	---	---	---	---	---
02-16-83	2.6	1.4	<.2	---	---	---	---	---	---	---	---	---	---
02-28-83	---	---	---	<.2	<.2	1.68	<.2	<.2	.5	<.2	.2	17.9	---
03-02-83	2.6	1.3	---	---	---	---	---	---	---	---	---	---	---
03-16-83	3.0	1.2	---	---	---	---	---	---	---	---	---	---	---

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
07-04-83	---	---	---	---	---	---	---	<0.2	0.3	<0.2	0.3	19.7	---
04-06-83	2.1	1.6	<0.2	---	---	---	---	---	---	---	---	---	---
04-20-83	1.1	1.8	---	---	---	---	---	---	---	---	---	---	---
05-04-83	1.4	1.6	<.2	---	---	---	---	---	---	---	---	---	---
05-05-83	---	---	---	---	---	---	---	<.2	.3	<.2	<.2	24.8	---
05-18-83	1.5	1.6	---	---	---	---	---	---	---	---	---	---	---
05-27-83	---	---	---	---	---	---	---	<.2	.3	<.2	<.2	24.9	---
06-01-83	.9	1.5	---	---	---	---	---	---	---	---	---	---	---
06-15-83	.4	1.0	---	---	---	---	---	---	---	---	---	---	---
07-05-83	.5	.8	.52	---	---	---	---	---	---	---	---	---	---
07-07-83	---	---	---	---	---	---	---	<.2	.5	<.2	.2	24.5	---
07-20-83	<.2	.6	---	---	---	---	---	---	---	---	---	---	---
08-01-83	---	---	---	---	---	---	---	<.2	.5	<.2	.2	26.5	---
08-03-83	<.2	.7	.52	---	---	---	---	---	---	---	---	---	---
08-17-83	1.0	.9	---	---	---	---	---	---	---	---	---	---	---
09-07-83	.6	.5	.88	---	---	---	---	---	---	---	---	---	---
09-21-83	.2	.4	---	---	---	---	---	---	---	---	---	---	---
09-28-83	---	---	---	---	---	---	---	.32	.3	<.2	.3	24.1	4.0
10-12-83	1.2	.4	.51	---	---	---	---	---	---	---	---	---	---
10-19-83	1.6	.4	---	---	---	---	---	---	---	---	---	---	---
11-01-83	---	---	---	2.59	0.64	2.03	<0.2	.92	3.4	<.2	1.3	24.3	14.3
11-02-83	4.6	.5	.49	---	---	---	---	---	---	---	---	---	---
11-16-83	5.1	.4	---	---	---	---	---	---	---	---	---	---	---
12-08-83	4.9	.4	.41	---	---	---	---	---	---	---	---	---	---
12-13-83	---	---	---	.23	.24	2.10	.51	<.2	.4	<.2	<.2	27.6	13.6
12-21-83	3.3	.4	---	---	---	---	---	---	---	---	---	---	---
01-04-84	1.4	.5	.26	---	---	---	---	---	---	---	---	---	---
01-18-84	.7	---	---	---	---	---	---	---	---	---	---	---	---
02-01-84	1.3	.6	<.2	---	---	---	---	---	---	---	---	---	---
02-15-84	2.2	.7	---	---	---	---	---	---	---	---	---	---	---
02-16-84	---	---	---	<.2	.59	1.81	<.2	<.2	.3	<.2	<.2	24.8	11.0
03-07-84	1.8	.6	.27	---	---	---	---	---	---	---	---	---	---
03-21-84	1.3	.5	---	---	---	---	---	---	---	---	---	---	---
04-04-84	.3	1.5	.23	---	---	---	---	---	---	---	---	---	---
04-12-84	---	---	---	.27	.35	1.79	<.2	.21	.5	.2	.3	29.4	7.9

Table 5. Tritium concentrations in water from wells completed in dolomite—Continued

[Dashes indicate no water sample collected on this date]

Date	Tritium concentration in nanocuries per liter												
	5167	5159	5158	DH-1	DH-2	DH-3	DH-4	DH-5	DH-6	DH-7	DH-8	DH-9	DH-10
04-18-84	0.3	1.7	---	---	---	---	---	---	---	---	---	---	---
05-02-84	.2	1.6	<0.2	---	---	---	---	---	---	---	---	---	---
05-16-84	<.2	1.5	---	---	---	---	---	---	---	---	---	---	---
06-06-84	<.2	1.2	---	---	---	---	---	---	---	---	---	---	---
06-20-84	<.2	1.2	---	---	---	---	---	---	---	---	---	---	---
07-11-84	<.2	.7	---	---	---	---	---	---	---	---	---	---	---
07-18-84	<.2	.7	---	---	---	---	---	---	---	---	---	---	---

METRIC CONVERSION FACTORS

For the convenience of readers who prefer metric (International System) units rather than the inch-pound units in this report, the following factors may be used:

Multiply inch-pound unit	By	To obtain metric unit
inch (in)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
gallon per minute (gal/min)	3.785	liter per minute (L/min)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A Geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "*Mean Sea Level.*"

Altitude, as used in this report, refers to distance above the NGVD of 1929.

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