HYDROLOGY OF THE MELTON VALLEY RADIOACTIVE-WASTE BURIAL GROUNDS AT OAK RIDGE NATIONAL LABORATORY, TENNESSEE

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of three wells each by solving three-point problems (table 2). Dips in Melton Valley between the wells cited range from 14 to 18 degrees southeast. Dip determined by this approach includes the effect of compression of strata by folding and faulting as well as possible fault-block movement between the three points, and thus is expected to be somewhat less than dip measured at outcrops. The range in dips reported by the several studies reflects the structural complexity of Melton Valley.

Table 2.--*Calculated approximate areal dip of strata in the waste-disposal area, based on contacts picked from gamma and neutron logs of wells*

Maryville-Rogersville contact				Rutledge-Pumpkin Valley contact			
Well numbers			Approximate dip	Well numbers			Approximate dip
400-S	600-N	OW-6	16° SE	OW-6	400-S	600-N	$18\ ^1/_2{}^\circ$ SE
400-S	469	OW-6	$14\ ^1/_2{}^\circ$ SE	OW-6	400-S	E-362	18° SE
400-S	600-N	113	16° SE	OW-6	600-N	E-362	18° SE
465*	OW-6	114	17° SE				

*Depth of contact estimated.

HYDROLOGIC UNITS

The variations in lithology, differences in bedding characteristics, and innumerable folds, faults, joints, and fractures make the Conasauga Group a highly-complex hydrologic medium. In order to describe the two-dimensional and three-dimensional movement of water below land surface, the geologic materials are divided into two hydrologic units, the regolith and the bedrock. They should not be conceived as two separate aquifers, however. The two units are hydraulically connected with water moving from one unit to the other.

REGOLITH

The regolith is the mantle of decomposed earthen materials that rests on bedrock. It is in this unit that all of the radioactive solid waste at ORNL has been buried.

The regolith in the Melton Valley area consists largely of in situ mixtures of clay, silt and rock fragments that have been derived from the weathering of bedrock. Its physical composition is highly variable. Auger holes north of Lagoon Road revealed it to consist largely of finely-powdered rock, whereas borings within burial ground 4 showed it to consist of wet, heavy clay containing many small pebbles. Trench excavations in burial ground 5-north exposed thin, very fissile, partially weathered shale beds lacking any substantial clay component, even close to land surface. In burial ground 6, trench excavations commonly exposed alternating deformed beds of clay and rock fragments, and less commonly, beds of rotten, shaley rock. In some of the topographically low areas of burial grounds 5 and 6, the regolith is sufficiently weathered to have the appearance of brown soil.

Weathering characteristics lack uniformity. Generally, in the mudstone, shale, and siltstone beds, a transition occurs from the surface soil, through the rotten rock, and finally to bedrock. In the carbonate beds the transition is less gradual and, in places, abrupt. Beds of resistant, relatively unweathered rock may be present in either lithotype, particularly in the lower regolith. Where clastic and carbonate beds are interbedded, the lower regolith commonly has alternating hard and soft beds. Differential weathering with depth results in the absence of a sharp boundary between the regolith and the underlying bedrock, and adds complications to a definition of ground-water flow through this material.

The thickness of the regolith in this valley is related both to topographic location and lithology of the parent rock. The thickness generally is least below the low areas of the valley and greatest beneath the ridges. Its reported range is from 4 to 16 feet at burial ground 4 (Lomenick and Cowser, 1961, p. 8), a few feet to 40 feet at burial ground 5 (Cowser and others 1961, p. 7), and 5 feet or less to as much as 40 feet at burial ground 6 (Lomenick and Wyrick, 1965, p. 5). In the general area of the ILW pits regolith thickness is reported to range from 10 feet under the lowland to approximately 30 to 40 feet under the low ridges (deLaguna and others, 1958, p. 105).

Joints, fractures, partings and interstitial spaces in the regolith provide narrow pathways for the flow of water. The unevenness in extent of weathering, the lithologic variety of materials, and the presence of many structurally-related openings make the aquifer inhomogeneous and anisotropic. Natural inhomogeneity has been enhanced by the burial of a diverse assortment of loosely-packed waste materials that have become an integral part of the geologic media. Anisotropy has been magnified by trenches that extend below the water table and which transect the beds for substantial distances.

BEDROCK

Bedrock is the solid rock that lies below the zone of weathering. Some of the partings, joints, fractures, and faults in the regolith extend into the bedrock and, where open, enable the continued passage of water. Locally, the carbonate bedrock contains small solution channels caused by dissolution of the limestone by circulating ground water. Typically, dissolution occurs where these beds have been broken by fractures or faults. The extent of solution-channel development below the waste-disposal area is thought to be minor in relation to the mass of rock involved.

The volume of openings represented by joints, fractures, and solution channels per unit volume of bedrock is far less than that of the regolith and tends to decrease as depth increases. Earlier studies (deLaguna, 1956; deLaguna and others, 1958; Cowser and Parker, 1958; Cowser and others, 1961; Cowser, deLaguna, Parker, and Struxness, unpublished manuscript, 1961;

unpublished report in USGS files about the Four-Acre site) concluded that most of the secondary openings in bedrock occur within 100 feet of land surface, and that very few openings persist to as much as 200 feet deep. Consequently, for the purpose of this study, 200 feet was taken as the lower limit of investigation by wells. More recent work (Haase and others 1985; this study) suggests that openings occur at greater depths, but below a depth of 200 feet, relatively little ground water is in circulation with that in the overlying network of openings. This is a result of the fewer openings as depth increases, the decrease in hydraulic continuity between openings, and the thinness of those openings under great overburden pressure. It is possible that relatively isolated, deeply cutting faults, if unfilled by secondary mineralization, may permit flow to greater depth, but if so, these are thought to represent minor flow paths and are beyond the scope of this study.

GROUND-WATER HYDROLOGY

LOCATION AND CONSTRUCTION OF WELLS

Published and unpublished records indicate that more than 350 wells have been constructed in or near the Melton Valley burial grounds since the late-1950's. Many of these wells have been destroyed as the sites were developed, and others have been destroyed later by site maintenance. At this time (1985) about 245 wells remain where water-level measurements can be made.

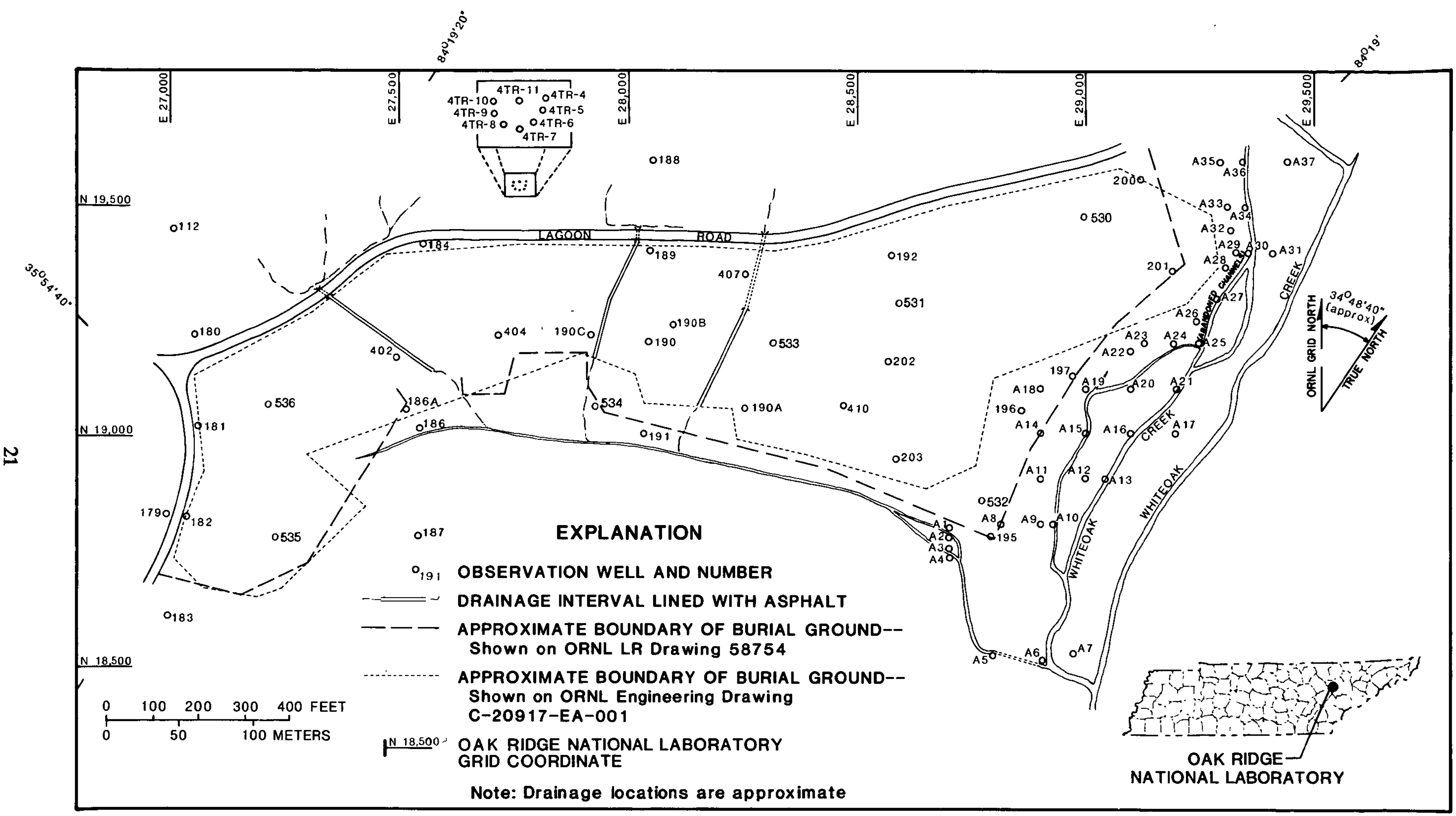
The locations of wells in burial grounds 4, 5, and 6 that have yielded data for this report are shown in figures 6, 7, and 8, respectively, and the location of wells in the vicinity of ILW pits 2, 3, and 4 is shown in figure 9. Figure 10 provides construction diagrams and lists characteristics of typical wells finished in the regolith and bedrock sections of the aquifer. Pertinent data of wells cited in this report are summarized in an appendix.

HYDROLOGY OF THE REGOLITH

METHOD OF INVESTIGATION

Water levels in the burial-ground wells were usually measured at 2 to 3 week intervals between 1975 and 1979. Additional measurements were made in burial ground 5 in 1982-1983 to include the newly constructed wells in the TRU area. The data of the regolith wells have provided the basis for preparation of hydrographs showing the pattern of water-level fluctuations at a large number of points in the burial grounds, depth to water maps, and water-table contour maps.

Slug tests were made of numerous wells in the disposal sites to determine a range of aquifer transmissivity and hydraulic conductivity. The method used differs from that described by Cooper and others (1967) and Papadopulos and others (1973) in that, instead of inserting a cylinder in a well to instantaneously raise the water level, a submerged cylinder was withdrawn from the column of water, causing an instantaneous drawdown of water level, and the rate of recovery was measured. Transmissivity and hydraulic



Base from ORNL Engineering Drawing C-20917-EA-001

Figure 6.--Location of wells in and near burial ground 4.

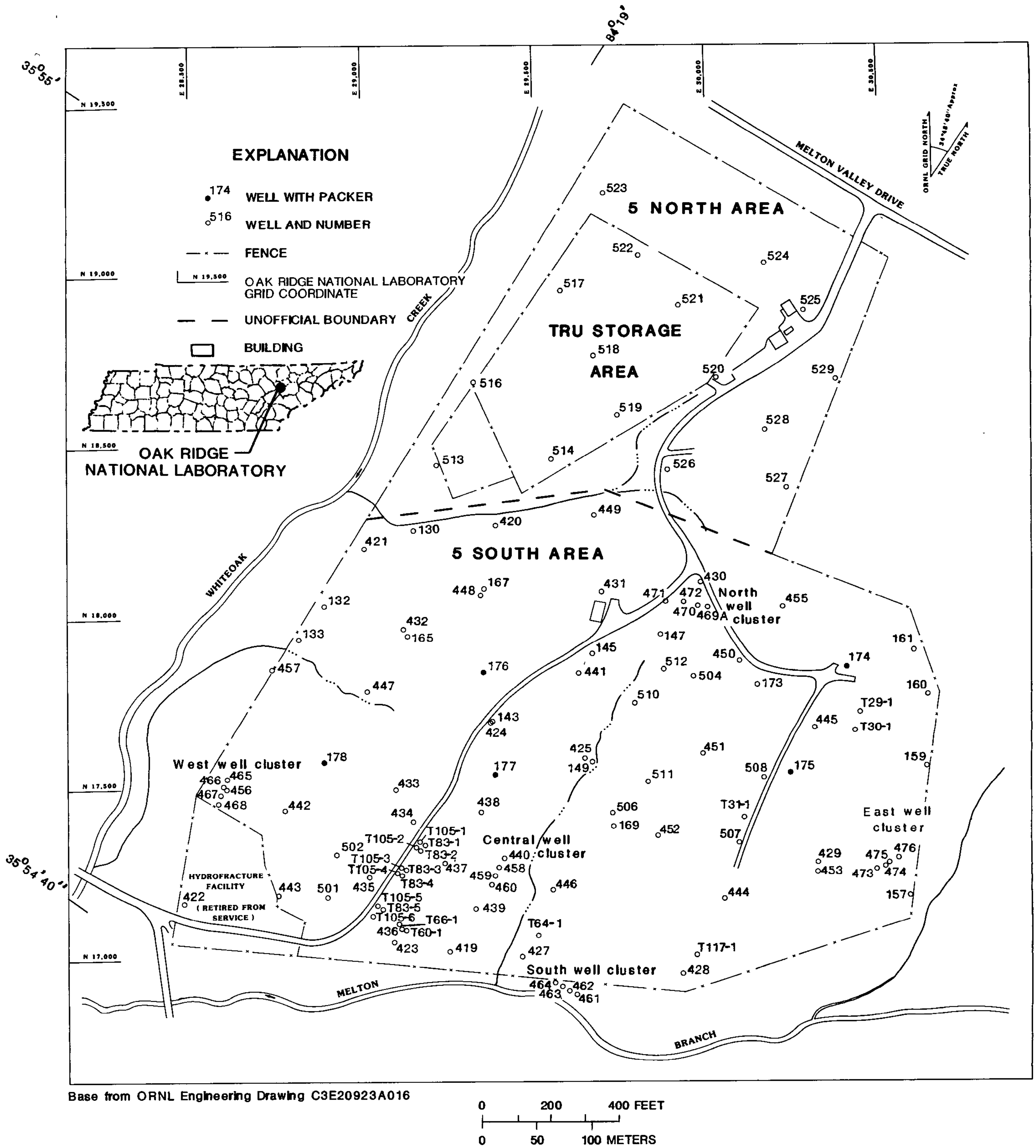
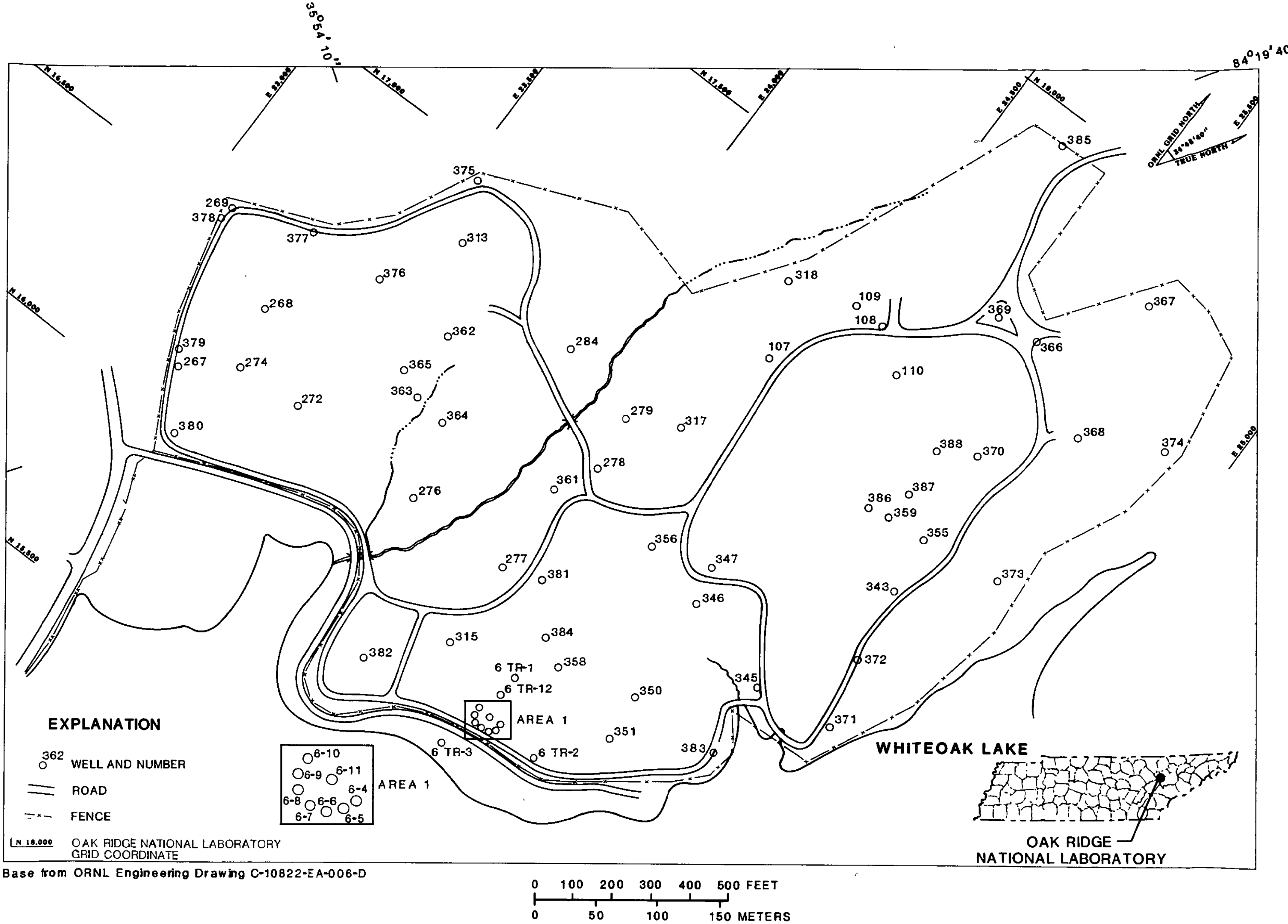


Figure 7.--Location of wells in burial ground 5.



Base from ORNL Engineering Drawing C-10822-EA-006-D

Figure 8.--Location of wells in burial ground 6.

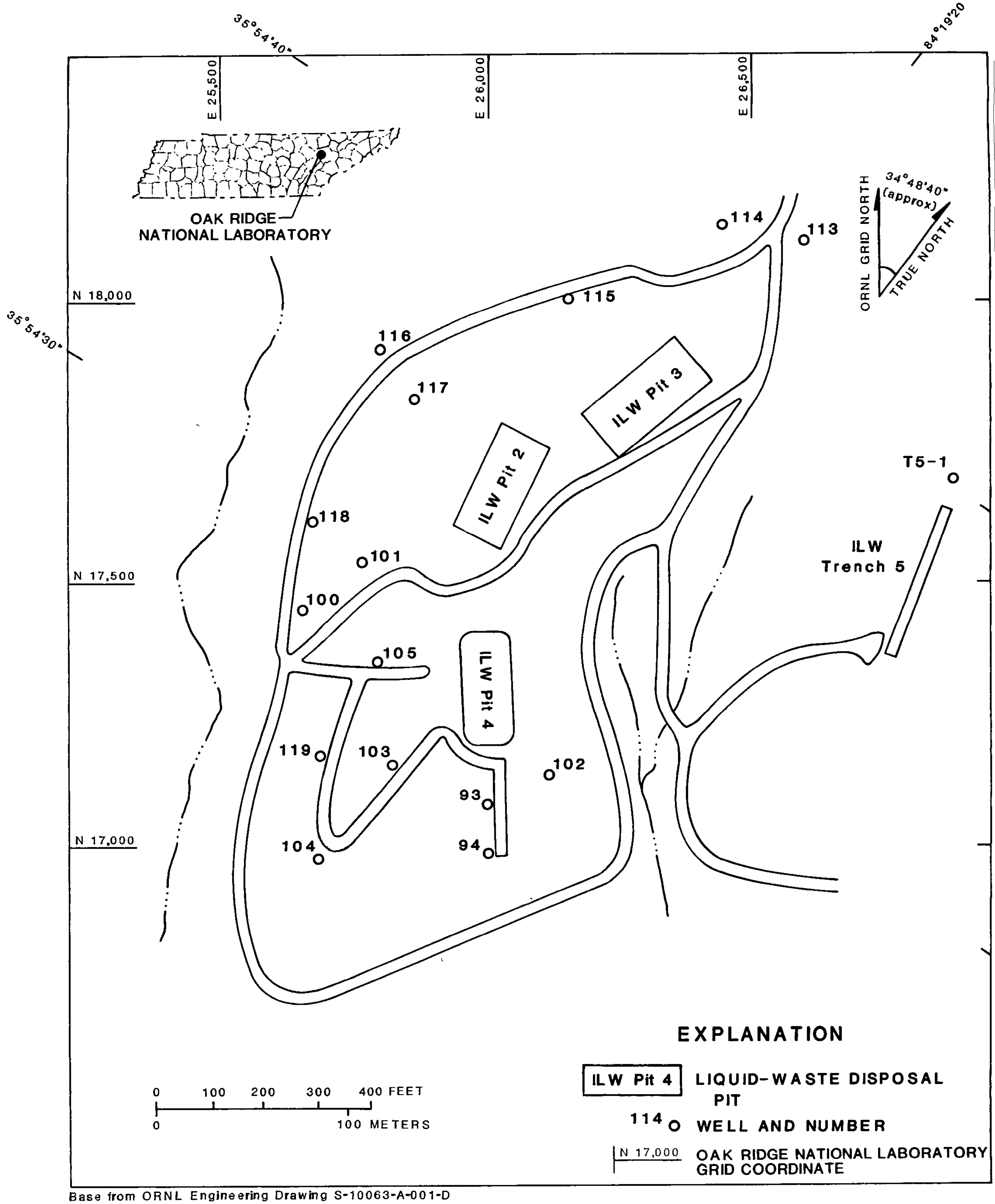


Figure 9.--Locaton of wells open to bedrock in the vicinity of intermediate-level liquid-waste (ILW) disposal pits 2, 3, 4, and ILW trench 5.

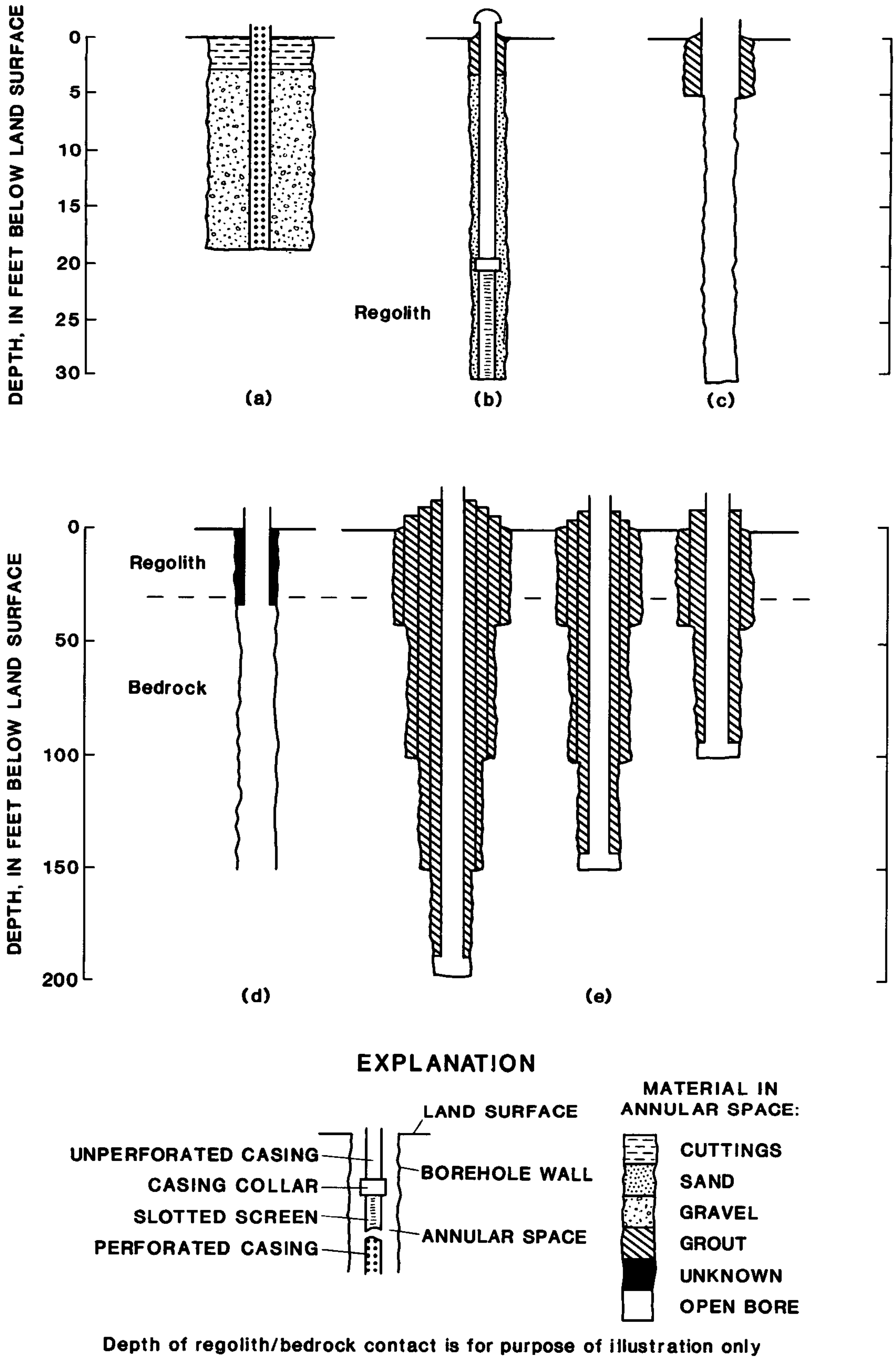


Figure 10.--Construction diagrams of typical wells finished in the regolith (a, b, c) and bedrock (d, e).

conductivity were computed after matching a curve based on the recovery data to a family of type curves. Because the approach falls short of measuring actual transmissivity or actual hydraulic conductivity of the aquifer for several reasons, subsequent references to these terms are as "apparent transmissivities" and "apparent hydraulic conductivities."[2] In the tables that give the results, not all wells at each site are included. Some wells were not tested, some yielded data that could not be matched to the family of type curves, and the tests at a few wells were abandoned because the water-level recovery time was excessively long.

Ground-water tracer tests were successfully completed in two areas to test the thesis that weathering and jointing have sufficiently reduced the integrity of the regolith near the water table to permit the flow of water across the beds. This is in contrast to the concept of fluid movement that was developed by studies of the Conasauga Group during the 1950's and 1960's. Those studies concluded that most flow occurs in a direction parallel to formation strike, indicating that partings, faults and other small openings between beds provide relatively greater permeability than joints or fractures that cross the beds. The conclusions may be applicable to bedrock, but for reasons considered in the next section, their projection to fluid flow in the regolith should be made with care.

Relatively little was done during this investigation to obtain water-quality data of wells terminating in the regolith. This is in view of the Laboratory's program of sampling those wells, well construction characteristics that may adversely influence the analytical results, and unresolved issues about the shipment of potentially contaminated samples off-site to the Geological Survey's laboratory for analyses.

CONCEPTUAL MODEL OF FLOW: THE REGOLITH

The conceptual model of flow is based largely upon observation of the regolith's physical characteristics, the results of tracer tests performed as part of this study and those of other studies, investigations of fluid movement in the ILW-disposal area, and geophysical logs of wells.

Much of the bedding observed in trench walls in burial grounds 5 and 6 consists of deformed beds of rock fragments and clay. Much of the detritus observed from the construction of shallow wells in burial grounds 4 and 5 also consists of similar material. To the extent that the

[2]The reasons for a divergence in values are given here for the benefit of the reader who is considering similar tests in his work. Site conditions do not conform to the analytical assumptions of a homogeneous isotropic artesian aquifer confined above and below by impermeable strata having uniform thickness, and screened (or open) throughout its thickness; the water level at time zero of each test (which can not be measured unless transducers are placed in the well) was estimated by projecting to time zero a rate of change based upon subsequent water levels, rather than calculated by determining the volume of the cylinder withdrawn (for these wells the latter provides erroneous values because of irregularities in borehole diameter, the interception of solution channels by some wells, bridging of sand packs in the annular space of the smaller diameter wells, and unknown borehole diameter of some of the older wells containing gravel packs); the area of influence of each test is small and may be atypical of a more representative section of the aquifer; the data may be prejudiced if the section above or below the open zone in the well is anisotropic with regard to that of the open zone; and the amount of water-level change relative to the height of the water column can be substantial and, therefore, the constantly changing saturated thickness of the aquifer tested may influence the test results. Despite these shortcomings, the consistency in application of the method permits comparison of hydraulic conductivities among geologic units.

decomposition of beds persists below the water table, it would be reasonable to expect that ground water flows between the fragments wherever a hydraulic gradient exists across the beds. This would indicate that the water-table gradient is the dominant factor controlling the direction of flow, rather than the orientation of openings between the beds.

To test the concept of flow as proposed, ground-water tracer tests were conducted on the hillside north of burial ground 4 and at the foot of a hillock in burial ground 6. They are in areas that we now understand to be underlain by the lower Pumpkin Valley Shale and the lower Nolichucky Shale, respectively, although the shale at the latter site has a substantial carbonate component. At each site an array of eight shallow wells were constructed to permit the examination of flow parallel to strike versus flow normal to the water-table gradient in the weathered material. Tritiated water was used as the tracer at each of the arrays.

Analyses of samples from the observation wells at the site near burial ground 4 showed that the largest concentration of tracer moved across the beds in the direction of the water-table gradient. A secondary intermittent pulse of tracer was found in a well adjacent to one of the end wells, and the pulses correlated with occurrence of precipitation. In time, tracer was found in all of the observation wells. The results demonstrate that the beds in the regolith at that location are sufficiently weathered and jointed to permit passage of water across them. Yet the fractures and partings between beds also provide pathways for the flow of water, and during storm events, new heads and gradients are imparted to drive fluid between the beds as well as across them.

Analyses of samples from the observation wells at burial ground 6 also revealed that the largest concentration of tracer moved across the beds in the direction of the water-table gradient. Again, in time, tracer was found in all of the observation wells, although relatively little was found in one well adjacent to that in which the greatest amount was found, indicating an impediment to flow at that point and demonstrating the anisotropy of the media. The finding of the largest concentrations of tracer at both sites in the well that parallels the water-table gradient and lies normal to the injection well (and formation strike) confirms the test hypothesis that the integrity of the regolith has been reduced by weathering and jointing to permit the flow of water across the beds, and within the area involved, the water-table gradient rather than bedding orientation exerts primary control on the direction of fluid movement.

Somewhat different results were reported by Vaughn and others (1982, p. 53-58) for a small demonstration area in burial ground 6. The site is near the contact of the Maryville Limestone and Nolichucky Shale. Using an homologous series of chlorofluorocarbons as a tracer, they found that the wells that lie generally parallel to the direction of strike from the injection well received the highest concentrations of tracer. They theorized that relatively rapid fracture-type flow occurred between the injection well and the observation wells, basing this conclusion on an attenuated arrival pattern of the tracer, an oval-shaped drawdown pattern upon subsequent pumping of one of the observation wells, a finding of two anticlines in the subsurface upon later excavation of a block of nine short trenches, and projection to this area of a strike-joint set that is associated with the Pumpkin Valley Shale (Sledz and Huff, 1981). They also suggested that some of the tracer traveled to the observation wells by intergranular flow, thus accounting for the attenuated pattern of arrival. Their work demonstrated that in this area the direction of flow is still strongly influenced by gradients within the underlying structural features, rather than the apparent water-table gradient as defined by water-level measurements in wells of that area.

The work of Olsen and others (1983) at ILW trench 7 also provides insight into the complexity of fluid movement in the Conasauga Group. They did not introduce tracers into wells, but studied the transport pathway of certain radionuclides in liquid wastes that were discharged to trench 7. A portion of the fluid later appeared in a seepage about 200 feet to the east; thus, in this area the waste fluid itself served as a tracer. Their field work revealed that the area between the trench and the seep (and probably beyond) is underlain by an east-west trending anticline that is bordered to both the north and south by fault zones. Analyses of water samples from several wells and examination of gamma logs of those wells led them to conclude that the fault zones represent significant pathways for the transport of radionuclides. They also concluded from the differences in water levels in wells across the fault zones, and the chemical constituents in water from wells in the fault zones, that there was little or no fluid movement across the anticline. Hence, this study also shows that fluid flow in some parts of the lower regolith is strongly influenced by structural elements and gradients within them.

Gamma logs of wells in this area provide additional detail about fluid flow. Those of wells drilled a decade ago to a depth of about 30 feet (approximately present water-table depth; the depth to the water table at these points during the time of trench operation is not known, but likely would have been somewhat less) encountered only low levels of radioactivity, but those of wells drilled more recently into the lower regolith or upper bedrock to a depth of about 50 feet encountered activity levels in the range of 10,000 to 20,000 counts per second. The logs have a serrated-like profile, indicating passage of a highly contaminated fluid between discrete beds rather than through the pores of a highly-weathered, granular-type medium.

The evidence from the numerous studies of the Melton Valley waste-disposal areas indicates that the saturated interval of the regolith has the flow characteristics of a porous medium in some areas, whereas in other areas it has some of the flow characteristics associated with a fractured-rock medium. This reflects the variable lithology, differing degrees of weathering in both the lateral and vertical directions, and structural complexity of the media.

Through much of the waste-disposal area, the beds at the top of the saturated interval have been reduced to heterogeneously-sized particles. With a porous medium of this type, fluids can move in any direction through the openings between the particles. The actual direction of flow is governed by the water-table gradient regardless of that gradient's orientation to the bedding.

In some places the beds at water-table depth, even when the water table is at its seasonal high, are only partly decomposed and have a low density of open joints or fractures. The beds thus become partial barriers to flow across them. Partings, which have developed along slippage planes between beds and which tend to be linear, provide the principal pathways for flow. The direction of flow is governed by the gradient within these openings, and may differ from that of the inferred water-table gradient based on contours of water-level data from wells spaced a few hundred feet apart. The actual flow paths could appear stair step, having segments oriented parallel to both the bedding and to openings that cross the beds, somewhat similar to that which might be expected in a fractured-rock medium.

Porous-media type flow may be characteristic of the entire column of saturated regolith underlying some areas. This probably is true of areas having an abrupt transition from regolith to bedrock. In other areas, fracture-type flow may increase in relative importance in the lower regolith as the completeness of weathering decreases, particularly as the water table undergoes its seasonal decline. There probably is a mixture of porous-media flow and fractured-rock flow in the interbeds of weathered shale and relatively unweathered limestone at the base of the regolith. Additional complications are introduced by faults which, as noted previously, may serve either as barriers to or conduits for flow, and by waste-filled trenches that penetrate the water table. The latter permit water to pass with some facility across beds that may have been partial barriers to flow. The resulting pathways of flow through the saturated regolith can vary from fairly direct to extremely tortuous.

To provide a generalized conceptualization of flow through media of this diversity, it may be helpful to portray flow direction as having two vector components and a resultant.

In areas that are void of unweathered beds or structural features that distort the flow pattern, a composite picture of flow through the regolith as suggested herein would show:

- A zone at and immediately below the water table where the largest vector of flow trends in the same direction as the inferred water-table gradient, especially during winter and spring when the depth to water is least. There also may be a small vector oriented parallel to the bedding. The relatively small angle between the resultant (the net direction of flow) and that gradient reflects the anisotropy of the medium.

- In some areas, an underlying transitional zone grading rapidly into bedrock where both inferred water-table gradient and bedding vectors have significant magnitude relative to each other. As the water table declines, the magnitude of the bedding vector relative to the gradient vector may increase. The resultant (the net direction of flow) may differ substantially from the gradient inferred from data of wells. This zone is absent where weathering to bedrock is complete.

In local areas having unweathered beds or certain subsurface structural features that influence the direction of ground-water flow, the largest flow vector follows the orientation of that feature. Such areas in the regolith of Melton Valley are thought to be subordinate in extent to those not having these features, but still represent a significant minority.

Most subsurface conditions that influence the pathways of water movement can not be readily discerned by simple field examination, and it is literally impossible if not impractical to conduct the number of ground-water tracer tests that would be required to characterize flow through numerous small segments of each burial ground. However, the general correspondence of water-table contours to topographic contours implies that the water-table gradient must be the primary control on flow through the upper part of the saturated zone at these sites. While the presence of concealed features that distort flow at indeterminable locations renders prediction of specific flow paths untenable, it appears that generalized, areal flow patterns in the regolith can be predicted by delineating the direction of maximum gradients on water-table contour maps of the disposal sites. On the maps that follow, broad arrows show the general direction of flow from areas of higher potential to those of lower potential, and to the inferred places of discharge. They have been drawn as if the aquifer is isotropic, even though it is apparent that differing degrees of anisotropy exist. Consequently, these flow directions are suggestive of flow patterns, and should be viewed as general rather than specific routes from point of recharge to point of discharge. A disadvantage of the contour maps is that they portray flow in only two dimensions, whereas flow in geologic media actually occurs in three dimensions. The reader should bear in mind that while much of the ground-water flow in the regolith occurs in the two dimensions shown, there is in addition a vertical component of flow in some parts of the disposal sites where the regolith is either supplying water to, or receiving water from, the underlying bedrock.

BURIAL GROUND 4

Ground water occurs under water-table conditions in the regolith of burial ground 4. In many trenches, the water surface stands above the water table after periods of rain, and in some of the trenches containing alpha wastes, water is temporarily confined by the concrete cap over the waste. Water at shallow depth also occurs under confinement, with pressure only slightly greater than atmospheric, in some areas beneath the Whiteoak Creek flood plain.

During winter, the depth to water in wells within the boundary of the disposal site ranges from less than 1 foot to about 5 feet below the present land surface. During fall, it ranges from about 1 to 15 feet below land surface. Minimal depths are found along the southern and southeastern edges of the site, the three drainages that cross the central part of the site, and the low terrace containing wells 196 and 197 (on the east end) which is thought to be part of the original burial-ground surface. Maximum depths are found in wells along the southwest perimeter in the vicinity of the road to the ILW disposal area, and along the east end where a substantial thickness of highly-permeable construction debris that drains rapidly has been dumped over the trenches.

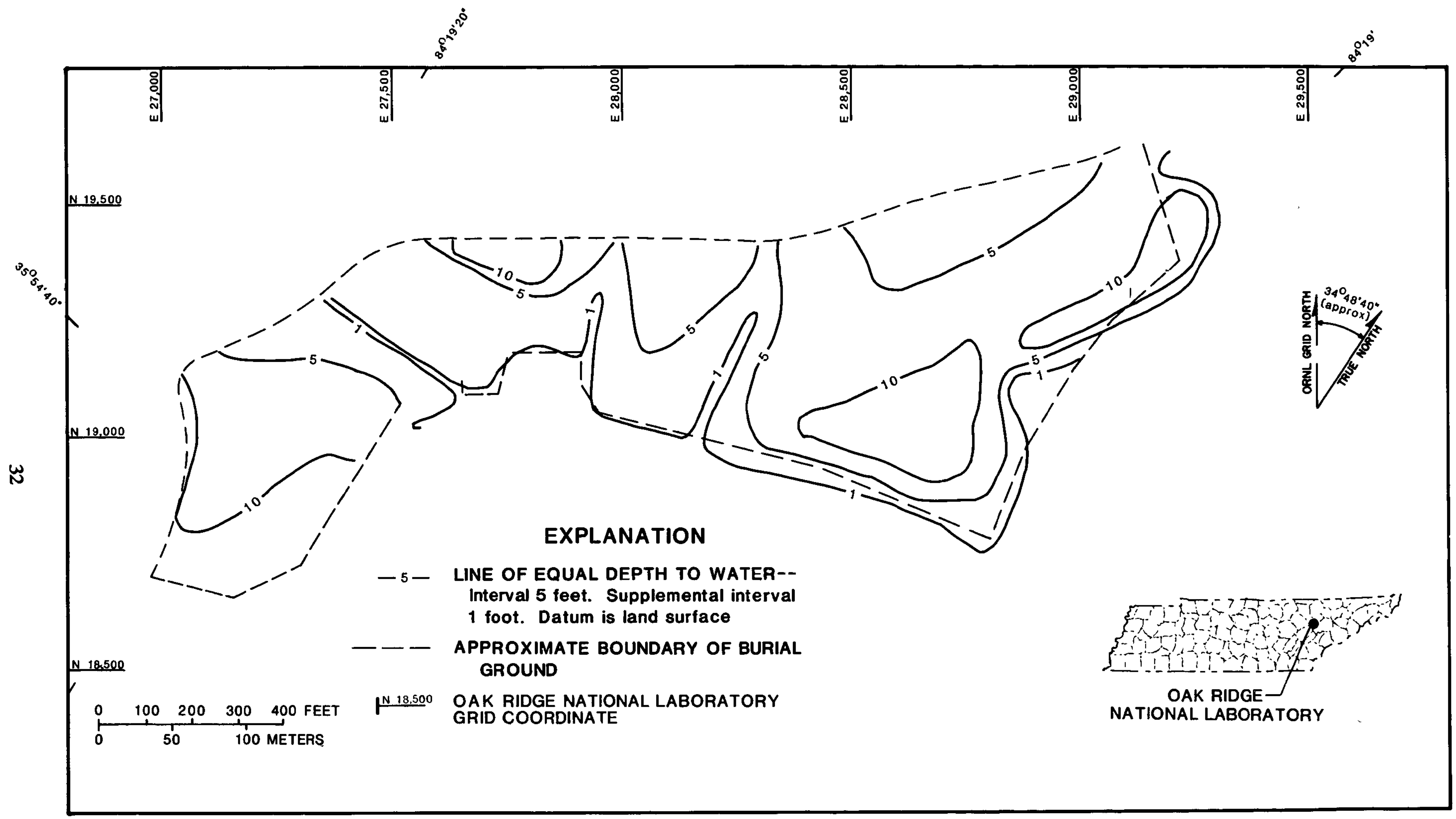
Annual fluctuation of the water surface in wells ranges from less than a foot in wells in the low-lying areas, to as much as 8 to 12 feet in wells near the west perimeter. The range in annual fluctuation in wells through much of the burial ground is 5 feet or less.

The depth to water on June 1, 1978, a time of year that may be considered typical of mid-season conditions, is shown in figure 11. If trench depth is 15 feet, it is apparent that water was present in all trenches in this burial ground on that date. Areas having the greatest thickness of saturated waste during mid-season are in the central and eastern parts of the site. Although the map shows as much as 10 feet of unsaturated material in some parts of the latter area, the waste is below the deposit of fill and therefore fully saturated. Data collected during other seasons indicate that a substantial part of the buried waste is saturated perennially.

Hydrographs of wells at and near the site reflect ground-water conditions of the area (fig. 12). The normal annual recovery and decline of the water table in an undisturbed area on the hillside north of Lagoon Road is shown in the hydrograph of well 188. The softer and in some cases rounded peaks shown on the hydrograph of well 189 indicate receipt of water from nearby trenches and possibly from a lined drainage about 35 feet to the west. Departure from the norm of the well 186A hydrograph suggests that this well either terminates in a trench or is influenced by seepage from a trench close by. Perennially-saturated conditions very close to land surface are reflected in the hydrograph of well 196. Rapid drainage of the deposit of spoils and construction debris on the site's east end is shown by the absence of well-developed peaks in the hydrograph of well 201. The hydrograph also implies that the contact between the highly permeable spoils and the poorly-drained native material occurs close to the water surface in the well.

A low storage capacity of the regolith is indicated by the rapid rise and decline of water levels in undisturbed areas close to the burial ground. A water level rise of 1 foot or more per hour during intense, all-day storms has been found characteristic of the tracer-test wells. In these wells the annular spaces were grouted to a depth of 5 feet and, therefore, the change in water levels is believed to represent actual aquifer response. Water levels in wells in the western part of the burial ground where the depth to water may be 10 feet or more also respond rapidly to substantial rainfall events, but because of the construction characteristics of these wells, it is possible that the rise may be partly due to runoff entering the well rather than entirely to aquifer response.

Results of slug tests made in 14 shallow wells in and near the site are given in table 3. Apparent transmissivities range from 1.4×10^{-1} to 1.2×10^{1} ft^2/day; apparent hydraulic conductivities range from 1.0 x 10-2 to 9.4 x 10-1 ft/day.



Base from ORNL Engineering Drawing LR 58754

Figure 11.--Depth to water table at burial ground 4, June 1, 1978.

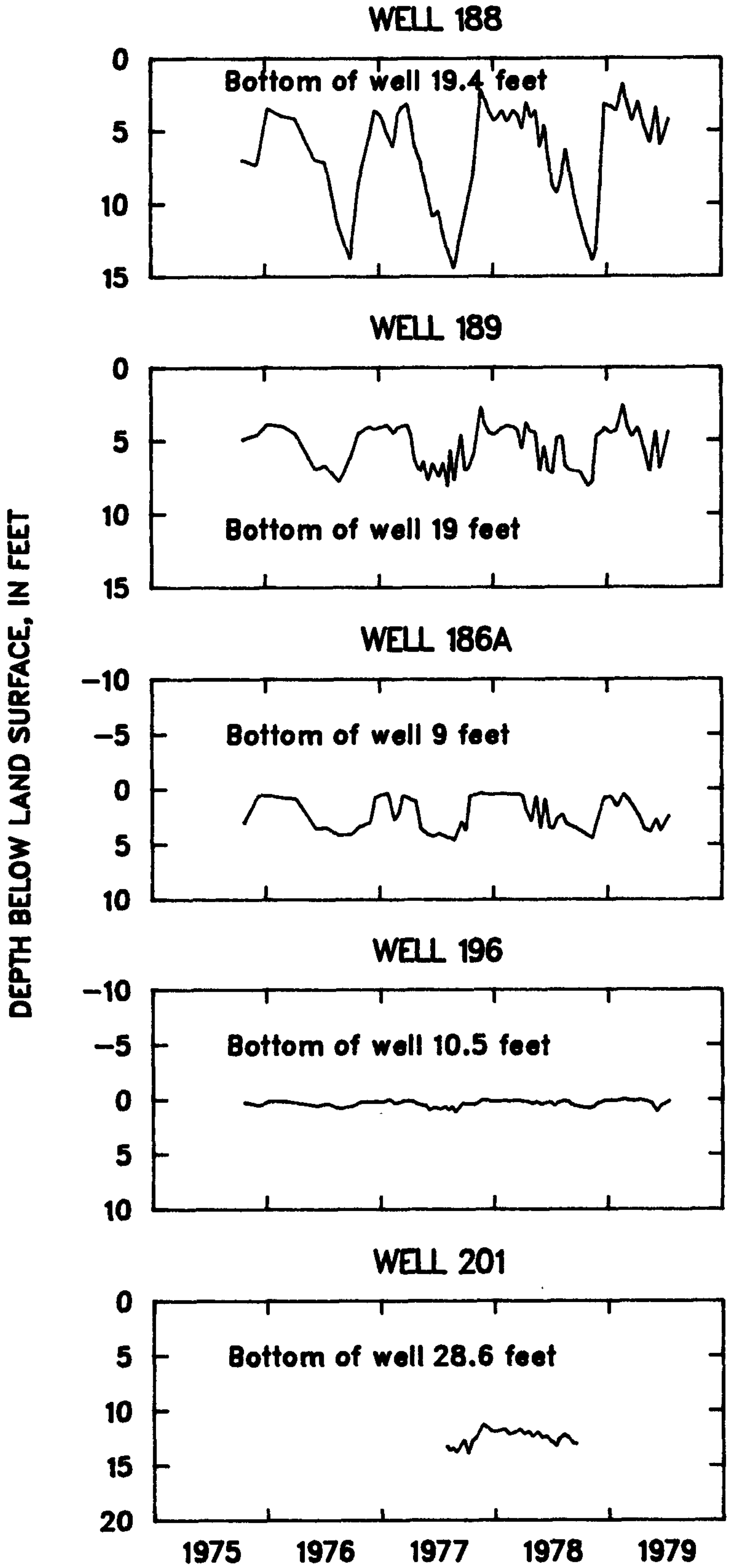


Figure 12.--Hydrographs of five wells illustrating ground-water conditions at burial ground 4.

Table 3.--*Aquifer-test data of wells completed in the regolith at and near burial ground 4*

[Formation: Crt, Rutledge Limestone; Cpvu, Pumpkin Valley Shale, upper member; Cpvl, Pumpkin Valley Shale, lower mumber; Queried (?), indefinite. Well is assigned to first formation designated for purposes of figure 19]

Well No.	Formation	Apparent transmissivity (ft^2/d)	Apparent hydraulic conductivity (ft/d)
4-4	Cpvl	2.3×10^{-1}	1.2×10^{-2}
4-5	Cpvl	3.6×10^{-1}	2.0×10^{-2}
4-6	Cpvl	4.5×10^{-1}	2.3×10^{-2}
4-7	Cpvl	5.7×10^{-1}	3.4×10^{-2}
4-8	Cpvl	2.5×10^{-1}	1.0×10^{-2}
4-9	Cpvl	5.2×10^{-1}	2.5×10^{-2}
4-10	Cpvl	7.4×10^{-1}	4.0×10^{-2}
4-11	Cpvl	1.4×10^{-1}	1.6×10^{-2}
192	Cpvl/Crt (?)	1.2×10^{-1}	9.4×10^{1}
203	Cpvu	2.9×10^{-1}	1.8×10^{-2}
531	Cpvu	2.2×10^{-1}	1.7×10^{-2}
533	Cpvu	6.1 x 10-1	2.4×10^{-2}
534	Cpvu/Crt (?)	5.4	5.0×10^{-1}
536	Cpvu	8.0×10^{-1}	3.9×10^{-2}

To compare the aquifer's ability to transmit water in different geologic units, the hydraulic conductivities of the wells may be compared. Eight of the wells (4-4 through 4-11) are located within a 12-foot radius of each other on the hillside north of the site. Wells in this area and possibly well 192 were augered into the lower member (siltstone) of the Pumpkin Valley Shale that underlies the northeast sector of the disposal site. The other wells were augered into the upper member (mudstone/shale) that underlies the central part of the site. No wells in the southwestern sector, underlain by the Rutledge Limestone, were suitable for testing, but tests were made of a few wells in this formation in the TRU area of burial ground 5. The data do not show any substantial difference in hydraulic conductivity between the upper and lower members of the Pumpkin Valley Shale.

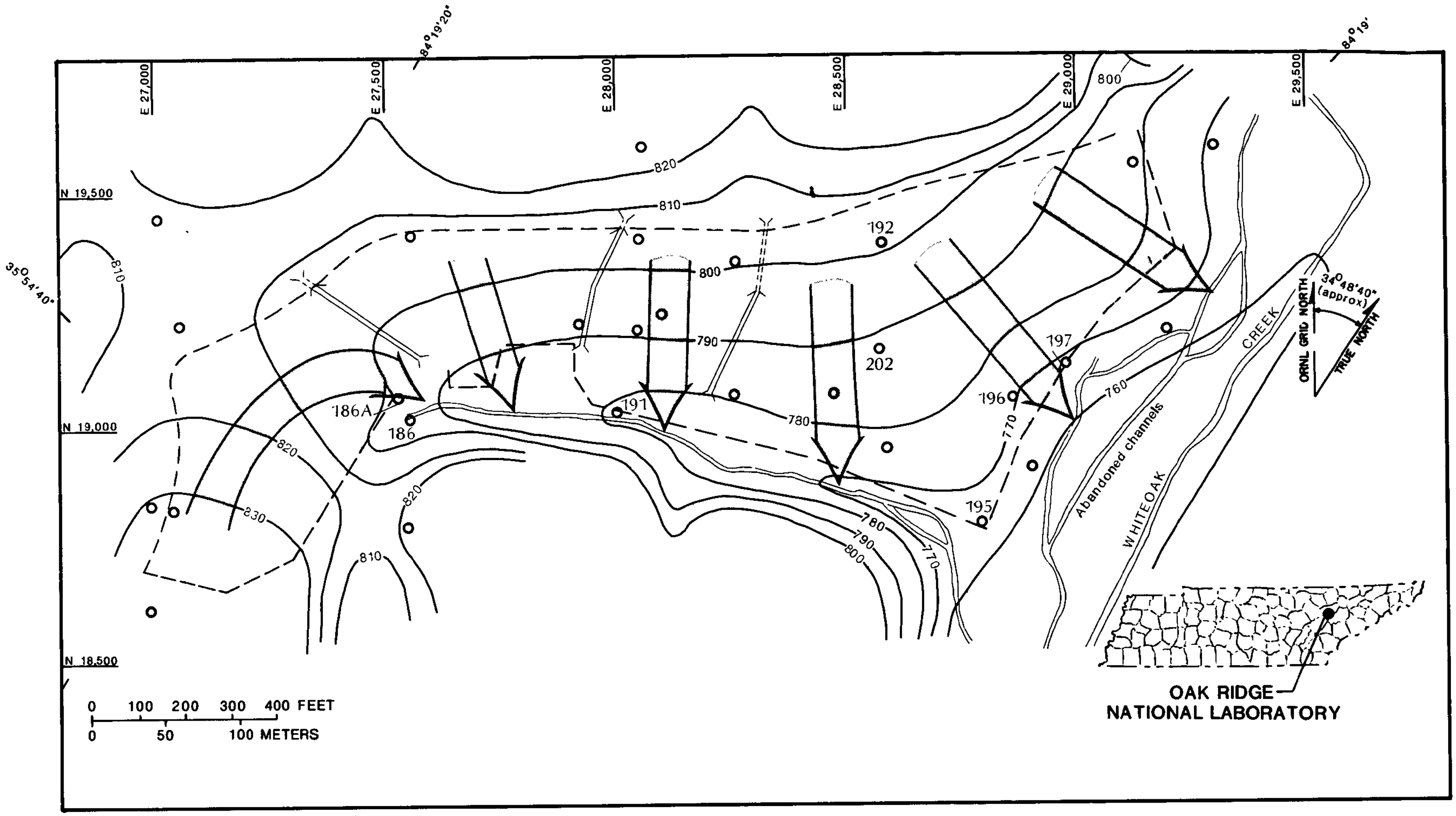
The ground-water reservoir below the burial ground is recharged by precipitation falling directly upon the site, runoff from Haw Ridge, and ground water flowing to the area from both Haw Ridge and the spiny ridge to the southwest.

The water-table contour map (fig. 13) indicates that ground-water below the site flows generally to the southeast and east, towards the south-boundary drainage and Whiteoak Creek. In the westernmost sector, the direction of flow changes sharply from north to southeast as water moves down-gradient to the drainage. Where the gradient crosses trenches, a large component of flow may be from one trench to another in the direction of the gradient.

Discharge from the aquifer is to the Whiteoak Creek drainage network. It is possible that a very small amount of ground water below the western perimeter of the site may discharge to a Whiteoak Creek tributary west of the ILW area. Ground water in the eastern third of the site, on a line from approximately well 192 to well 195, discharges to the abandoned channels of Whiteoak Creek and possibly to the relocated main channel; water below the rest of the site discharges to the tributary along the south boundary. Discharge from the west half of the site occurs between wells 186 and 191. This area also is the terminus for two of the three surface drainages; the third drainage terminates a short distance east of well 191. Thus, this short stream interval receives a disproportionately large amount of the ground-water and surface-water discharge from the site and the upland area to the northwest. The map also suggests that discharge from part of the eastern quarter is focused on the terrace containing wells 196 and 197. This appears to be borne out by the nearly perennially wet, swampy area in the vicinity of well 196. It is likely that the sharp decrease in permeability along the contact between the fill and the regolith contributes to the discharge of water in this area.

Historically, several trenches have filled with water and overflowed at their low-end as "seeps" as this type of discharge is termed in the ORNL literature. The most common location of seeps has been in the vicinity of the three drainages that cross the site, the low terrace on the eastern end, and the slope to the west of well 186A. Occasionally, trenches in the general area between well 192 and 202 also have overflowed. After the three drainages crossing the site were lined in 1975, discharge from the trenches in that area was reduced substantially, but at least one new seep developed south of the point where the pavement terminated.

At least a few historic studies (Lomenick and Cowser, 1961; Gera, unpublished manuscript, circa 1964; Duguid, 1975, 1976) have shown that the discharge from seeps transports radionuclides originally buried in trenches. More recently, Huff and others (1982, p. 60-61) found that the highest concentrations of strontium-90 in the ground and surface waters of this site were in the area between the outfalls of the three lined drainages and the adjacent stream interval, and Huff and Farrow (1983, p. 84) found by analyzing cores of soil and regolith in this area that the highest concentrations of radioactivity are at land surface and decrease rapidly as depth increases. They concluded that trench overflow is the major mode of transport beyond this part of the burial ground, followed by overland transport to the south-side tributary. The relatively small discharge of water from seeps thus can



Base from ORNL Engineering Drawing 58754

EXPLANATION

—760— WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval 10 feet. Datum is sea level.

GENERAL DIRECTION OF GROUND-WATER FLOW IN REGOLITH

WELL--Selected wells identified by number

APPROXIMATE SITE BOUNDARY

DRAINAGE--Asphalt-lined

CULVERT

N 19,500 OAK RIDGE NATIONAL LABORATORY GRID COORDINATE represent as significant a transport mechanism for radionuclides as the larger discharge to the drainage system from the ground-water reservoir.

The low hydraulic conductivity values of wells in the regolith of the Pumpkin Valley indicate that flow velocity in that medium is low unless the slope of the water-table becomes quite steep. An approximate velocity for the mid-section of burial ground 4 can be derived using the equation

$$V = \frac{Kdh}{ndl}, \qquad (1)$$

where

V = average linear velocity,
n = effective porosity,
K = hydraulic conductivity, and
dh/dl = hydraulic gradient.

For this purpose, K is taken as 0.060 ft/day (the geometric mean of the K values of 7 wells, taking the mean of the 8 tracer wells, 0.020 ft/day, as a single well so as not to give that area disproportionate weight); n as 0.017, calculated from the tracer test results; and dh/dl as 0.068, the gradient through the central part of the burial ground during mid-season. Calculated velocity then is about 0.24 foot per day. (For comparison, average velocity of the tracer, measured from the time of injection to the first peak in concentration, was 0.18 foot per day. Low concentrations of tracer also moved through fractures at a rate approaching 1 foot per day.) Thus, the time required for a particle of water to flow from Lagoon Road (fig. 6), entirely through undisturbed regolith underlying the site, to the south-tributary drainage may be in the order of 5 years. Actual velocity could be faster because of the slightly higher gradient during winter and the possibility of flow through fractures or other continuous pathways that have a hydraulic conductivity higher than average. Where flow through trenches results in spillage and subsequent overland flow, velocity can be many times more rapid than in ground water.

Although the full impact of the French drain constructed in 1983 along the northwest side of Lagoon Road is yet to be determined, one effect could be to decrease the average velocity of ground-water flow. Melroy and Huff (1985, p. 26) estimated that 141,000 m^3 of water, or 66 percent of flow from the hillside northwest of the site, was diverted by the drain during calendar year 1984. Over a period of time, the water table may respond to this continued stress by dropping in elevation on the south side of Lagoon Road, thereby decreasing its gradient across the burial ground. With less driving force, ground water would traverse the site at a slower speed.

BURIAL GROUND 5

Ground water occurs in the regolith below burial ground 5 under unconfined, semiconfined, locally confined, and perched conditions. In most parts of the site, ground water is either unconfined, or confined under pressure only slightly greater than atmospheric where a bed of relatively unweathered rock locally excludes ground water. Hydrostatic pressures in these beds are insufficient to cause flow at land surface. One well (well 446), however, was augered into a small solution cavity, whereupon the well flowed for several minutes. This is the only shallow well in the burial ground that had sufficient pressure to cause flow.

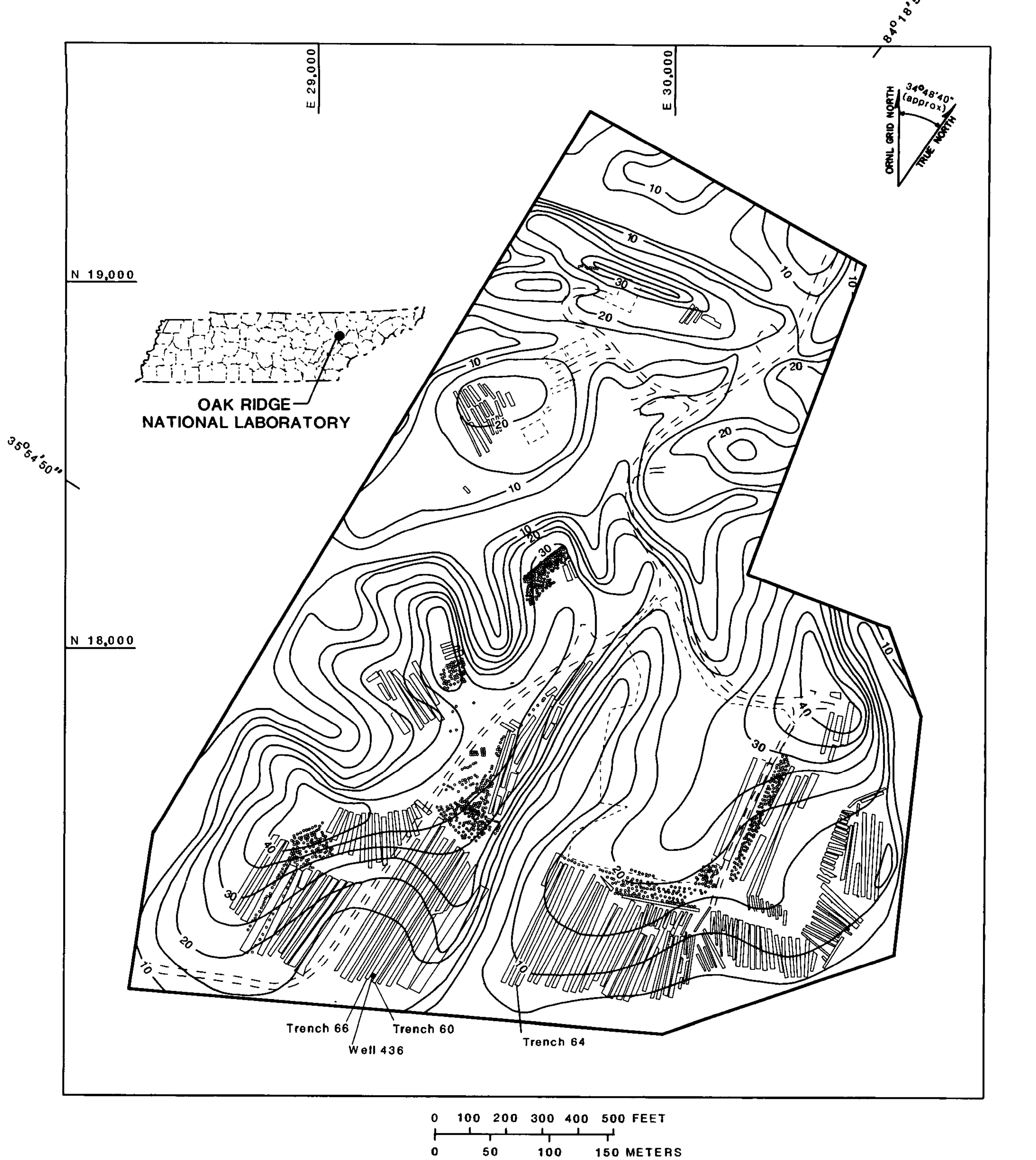
Occasionally, shallow bodies of perched water occur where infiltrate is ponded on local remnants of unweathered rock. Such remnants have been structurally warped into local basins that catch and hold fluids. The current investigation found no areas of naturally perched water, but Cowser and others (1961, p. 10) reported water perched intermittently near three of the shallow wells constructed for their investigation. Trenches above the water table also contain perched water intermittently. The latter is an unnatural occurrence resulting from the relatively greater permeability of the earthen covers over the trenches than that of the regolith in which the trenches have been excavated.

The depth to the water table ranges from less than 1 foot to about 50 feet below land surface, and is related to both topographic location and season. The shallowest depths are found near the drainages; the greatest depths are found near the summits and ridges. At any location minimum depth usually occurs in winter and early spring. Water-table depth gradually increases to reach a seasonal maximum in late fall.

The range in annual fluctuation of the water surface in wells varies from less than 1 foot to a maximum of about 14 feet. Wells having minimal fluctuations usually are located near the drainages; those having maximum fluctuations generally are located in the upland areas of the site. Several exceptions to these generalizations show that topographic location is only one of several factors contributing to the magnitude of fluctuation.

The depth to the water table on July 14, 1983, superimposed upon a map of trench and auger-hole locations, is shown in figure 14. At that time of year water levels in most wells had receded slightly beyond their midpoint in annual fluctuation. The depth to water is 15 feet or less from land surface throughout a sizeable part of the southern and eastern areas of the disposal site. This is considered a critical depth because it is the reported maximum potential depth of trench excavation during the development of this site. (The maximum depth that holes were augered is reported to be 18 feet.) Trenches that are deeper than the depths shown by contours penetrate the water table, and typically during mid-summer have a column of water in them that is approximately equal in height to the difference between trench depth and contour value. Waste in them is buried in water to this level. In contrast, the depth to water at the highest points of the burial ground, which is where the wastes with the highest activity levels generally have been buried, was about 40 feet at that time. Assuming trench depths of 15 feet, these wastes rested about 25 feet above the water table on that date.

Minimum depth in winter varies from less than 1 foot at wells that are in low-lying areas to about 35 feet for wells situated in the highest parts of the burial ground. The 15-, 10-, 5-, and 1-foot depth contours for early winter correspond approximately to the location of the 20-, 15-, 10-, and 5-foot depth contours, respectively, of mid-summer. It becomes apparent that waste buried in trenches in the southern and eastern parts of the site is saturated during much of the year. In some of the lowest-lying areas, waste is saturated perennially.



EXPLANATION

—15—	LINE OF EQUAL DEPTH TO WATER--Interval 5 feet. Datum is land surface		BELOW GRADE, WASTE-STORAGE STRUCTURE--TRU area only
	TRENCH WITH RADIOACTIVE WASTE-- Selected trenches identified by number	= = =	ROAD
			SITE BOUNDARY
	AUGER HOLES	N 19,000	OAK RIDGE NATIONAL LABORATORY GRID COORDINATE

Figure 14.--Depth to water table at burial ground 5, July 14, 1983, and location of trenches, auger holes, and below grade waste-storage structures.

Conditions of this area are reflected in the hydrographs of the riser pipes, installed to trench depth, in trenches 60 and 64 (fig. 15). Trench 60 is on the south-facing hillside of the west lobe and is about 450 feet long. The hydrograph of the riser pipe in its low end shows that much of the waste in this trench undergoes seasonal saturation and de-watering. Its hydrograph corresponds closely to that of well 436, augered into the septum between trenches 60 and 66. The replication of hydrographs indicates that water in the trench is not just the result of infiltrate that has run down to and accumulated in the low end, but due to the trench's penetration of the water table in this area. The conditions in this trench are thought to be typical of other trenches in the west lobe.

Trench 64 is located on a more gentle slope of the east lobe. It is about 375 feet long, and is at a somewhat lower altitude than trench 60. The hydrograph of the trench 64 riser pipe shows that waste in the lower part of the trench is saturated perennially. Continuous record (not shown) indicates that the water level responds quickly to storms, and with the more substantial rains, the trench fills with water to discharge fluid from its low end. This condition is typical of many of the trenches on the southeast side of the site. Discharge from many of the trenches in this area does not occur as seeps, but as shallow underflow near the contact of the undisturbed material and the thin deposit of permeable spoil placed on the former land surface.

Trenches on the higher ground also collect water during storm events, but none are known to overflow.

The numerous trenches with permeable covers throughout the site function as a network of infiltration galleries. They allow the subsurface to absorb more surface runoff from storm events than would occur under the natural forest conditions. This additional increment of recharge supplied to the ground-water reservoir, plus the reduced rate of transpiration effected by replacing the deep-rooted vegetation with shallow-rooted grasses, has resulted in a net rise of the water table and a decreased depth to water from the original site conditions.

The influence of geologic features upon aquifer characteristics is reflected in the hydrographs of all wells. For example, the normal annual rise and recession of the water table in an undisturbed area of the upland, underlain by limey shale of the lower to middle Maryville Limestone, is typified in the hydrograph of well 455 (fig. 16). Note the serrated character of the record resulting from storm recharge filling the small volume of secondary openings in the aquifer on several occasions, and then quickly draining. This again reflects a low storage capacity of the aquifer. The hydrograph of well 450, augered into the middle Maryville, is smoother, and reflects poor hydraulic connection with the aquifer, that is, the well intercepts very few secondary openings. The slug test of this well was abandoned because of the very slow water-level recovery. The hydrograph of well 438 in the relatively lime-rich upper Maryville also is comparatively smooth, but this well intercepts a greater volume of joints, fractures or other openings that enables this part of the aquifer to assimilate recharge without the rapid rise and decline characteristic of the well 455 area. The hydrograph of well 446, also in the upper Maryville, has a

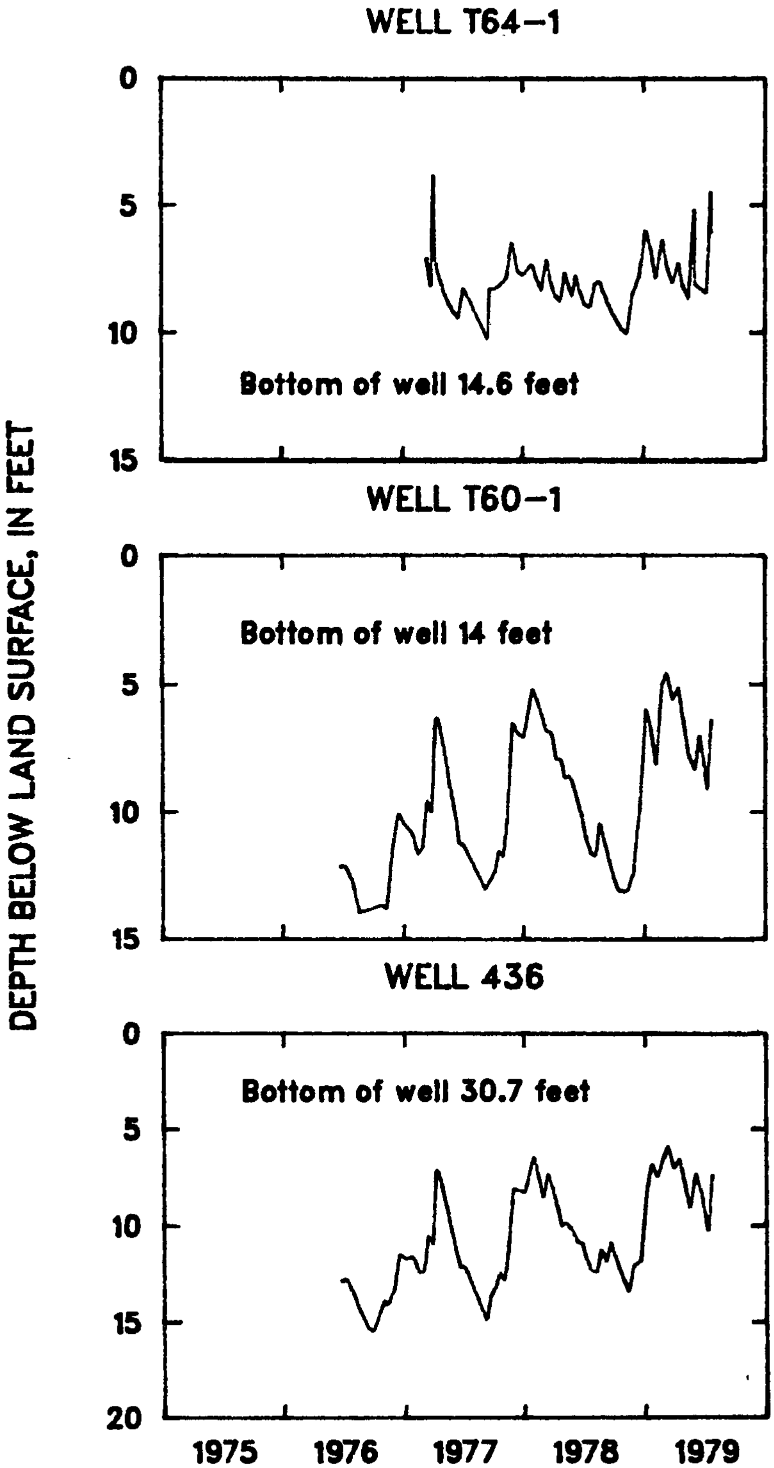


Figure 15.--Hydrographs for well 436 and riser pipes in trenches 60 and 64.

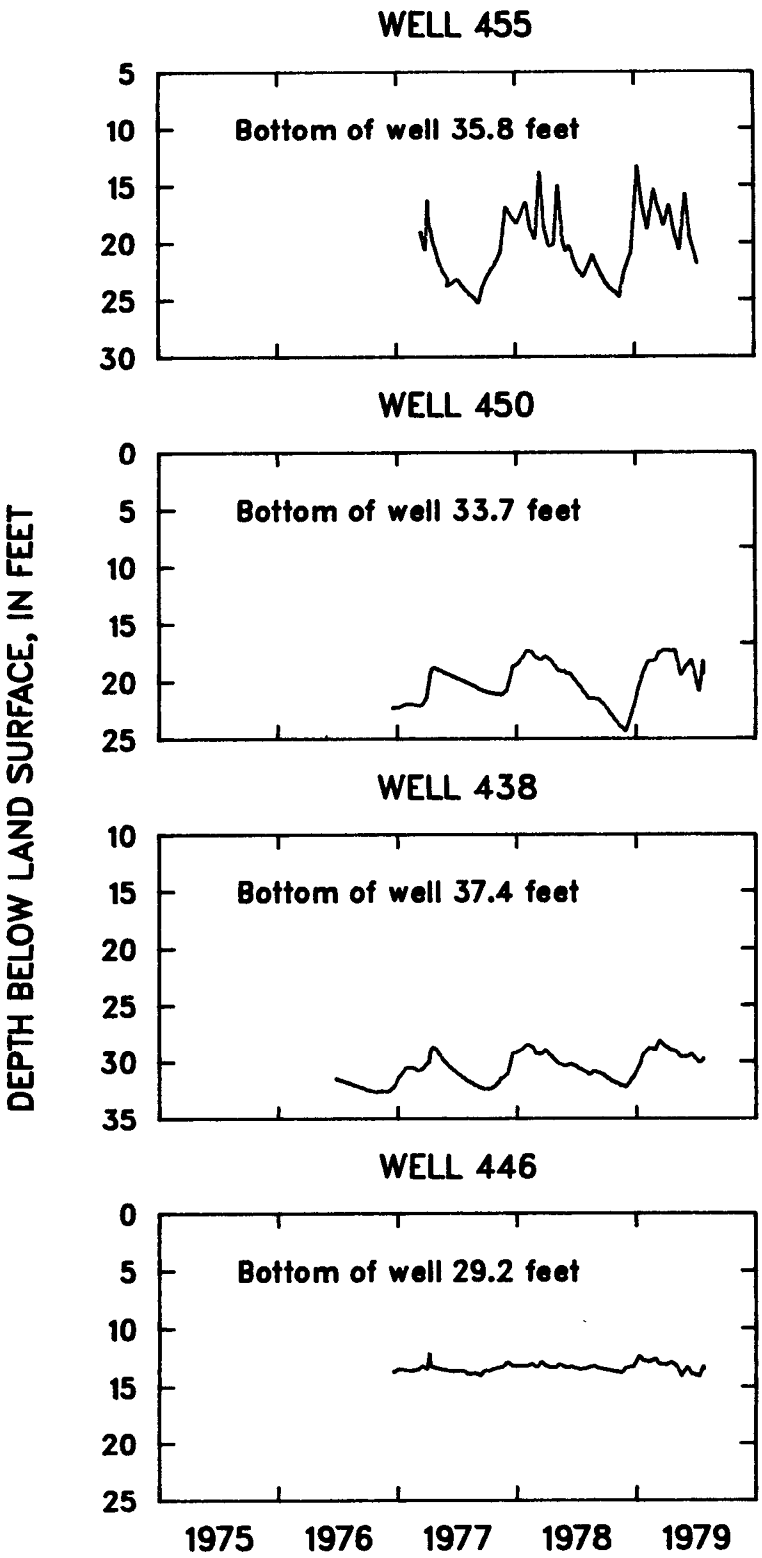


Figure 16.--Hydrographs for four wells illustrating aquifer characteristics at burial ground 5.

different pattern, and reflects the influence of a solution opening with artesian conditions.

Slug tests were completed in 30 shallow wells in the 5-north and 5-south areas. Most of the wells in the 5-north area were augered into the Rutledge Limestone and Rogersville Shale; two of the wells in this area (513 and 526) probably were augered into the lowermost Maryville Limestone. All of the wells in the 5-south area were constructed in the Maryville Limestone, except wells 436 and 464 which were constructed in the Nolichucky Shale.

Results of the tests are given in table 4. Apparent transmissivities range from 7.5 x 10^{-2} to 53.6 ft^2/day. Apparent hydraulic conductivities range from 2.9 x 10^{-3} to 2.5 ft/day. The lowest value is for well 522 (68 feet deep), and is more characteristic of the bedrock than the regolith. The geometric mean of the hydraulic conductivities, excluding that of well 522, is 2.9 x 10^{-1} ft/day. For purpose of comparison, Rothschild and others (1984a, p. 103) reported a geometric mean of 7.28 x 10^{-2} feet per day of 12 wells at proposed burial ground 7, which also spans several formations of the Conasauga, and Davis and others (1984, p. 84) reported a geometric mean of 1.79 x 10^{-1} feet per day of 36 wells in the demonstration area of burial ground 6. In both of these studies, the means included data of wells finished in both the regolith and the bedrock, and the analyses were done by the method of Hvorslev (1951).

Data of the burial ground 5 tests show no apparent relationship between the regolith hydraulic conductivity and the lithotype indicated by formation name. Values for both shale or limestone range from about 10^{-2} to 10^{0} ft/day. This reflects the lithologic impurity of each formation despite its formation name, differences in extent of weathering, and depth of the saturated interval open to each well.

Qualitative judgment is required for estimating the coefficient of storativity (S) because the analytical procedure is insensitive to differences in S. It is suggested that S values for much of the saturated part of the regolith likely fall within the range of 10^{-2} to 10^{-5}. This is based on a match of a majority of the data curves of the slug tests to type curves of this magnitude, and is in general agreement with values found by other investigators (Davis and others, 1984, p. 83-86; Law Engineering Co., written commun., 1983) using both slug tests and other types of analytical approaches.

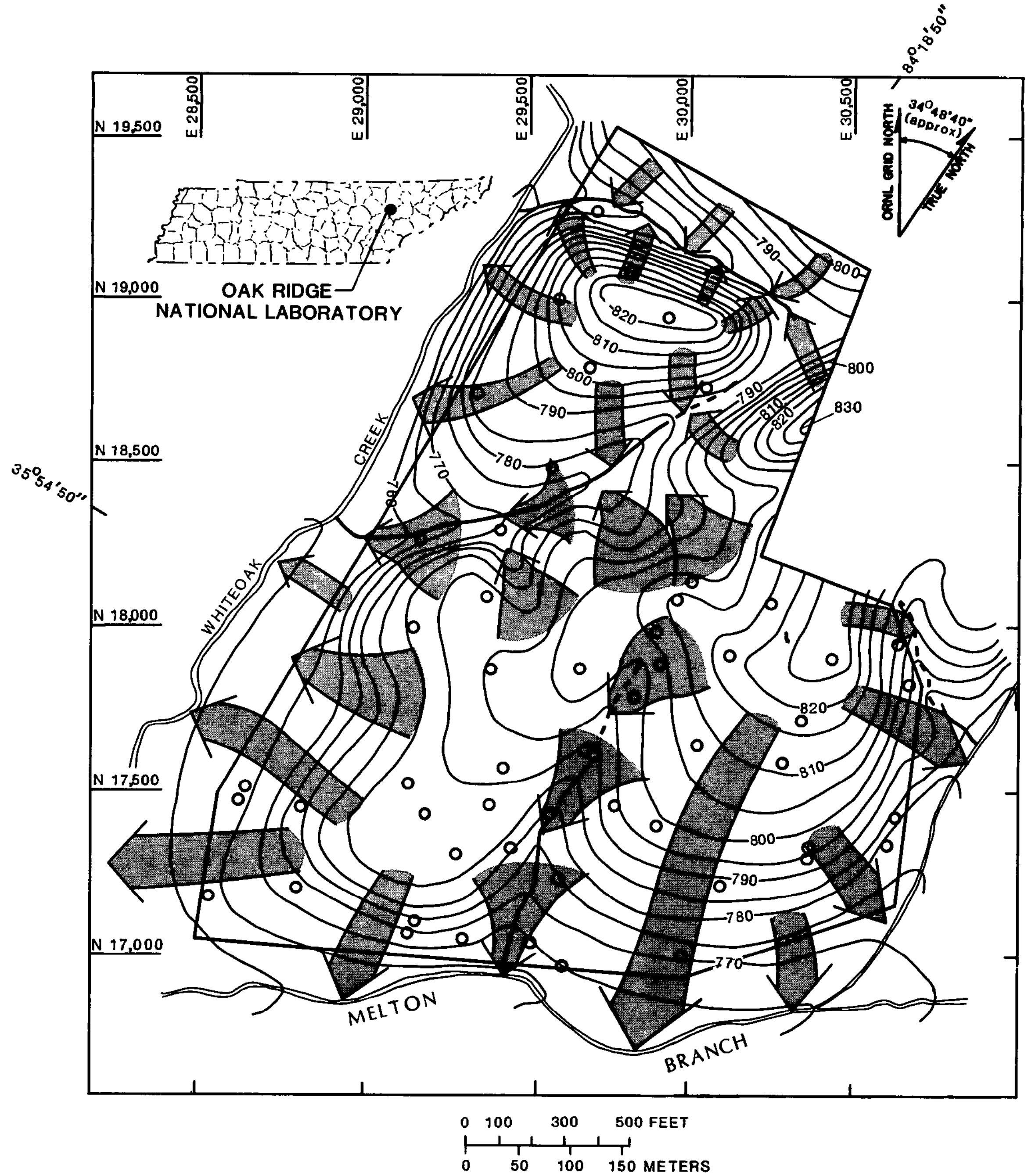
The water-table contour map of burial ground 5 (fig. 17) shows that the site has four primary ground-water recharge areas, and these correspond to the four lobate remnants etched out by the incision of drainages into the landscape: (1) the hill in the TRU area, (2) the hill along the northeast border of the 5-north area, to the east of the TRU waste-storage facilities; (3) the upper half of the east lobe at the 5-south area; and (4) the broad summit and surrounding area of the west lobe at the 5-south area. These areas generally comprise the upper two-thirds of the site.

The direction of flow probably is influenced to some degree by the orientation of the trenches. In the unsaturated zone, infiltration that is intercepted by sloping trenches can be channeled down the length of the trenches.

Table 4.--*Aquifer-test data of wells completed in the regolith at burial ground 5*

[Formation: Crt, Rutledge Limestone; Crg, Rogersville Shale; Cnl, Nolichucky Shale; Cmr, Maryville Limestone. Queried (?) where indefinite. Well is assigned to first formation designated for purposes of figure 19]

Well No.	Formation	Apparent transmissivity (ft^2/d)	Apparent hydraulic conductivity (ft/d)
432	Cmr	1.5×10^{-1}	1.4×10^{-2}
433	Cmr	11.2	1.4
434	Cmr	7.0×10^{-1}	5.8×10^{-2}
435	Cmr	8.3	3.8×10^{-1}
436	Cnl	13.6	5.3×10^{-1}
437	Cmr	1.7	7.1×10^{-2}
438	Cmr	6.4	4.8×10^{-1}
439	Cmr	12.5	5.8×10^{-1}
440	Cmr	9.8×10^{-1}	5.3×10^{-2}
443	Cmr	10.2	3.6×10^{-1}
444	Cmr	9.8	6.6×10^{-1}
445	Cmr	17.3	4.4×10^{-1}
446	Cmr	6.1	3.4×10^{-1}
447	Cmr	20.4	2.1
448	Cmr	53.6	2.4
451	Cmr	35.2	2.0
452	Cmr	38.79	2.5
453	Cmr	8.3×10^{-1}	6.1×10^{-2}
455	Cmr	9.0×10^{-1}	4.5×10^{-2}
464	Cnl	6.7	7.6×10^{-1}
468	Cmr	3.3	4.9×10^{-1}
472	Cmr	2.2	3.3×10^{-1}
513	Cmr	3.3	2.5×10^{-1}
514	Crg/Cmr (?)	1.8	1.6×10^{-1}
517	Crt	3.2×10^{-1}	1.7×10^{-2}
520	Crt/Crg (?)	16.7	7.1×10^{-1}
522	Crt	7.5×10^{-2}	2.9×10^{-3}
525	Crt/Crg (?)	4.3	3.3×10^{-1}
526	Cmr/Crg (?)	2.5	1.2×10^{-1}
527	Crg/Cmr (?)	2.7	1.9×10^{-1}



EXPLANATION

—790— WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval 5 feet. Datum is sea level

o WELL

SITE BOUNDARY

DRAINAGE

GENERAL DIRECTION OF GROUND-WATER FLOW IN REGOLITH

N 19,500 OAK RIDGE NATIONAL LABORATORY GRID COORDINATE

Figure 17.--Water-table contours at burial ground 5 for typical late, mid-season condition, July 14, 1983, and general direction of ground-water flow.

Where trenches penetrate the water table, a particle of water may move through the reservoir in the trench and exit at any point of lower head within the trench. Flow may be from trench to trench where gradients cross trenches such as near the east boundary of the site. In the saturated zone below the trenches, flow occurs down gradient in the general directions indicated by broad arrows (fig. 17). In some areas, flow may be diverted locally to a direction more closely related to strike by gradients within concealed structural features.

From interpretation of the contours, it is inferred that ground water of this site discharges to Whiteoak Creek, Melton Branch, the unnamed tributary near the east boundary, and four drainages within the site. While a quantitative analysis of the map can not be made, there does not appear to be a concentration of discharge into any segment of the drainage as the contour pattern of the burial ground 4 map indicates. Discharge also occurs by trench overflow along the southside of the site. This water reaches Melton Branch either as overland flow or as shallow subsurface flow.

The only area where hydraulic potentials can be extended across the perimeter streams with available data is just west of the TRU waste-storage area into burial ground 4. Elsewhere, the potentials can be projected on the observation that at burial ground 5 and at all other areas studied in this valley, water-table contours generally follow topographic contours. With upland areas to the east, south, and west having higher potentials than that of the regolith around the perimeter of burial ground 5, it can be reasoned that ground water from this disposal site cannot flow under the streams and travel to points beyond, but must discharge into these streams. Thus, these perimeter streams and their tributaries are thought to be the discharge points for ground water in the regolith of this site.

The velocity of flow can be estimated by using equation (1). For this computation, data of the 5-south area only are considered. Using the following values,

K = 0.35 ft/day, representing the geometric mean of the hydraulic conductivities of wells in the 5-south area;

n = 0.03, derived from the ground-water tracer test results in burial ground 6; and

dh/dl = 0.05, the average hydraulic gradient during mid-season, an average velocity of 0.58 foot per day is indicated. If a gradient more typical of winter conditions (0.06) is used in the computation, the velocity increases to 0.69 foot per day. These values are in general agreement with those reported by studies (Davis and others, 1984, p. 77; Lomenick and others, 1967, p. 902) of other areas in Melton Valley underlain by equivalent geologic units. Assuming isotropic conditions and a gradient typical of mid-season, the time required for a particle of water to travel along the longest flow paths from the most distant point of recharge underlying buried waste to point of discharge in Melton Branch would be about 5 to 6 years. Actual travel time probably would be less because of the likelihood of intercepting fractures or other relatively highly-permeable zones en route, and the increased hydraulic gradient of winter. Since all other flow paths are of shorter distance, water traveling along them would discharge to the drainage system in some shorter period of time.

BURIAL GROUND 6

Ground water occurs under unconfined, semi-confined, and perched conditions in burial ground 6. Unconfined and semi-confined conditions are found throughout the site. Perched conditions have been found below the hill in the southwest corner of the site, below the hill along the southeast boundary, and occasionally in new trenches. It is likely that perched water also occurs temporarily in many of the closed trenches that are above the water table.

The depth to the water table is related to topographic location and season, as it is in burial ground 5. In winter, the depth ranges from essentially land surface along the drainages within the site to about 45 feet below the summit of the hill in the southwest corner. In fall, the range is about 1 to 2 feet to nearly 60 feet at these same locations.

Perched water occurs at shallower depths. Water is found in some of the shallow wells on the hill in the southwest corner of the site at as little as 5 feet depth after storms, and locally (well 351) at as little as 10 feet depth below the hill near the southeast boundary. Water commonly is perched above the water table in some of the trenches about 5 to 6 feet deep that contain compacted waste, located between wells 343 and 355. Water also has been reported perched in several of the trenches in the 49-trench area (in the vicinity of wells 107 and 317; Arora and others, 1981, p. 20-25), although the liquid in many of these trenches could result from a seasonal rise of the water table.

The depth to the water table on May 31, 1978, a date typical of mid-season conditions, is shown in figure 18. Depth at that time of year is 15 feet or less through as much as half of the area within the burial ground. Wastes have been buried in this zone, but most of the trenches have been cut to depths of less than 15 feet. Some trenches in this area, however, are known to penetrate the water table seasonally, if not perennially. Most trenches between the 5-foot and 10-foot contours contain animal tissue having very low levels of radiation. Trenches with this category of waste are shorter, narrower, and shallower than those containing other forms of contaminated waste. Wastes with elevated levels of activity have been buried in the topographically higher areas of the site. These wastes rest in trenches generally about 10 to 35 feet above the water table.

Water levels in wells fluctuate from less than 1 foot to perhaps as much as 20 feet annually. Minimal fluctuations are associated with the wells near drainages; maximum fluctuations are associated with the wells on the hill in the northwest corner of the site. In the latter area this range includes perched water. Actual fluctuation of the water table below the higher areas of this hill is about 10 to 12 feet annually, and is the maximum water-table fluctuation for the site.

Hydrographs of the shallow wells in burial ground 6 generally resemble those of burial ground 5, and again reflect the lithologic and hydrologic properties of the aquifer. The character of the individual hydrographs commonly