Storage of Ground Water Behind Subsurface Dams in the Columbia River Basalt Washington, Oregon, and Idaho

By R. C. NEWCOMB

HYDROLOGY OF VOLCANIC-ROCK TERRANES

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By R. C. Newcomb

ABSTRACT

The Columbia River basalt, a thick sequence of accordantly layered lava flows, forms the bedrock beneath about 50,000 square miles in Washington, Oregon, and Idaho.

The rubbly rock at the top and bottom of some of the flows is permeable and transmits water laterally between the flows. Where the strata are displaced vertically by faults, barriers to movement of the water are common. Where these barriers are transverse to the dip of the basalt layers, ground-water reservoirs are formed. Many such reservoirs are present in mountainous areas or on the flanks of mountain uplands, and their water has been little used to date.

Properly designed and constructed test wells are suggested as a means of determining the feasibility of withdrawing water from these reservoirs during the growing season and allowing the reservoirs to refill during the winter and spring. Benefits from such a practice may be especially great in stream valleys where water is needed in the late summer.

INTRODUCTION

Data gathered in studies of ground water in the Columbia River basalt have made it increasingly clear that, in places, the basalt contains replenishable bodies of water in virtually "dead" storage. Structural barriers, which impede the movement of ground water, are the cause of one type of ground-water reservoir. Some of these reservoirs are in upland or mountainous areas, where the stored water would be available for use during the months of low streamflow each year. Though the amount of water that might be withdrawn annually from any one reservoir may be a modest few hundreds or thousands of acre-feet, the total may be a very important addition to water resources in areas where water is greatly needed.

The existence of these upland reservoirs has been noted in previous reports. This paper is intended to indicate more explicitly their mode of occurrence and to outline a possible method of making tests to determine what part of the water might be replenishable. The paper is intended also to estimate the costs of testing and to point out some of the benefits to be derived from the development of this stored water.

Because the proposed test wells would be of the same type as the operational producing wells tapping these reservoirs, they should be constructed as though they were to be merely the first of the permanent producing wells; many features of the foreseen operational-well installations have been incorporated in this method for testing the reservoirs.

The water to be withdrawn from such a reservoir is referred to as "new" water because it would otherwise be unavailable. Under the assumptions of this plan, the water taken from storage as new water during the months of greatest need would be replaced during the winter and spring when runoff is in excess of needs.

The presence of these reservoirs has been noted in several reports on local areas, and there have been many inquiries for additional information and for suggestions on suitable methods of development. This plan for testing and the suggested procedure for any subsequent development of these reservoirs carry no implications as to who might undertake that work. If the first tests show development to be feasible, many organizations may be interested in the use of such reservoirs.

The paper was prepared under the Federal project for study of the hydrology of the Columbia River basalt. Much of the supporting information is contained in reports on areas studied in cooperation with the State Engineer of Oregon, the Department of Conservation of Washington, and other local agencies.

ENVIRONMENT OF THE BARRIER RESERVOIRS OF GROUND WATER

The Columbia River basalt is a thick sequence of accordantly layered lava flows of basaltic and basic andesitic composition. The main part underlies most

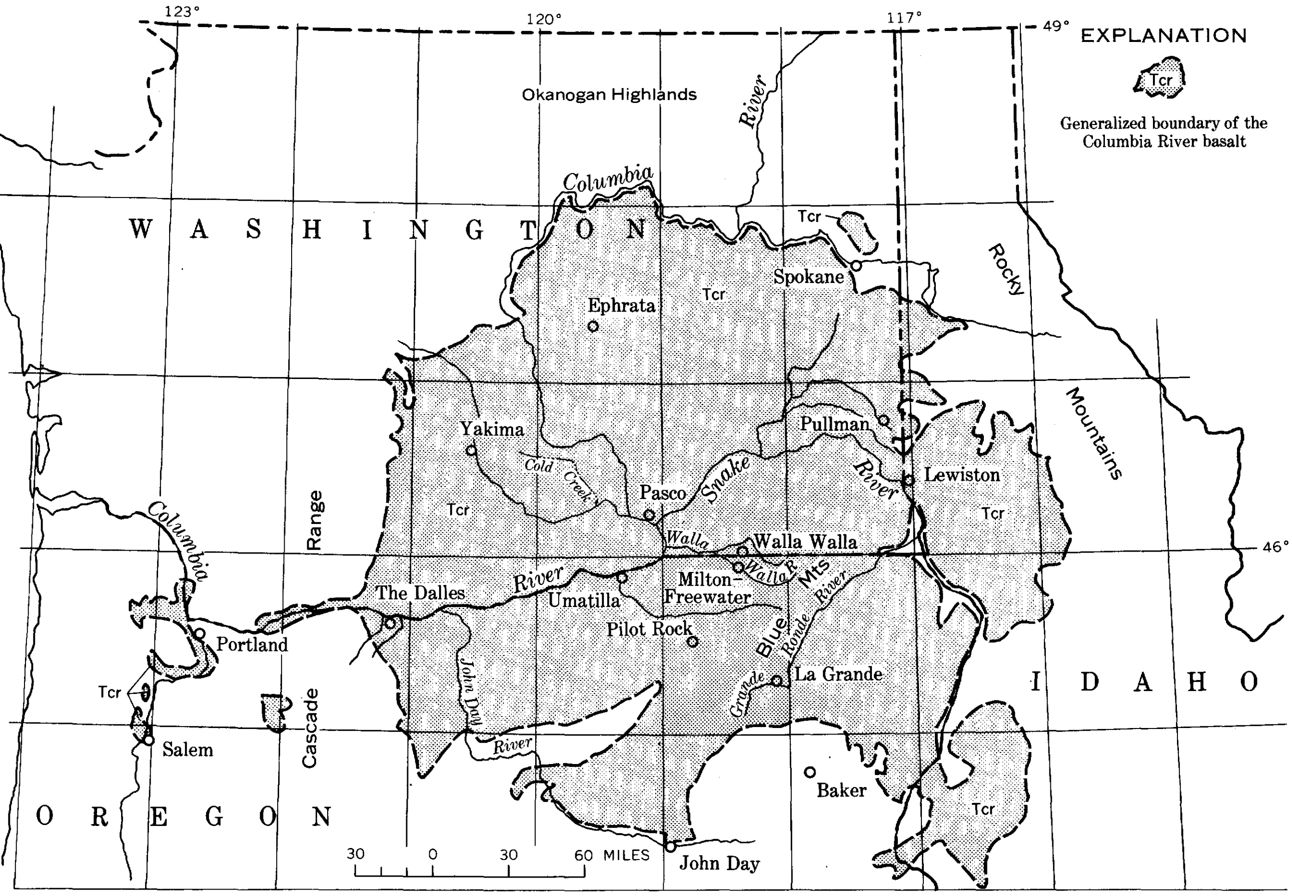


FIGURE 1.—Map showing the main area underlain by the Columbia River basalt, Washington, Oregon, and Idaho.

of the area that extends westward from the northern Rocky Mountains to the northern Cascade Range, and southward from the Okanogan Highlands to the mountains of central Oregon (fig. 1). In the central part of this area the basalt is known to be more than 5,000 feet thick in places, and it tapers to zero on the older rocks at its margins. The individual lava flows range in thickness from 5 to 150 feet and average about 50 feet. The average flow consists of dense, almost flintlike, partly fractured rock at its base; grades vertically to dense, massive columnar-jointed rock at its center; and then to vesicular—and in some places rubbly—rock at its top. Systems of fractures cut the rock into irregular columnar, cubical, and platy blocks that range from 2 to 60 inches across; the fractures formed when the lava was cooling.

OCCURRENCE OF GROUND WATER IN THE BASALT

Ground water moves through the rock largely in the permeable zones at the top of some flows. These tabular zones commonly are about 3 to 10 feet thick. In places where 2 of these permeable interflow zones are separated by highly jointed lava, the total thickness of a single water-bearing stratum may be 25 feet or more.

The massive centers of some flows are relatively impermeable, and in places thick zones of the rock consist of several successive flows which are tight and nonwater bearing. Above the water table, these impermeable zones cause water to be perched, and below that level, in places, they cause the water-bearing zones to have no hydraulic continuity and, therefore, to have different water-pressure levels. Also, where the basalt is tilted or where the water movement is impeded by barriers, the water below these impermeable zones may be confined under pressure.

Exact data are lacking not only on the percentage of interflow zones that are permeable and on their average water-yielding capacities, but also on their average thickness and permeability. These factors have been partly evaluated in a computation of the yield of water to an average well. A computation made by the writer in 1947, based on records of several hundred wells that penetrated 300 feet or more of the basalt, shows that 1 gallon of water per minute for each foot of well that is below the regional water table is the approximate average yield obtained by a 10- or 12-inch well when pumped at the common drawdown of 50 to 100 feet (Newcomb, 1959). Subsequent records show that this estimated average is conservative for the yields obtained from the better designed wells now being constructed.

Data indicate that the average capacity of the basalt to transmit ground water is generally uniform to a depth of about 1,500 feet, where the basalt is that thick. Not enough wells have been drilled deeper than 1,500 feet to warrant making estimates of the average permeability of the basalt below that depth.

TECTONIC DEFORMATION OF THE BASALT

TILTING AND WARPING

The basalt was extruded, in Miocene and Pliocene(?) time, as nearly horizontal flows. Subsequently, it was warped during at least two periods of folding. In most places, the basalt is now tilted in broad warps of the earth's crust. The general pattern of the regional tilting includes gentle dips inward from the older rocks near the boundary mountain ranges, a series of anticlines and intervening synclines that extend through central Washington eastward from the Cascade Range, and a broad anticline—known as the Blue Mountain anticline—that curves northeastward from the mountains of central Oregon. There are also many local structures. (See fig. 2.)

Because ground water, which has percolated into the basalt, finds the easiest path of travel in the permeable interflow zones, it moves generally down the dip of inclined strata. Thus, in general, the anticlines cause water to transfer laterally into the downwarped synclines, which are gathering places for the ground water in the basalt. Consequently the water table, or the piezometric surface of the ground water, beneath areas of inclined basalt commonly lies at or near the level of the principal streams. In synclines the water table may lie at or near the drainage level, or the ground water may be confined under artesian pressure.

Most of the highly productive wells in the basalt are in downwarps such as occur at Walla Walla, Cold Creek, and Ephrata, Wash.; The Dalles, Umatilla, and Pilot Rock, Oreg.; and Lewiston, Idaho.

FAULT-BARRIER CONDITIONS

During the deformation of the basalt, bending did not relieve all the stress in the rock at some places. Locally, these unrelieved forces produced fractures, called faults, along which the rocks on opposite sides were displaced. These faults range from large shear fractures along which the rocks on opposite sides were displaced several thousand feet, to small ones where

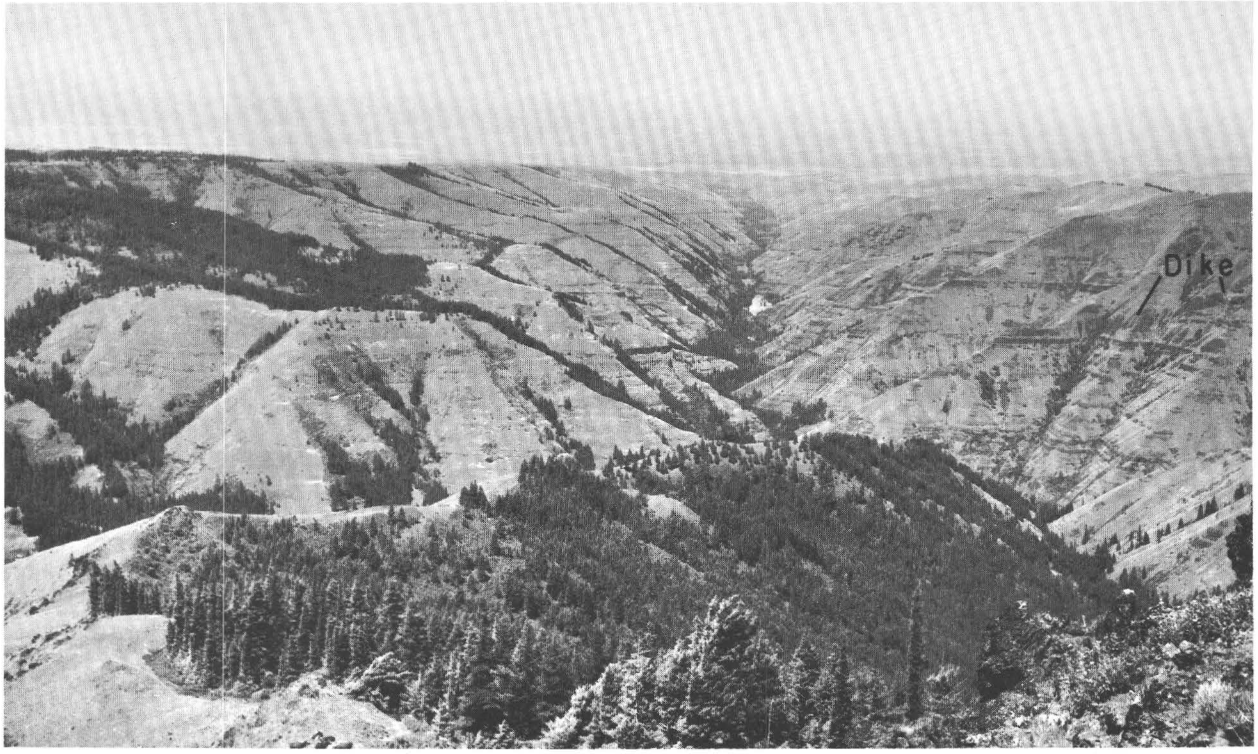


FIGURE 2.—View northwest from the Blue Mountain upland near McIntyre Lookout, Oreg., down the valley of the South Fork of the Walla Walla River, where the downstream dip of the basalt is apparent.

FIGURE 3.—View of a fault zone exposed by a road cut in the northwest bluff of the Grande Ronde River above La Grande, Oreg., in sec. 31, T. 2 S., R. 37 E.

FIGURE 4.—Close view of part of figure 3 showing the shearing common to fault zones in the basalt. (Pick, at lower right of the center, is 14 inches long.)

little displacement occurred. Rather than a single plane of fracture, the larger faults consist of zones of shattered and broken rock several tens or hundreds of feet wide (fig. 3). Even some of the small faults, along which the displacement is measured in tens of feet, are zones of sheared and shattered rock.

Nearly all the faults are of the type commonly called normal faults, in which the fracture plane dips toward the downthrown side. This type generally is considered to indicate that tensional strains were responsible for the faulting. The most common inclination, or dip, of the fracture planes is between 60° and 70° below the horizontal.

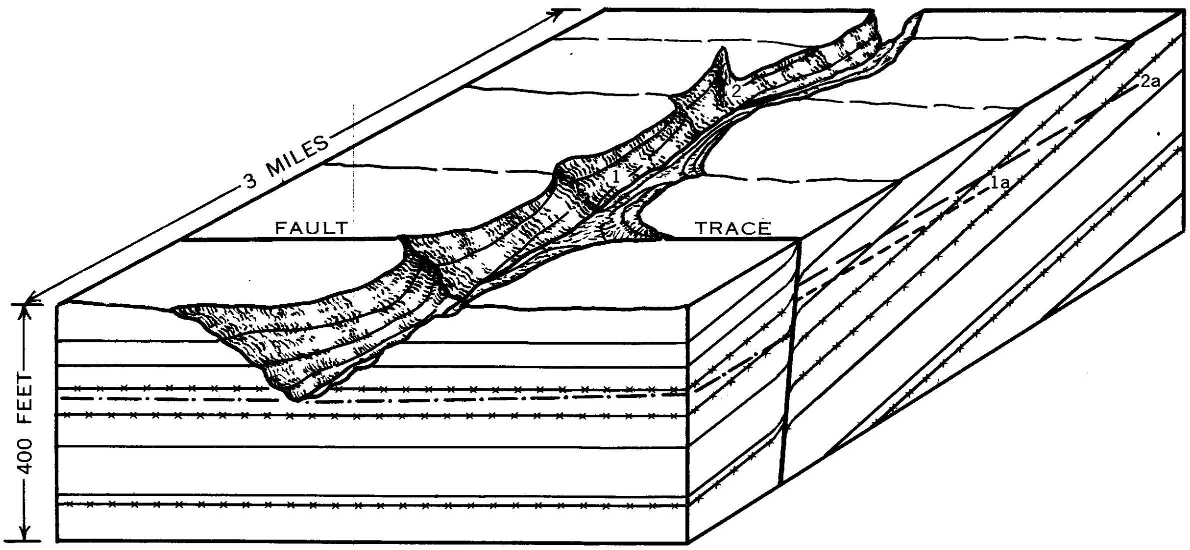
The water-transmission characteristics of the fault zones differ considerably from those of the unbroken basalt. The fault fracturing provides a zone of low permeability (fig. 3), along which small amounts of water can move vertically in some places. The lowest sags in the fault traces, where they cross stream valleys, are generally marked by small seepage springs. The permeable interflow zones that provide the lateral, or generally horizontal, routes of ground-water movement are obliterated in the fault zones and the lateral movement of the water is virtually stopped. Thus, a fault zone constitutes a barrier to the otherwise normal lateral movement of ground water.

In addition to those created by faulting, barriers can occur also along the axis of sharp folds owing to disruption of the permeable zones by the interflow grinding as the rock stretched over sharp bends of the basalt. These two types of localized destruction of the tabular paths of lateral movement of water in the basalt are grouped together under the term "structural barriers" (Newcomb, 1959). Intrusive dikes can also form barriers. However, dikes are not so numerous or so continuous as the structural barriers, and in many places they are not arranged transverse to the direction of ground-water movement.

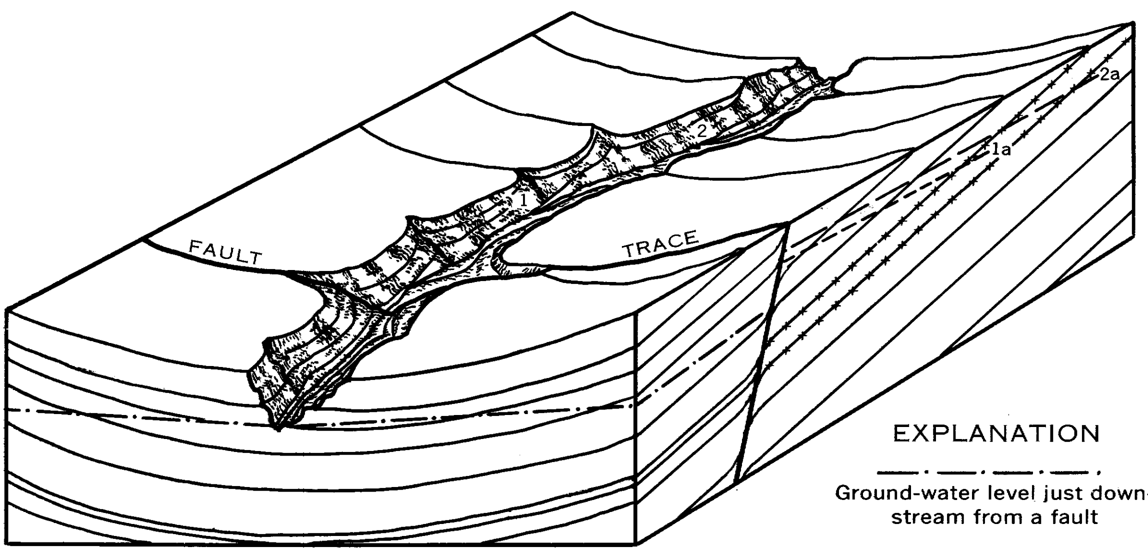
RESERVOIRS BEHIND STRUCTURAL BARRIERS

STRUCTURAL CONDITIONS CREATING BARRIER RESERVOIRS

If a fault zone is parallel to the direction of ground-water movement, it has little effect on the lateral movement of the water. However, if the fault zone is transverse to the direction of movement, the percolation down the gradient may be blocked and the water deflected around it; or, if the fault is extensive, the water may be dammed and may reach the surface above the barrier (fig. 5*A*). Thus, if a fault zone crosses the axis of a syncline, an almost complete barrier may be formed (fig. 5*B*). Surface outlets (and inlets) commonly occur at the points where the individual water-



A. A monoclinal dip of the basalt cut by a transverse fault barrier



B. A plunging syncline cut by a transverse fault barrier

EXPLANATION

Ground-water level just downstream from a fault

2a
1a
Ground-water level, near the barrier, in a well that taps an aquifer cropping out at point 1 or 2

Water-bearing layer shown on the sides of the diagrams

FIGURE 5.—Structural features creating barrier reservoirs.

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bearing zones crop out in streambeds above the barrier. The outlets of some reservoirs may occur also at other points in the streambeds upstream from the fault zone, because of upward cross-strata leakage from the aquifer.

KNOWN AND TESTED STRUCTURAL RESERVOIRS

In the quest for water in the Columbia River basalt, several ground-water reservoirs of the type described have been tapped by wells. Some reservoirs have been rather thoroughly developed and their extent and mode of occurrence are well defined. Others have been less well developed, and some have been tapped by only a few wells or by a single well.

Possibly the most thoroughly developed ground-water reservoir of this type is that impounded behind the fault or sharp fold which passes through the basalt bedrock north of College Place, Wash., in the Walla Walla syncline. The fault or sharp fold is marked by a 200-foot-high ridge in the bedrock surface beneath the 500 feet of sedimentary deposits which underlie the valley floor. The ridge trends east-northeast across the broad slope of part of the south limb of the Walla Walla syncline. It marks a vertical barrier to the lateral movement of ground water. When the first wells were drilled, during the years 1900–10, the artesian head of the water in the deep wells tapping the uppermost 200 feet of the basalt on the upgradient side of this barrier was about 140 feet above the land surface and 200 feet above the level of the water table in the nearby wells tapping the same rocks on the downgradient side of the barrier (Newcomb, 1951).

Another developed reservoir upgradient from a fault (or sharp fold) occurs in the Upper Cold Creek syncline east of Yakima, Wash. The main part of the reservoir area lies in secs. 25, 26, 27, 34, 35, and 36, T. 13 N., R. 24 E., and secs. 30 and 31, T. 13 N., R. 25 E. (Hart, 1958). The lower part of this plunging syncline is mantled by sedimentary deposits, which continue eastward beneath the high terraces in the Hanford Reservation of the U.S. Atomic Energy Commission. The ground-water reservoir of artesian water terminates abruptly in alinement with the sharp east edge of the Yakima Ridges to the north and south of the syncline. The easternmost well, the McGee, is about a quarter of a mile upslope from the inferred location of the barrier. Originally, the pressure level of the ground water at the McGee well was 212 feet above the land surface and about 580 feet above the level of the ground water in the basalt east of the barrier.

An area south and southwest of The Dalles, Oreg., has several partly known ground-water reservoirs behind fault barriers in the basalt (fig. 6). The basalt to the south, east, and west dips into the Dalles syncline (Piper, 1932). It is covered in many places by several hundred feet of sedimentary beds called the Dalles formation. Numerous faults are known to trend northwestward across the northeastward-plunging syncline; other faults are believed to be present but have not been mapped. A fault or fold escarpment runs south-southeastward through the western part of The Dalles and between the Renken well, 704 feet deep and at an altitude of about 625 feet, in the NW¼NE¼ sec. 22; and the Stark well, 536 feet deep and at an altitude of about 700 feet, in the NW¼SW¼ sec. 27, T. 1 N., R. 13 E. The Stark well, three-quarters of a mile upgradient from this apparent barrier, has a static water level slightly above the land surface. The Renken well, half a mile downgradient from the apparent barrier, has a water level 520 feet below the land surface. The difference of about 600 feet in the water level of these two wells is apparently due to the barrier effects of the intervening fault or sharp fold (fig. 6). Other reservoirs of ground water stored behind structural barriers occur in the Mill Creek and upper Threemile Creek areas near The Dalles.

Ground-water reservoirs that are believed to be due to structural barriers occur in other areas underlain by the basalt, but most of the barriers are too imperfectly known to serve as examples at this time.

Individual wells known to illustrate the effects of barriers in creating ground-water reservoirs of relatively high water-pressure levels are (1) the Marion Cockburn well on Pine Creek, northwest of Milton-Freewater, Oreg., (Newcomb, 1951); (2) the Bureau of Reclamation test hole 1 at the Harris Dam site on the South Fork of the Walla Walla River in the NW¼SE¼ sec. 12, T. 4 N., R. 37 E. (G. E. Anderson, written communication); and (3) the flowing well of the city of John Day, Oreg., on the north side of the fault which follows the center of the John Day River valley at that place.

UNDEVELOPED STRUCTURAL RESERVOIRS

Many untested reservoirs that have been formed by structural barriers should occur in the type conditions present in the mountain areas and on the flanks of uplands. At those places little immediate need exists for additional water for public supply, irrigation, industrial, or other uses, but farther downstream there is urgent need for additional water, especially in the summer and autumn when local supplies are inadequate. Thus, the present utilization of much of this stored ground water may require transporting it in streams, pipelines, or flumes to points of use. Development of these supplies might also be of use in fish culture, power generation, waste disposal, recreation,

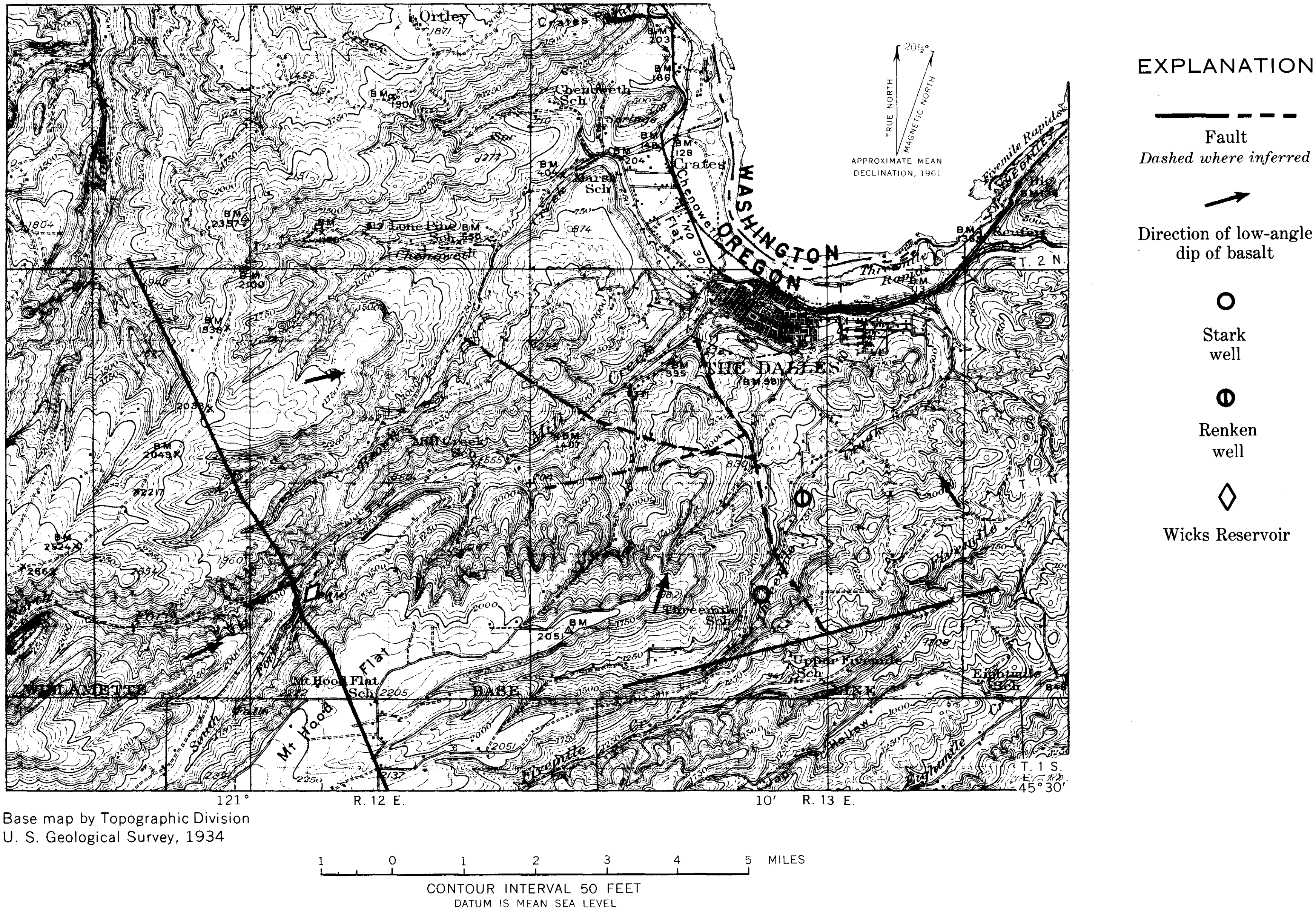

FIGURE 6.—Map of area adjacent to The Dalles, Oreg., showing fault barriers.

and other activities. The use of the upland reservoirs, as proposed in this paper, is foreseen as a future source of supplemental water to supply some water-short valleys.

SITES PROPOSED FOR TESTING FOR IMPOUNDED GROUND WATER

Areas (shown on figs. 1, 6, 7, and 8) in which transverse faults are known to cut the basalt, where it dips on a wide front toward a valley or is warped into a syncline, are present in the valleys of the Walla Walla River, Grande Ronde River, Mill Creek near The Dalles, and John Day River. Some of these areas appear to overlie structural conditions nearly ideal for barirer reservoirs in the basalt. There are many other areas where such reservoirs may occur, but the conditions are not now sufficiently known to warrant testing before further geologic investigations are made.

In the Walla Walla River basin the layered basalt dips generally westward from the crest of the Blue Mountain anticline and extends beneath the alluvial fill which underlies the valley plains. The South Fork, North Fork, Mill Creek, and lesser tributaries flow down the regional slope in deep canyons, and the basalt is cut by several faults which trend generally transverse to the dip of the basalt (fig. 7). The basalt is believed to be at least 500 feet thick beneath the channel bed in most of these canyons. On the basis of the conditions observed in areas of similar geologic structure and on the few well data for this area, the fault zones probably impound ground water in the basalt. Sites where drilling is considered desirable to test for reservoirs of ground water are (1) along the South Fork, just south of the center of sec. 7, T. 4 N., R. 38 E., upstream from the large fault called the Tom Hite fault; (2) along Mill Creek near the northeast corner of sec. 19, T. 6 N., R. 38 E., upstream from the Kooskooskie fault; and (3) along the South Fork, near the east line of sec. 14, T. 4 N., R. 37 E., upstream from the Elbow Bend fault. These and other likely sites are shown on figure 7.

In the upper part of the Grande Ronde River basin (figs. 1 and 8) the basalt dips southeastward off the Blue Mountain anticline and northwestward from the Elkhorn Ridge to form an elongate synclinal sag, which is followed eastward by the Grande Ronde River from near Starkey to the valley plain at La Grande (Hampton and Brown, in press). The syncline is cut transversely by northward-trending faults (fig. 8), and some should impound ground water. The following sites considered advisable to test for potential ground-water reservoirs are all upstream from faults: (1) along the Grande Ronde River in the SW¼ sec. 36, T. 3 S., R. 35 E., (2) in the NE¼ sec. 15, T. 3 S., R. 36 E., and (3) in the SW¼SE¼ sec. 31, T. 2 S., R. 37 E.

South and west of The Dalles, Oreg., the strata of basalt and the overlying sedimentary rocks of the Dalles formation dip into a plunging syncline that trends northeast through The Dalles (fig. 6). The basalt in this syncline is broken into blocks by faults, many of which are imperfectly known because they are obscure in the softer materials of the overlying sedimentary rocks. Some of the barrier reservoirs in the basalt have been tapped and partly developed by present wells. A well along the South Fork of Mill Creek, near the N¼ cor. sec. 33, T. 1 N., R. 12 E., would provide a test of ground-water-reservoir conditions above the strong fault zone that crosses the South Fork near the Wicks Reservoir of The Dalles City Water Department. Other possible barrier reservoirs may be present in that area, but their testing can be deferred until the fault system is known in more detail.

PLAN FOR TEST DEVELOPMENT OF BARRIER RESERVOIRS OF GROUND WATER

TEST-WELL LOCATION

The present data for developed barrier reservoirs indicate that it is preferable to drill wells near enough to the fault zones to obtain the maximum hydrostatic pressure, but far enough from them to avoid drilling in the disturbed or shattered rock. The proposed site of each production well should be on the upstream side of the fault zone. The faults of the Walla Walla River basin (fig. 7) and the Mill Creek area (fig. 6) dip steeply downstream; at the Grande Ronde River sites (fig. 8) some faults dip steeply upstream and others dip steeply downstream. In drilling on the upthrown side of a normal fault, the well can be sited reasonably close to the fault (as near as 200 or 300 feet). On the downthrown side of a normal fault, because the fault plane dips toward the well, a greater distance should be allowed—probably at least 300 feet plus a distance equal to the expected depth of the well.

It is proposed that the test wells be located near stream level, so as to gain full advantage of any free artesian flow, and still be adequately sited and equipped with foundations and buttresses to be protected against damage by floodwaters of the stream. Also, the wells will need to be situated to permit the access of mobile drilling equipment.

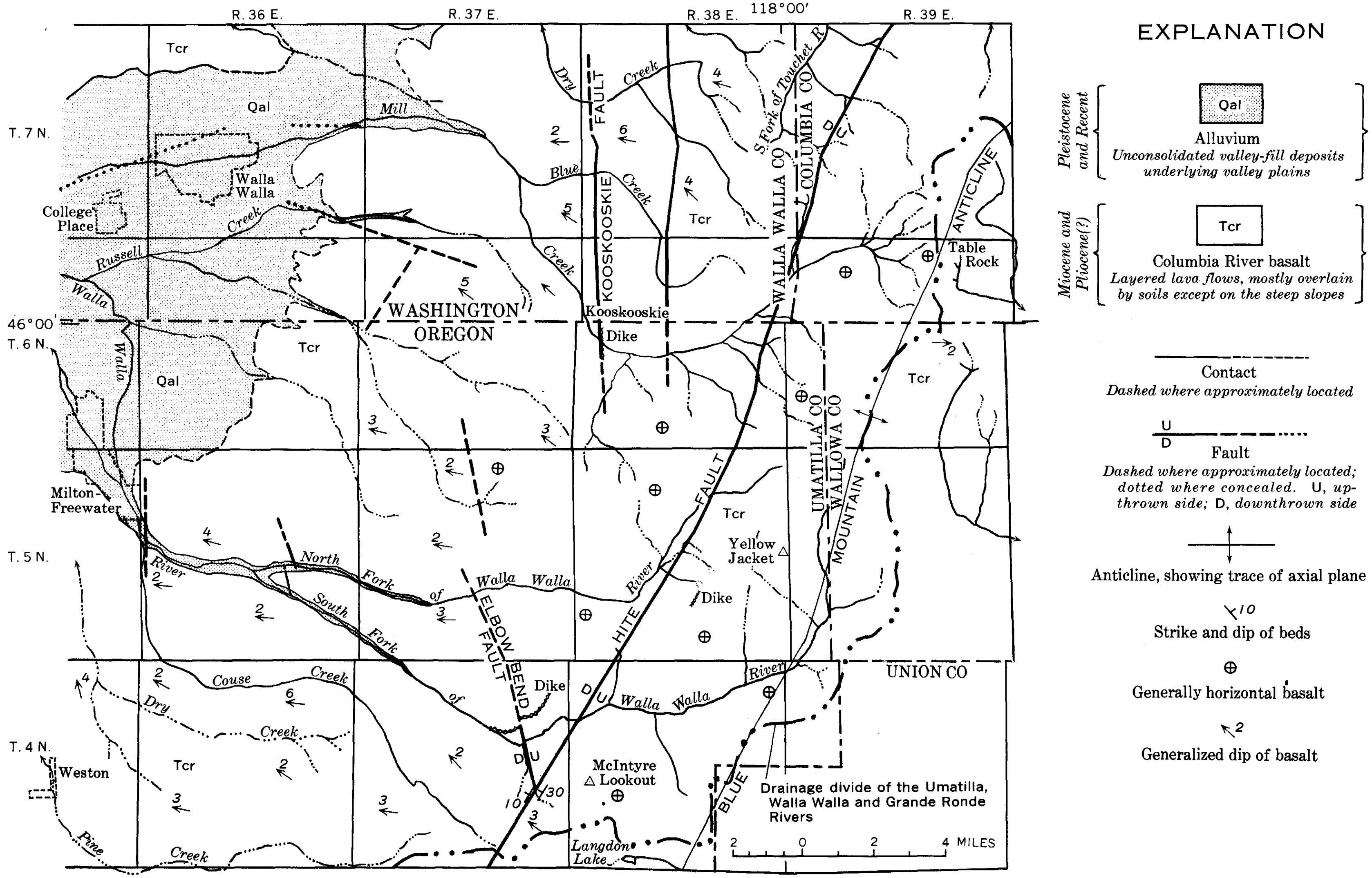

FIGURE 7.—Geologic map of the upper part of the Walla Walla River basin, Washington and Oregon. (After Newcomb, 1951.)

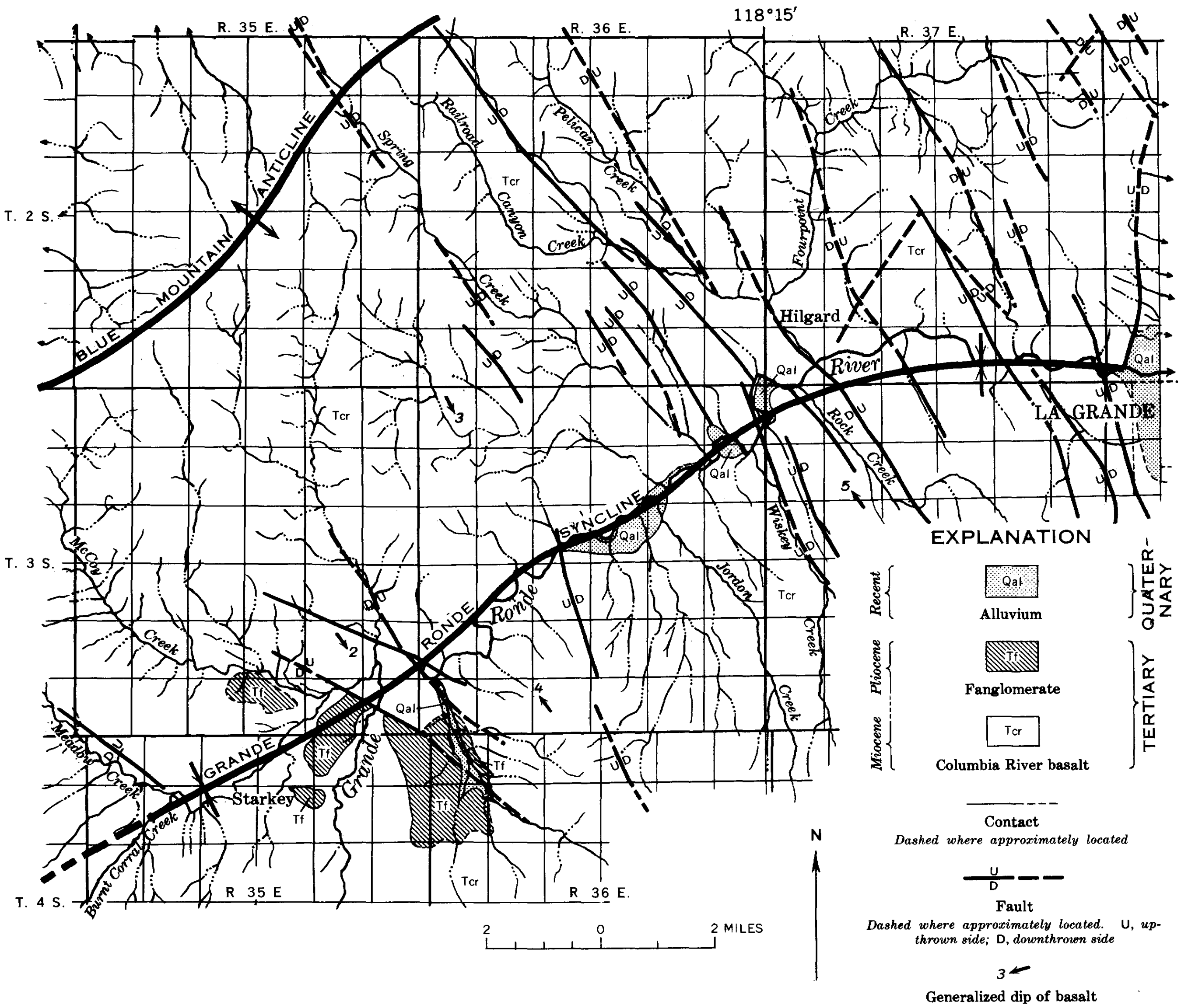

FIGURE 8.—Geological map of the Grande Ronde River valley above La Grande, Oreg. (From Hampton and Brown, 1959.)

SUGGESTIONS AS TO GENERAL SPECIFICATIONS FOR TEST WELLS

The dip of the layers of the basalt in most of the stream valleys where testing is proposed ranges from 1° to 5° and averages 2° to 3° downstream, or an average of 200 to 300 feet per mile. This average dip, together with a stream gradient of about 50 to 75 feet per mile, indicates that a 300-foot well would intercept the permeable zones that crop out in the first mile of the river above the well. Because different hydrostatic pressures probably exist in different aquifers, those of greater depth generally having the higher pressures, it is undesirable for one well to develop water from more than one aquifer or from more than one group of aquifers having similar hydrostatic pressures. Neglect of this precaution may lead to waste of reservoir water through aquifers of lower pressure. Consequently, the pairing of wells, one approximately 300 and one 600 feet deep may be a desirable arrangement for the testing of each barrier reservoir. In places where the basalt is thick and the reservoir is to be fully developed, a third well, about 1,000 feet deep, may be needed during later productive operation (fig. 9).

The proper evaluation of the effect that the use of a ground-water reservoir will have on the nearby stream necessitates gaging the stream. The cost of establishing stream-gaging stations and operating them will be lessened if several nearby wells are served by one station. Also, savings on other surface facilities may be possible by grouping the wells producing water from different depth zones in one barrier reservoir. However, because one well can partly establish the presence

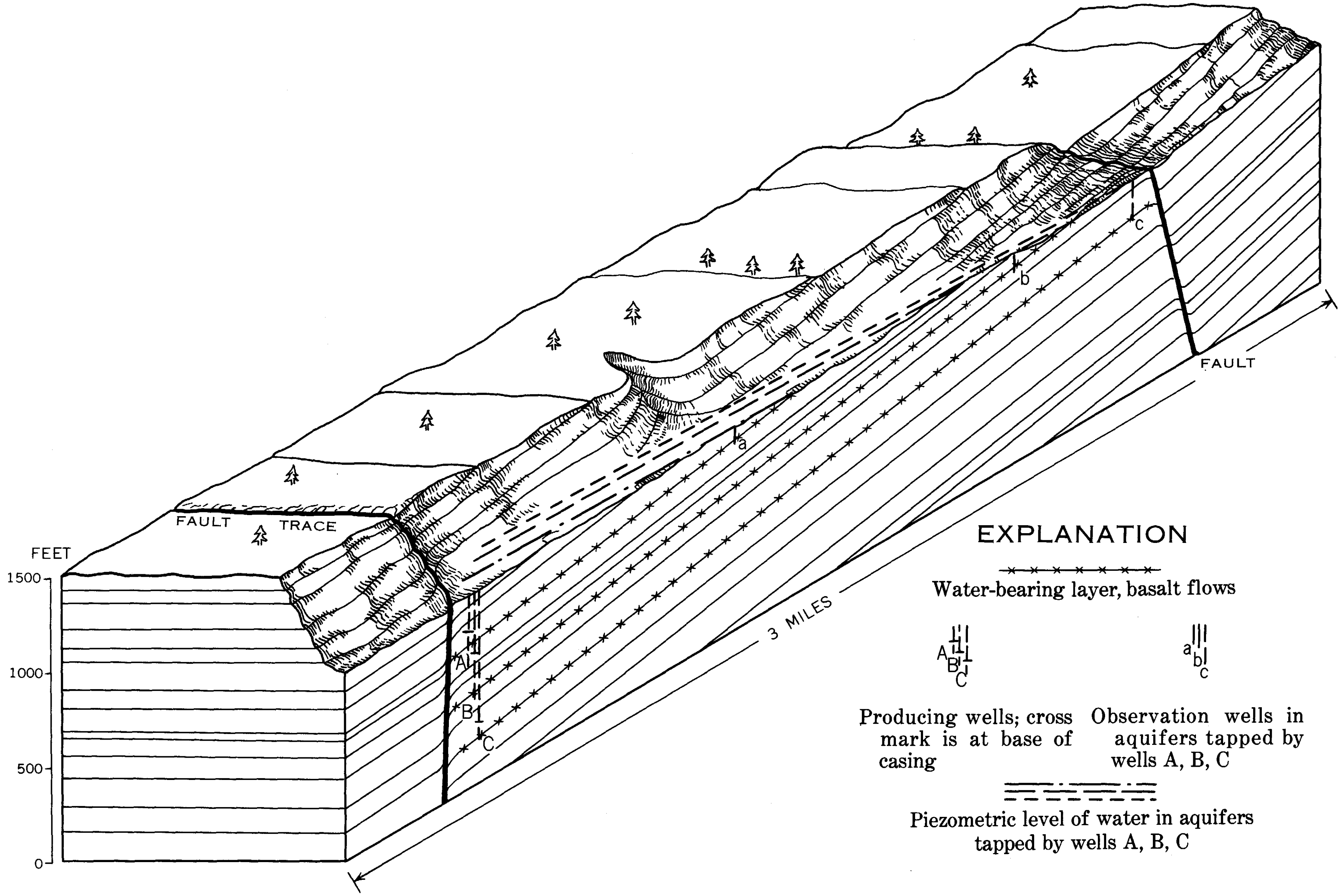

FIGURE 9.—Block diagram of an idealized fault-barrier reservoir with producing and observation wells. (The diagram is cut away along the vertical plane of the stream-valley axis.)

and utility of a reservoir, it is probable that the initial testing of reservoirs will be by means of single wells.

To serve the intended purpose, the wells must be properly cased. As the geologic conditions foreseen in these reservoirs indicate successively greater water pressure with successively greater depth, the sealing of upper aquifers of relatively low pressure head will be necessary in some wells. Some possible arrangements of casing are shown in figure 10. Casing should be equal at least to standard well casing having a minimum wall thickness of 0.33 inch. It should be sealed to the impermeable parts of the rock by grouting with cement. The construction and arrangement of a permanent producing well should be planned to obtain at least a 100-year use before recasing is necessary.

The surface appurtenances must include proper valve equipment, frost-protection outlets, fireproof protective shelters, and flood-damage protection. Equipment for measuring the flow of the well and the flow of the stream passing the well must be included. Facilities for recording these measurements and keeping the records also must be provided.

At least one observation well is necessary in each reservoir during the test period and after full development. One 6-inch observation well located upstream from each producing well may be necessary during ultimate full use of a reservoir.

TEST OPERATION OF THE WELLS

The operation is foreseen as a flow or, if necessary, a pump discharge from the wells in the general period July 1 to November 1 of most years and a period of shut down to allow recovery during the remainder of the year. Records of the discharge of the wells, the temperature of the water, and the flow of the adjacent stream are to be taken during the 4-month period of use. Records of water level, or water-pressure level, in the wells and the discharge of the nearby stream are to be maintained throughout the year. The facts regarding water-level recovery in the aquifers will determine the amount of water that can be extracted from each barrier reservoir and also the rate and timing of the extraction.

The structural reservoirs suitable for testing include both the type in which the aquifer crops out in the bed of either a permanent or an intermittent stream, and the type in which it does not. The draining of a barrier

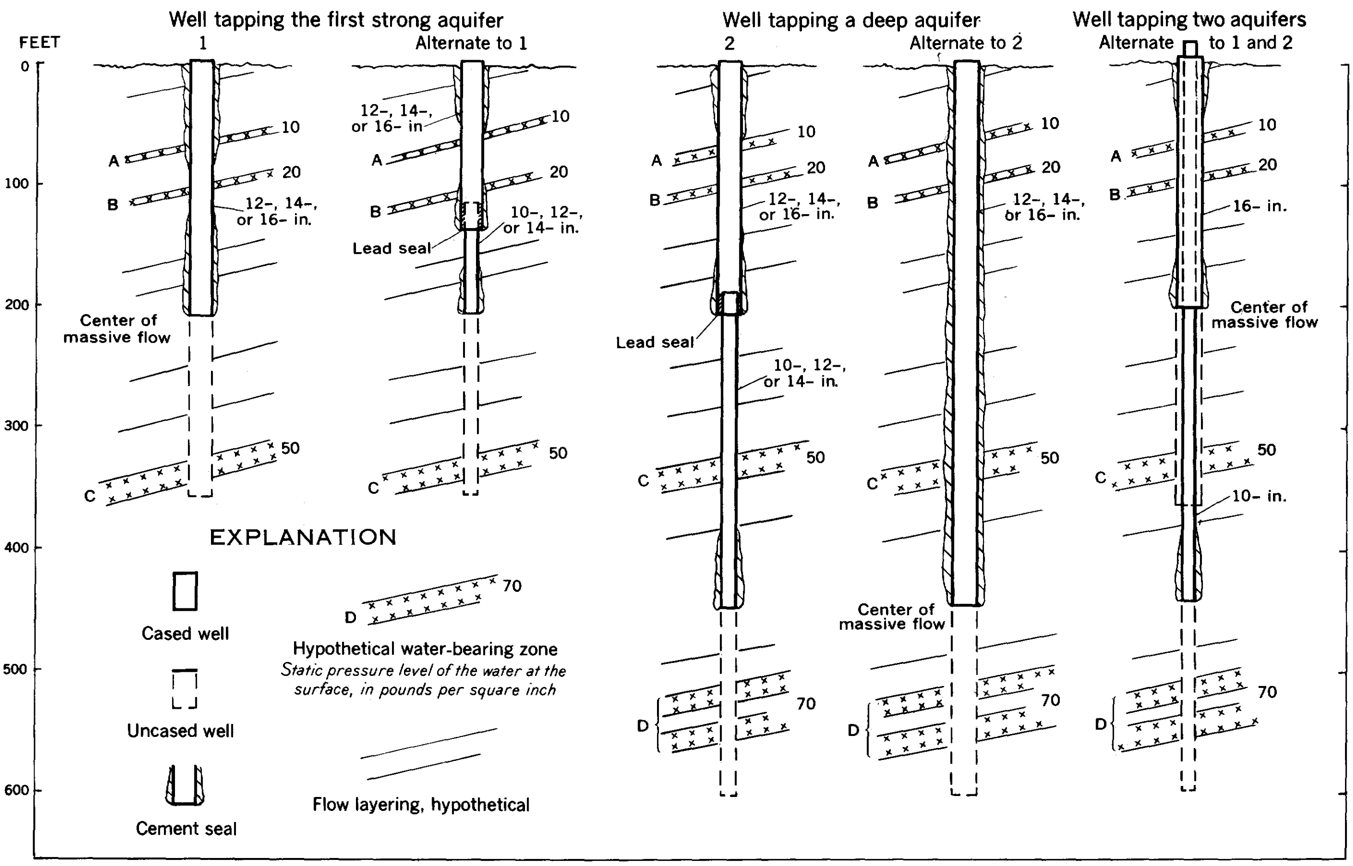

FIGURE 10.—Schematic diagram of some possible arrangements of casing and wells to tap water stored in a barrier reservoir in basalt.

reservoir is expected to induce some recharge as a diversion from any flowing stream that crosses the outcrop of the aquifers. Consequently, the withdrawal of water from storage will be expected to cause some decrease in streamflow downstream from the outcrop of those aquifers. However, the amount of water tapped from storage in the reservoir is expected to be many times the amount of streamflow depletion induced during the period of well operation. The subsequent refilling of the ground-water reservoir, partly by continued seepage from the stream, would occur during the fall and winter runoff period when such diversion from the stream is either beneficial or nondetrimental (fig. 11). It is expected that bedload movement and channel scour will continue the effective infiltration of water at the streambed outcrop of a depleted aquifer.

The possibility of artificial recharge to augment natural infiltration is present but, for brevity, is omitted from this report. Presumably, artificial recharge of clean water could be achieved by pumping water through injection wells during the period of reservoir recovery.

The approximate amount of streamflow depletion during the period of well use can be calculated, for idealized conditions, by the use of the Theis non-equilibrium equation (Theis, 1935). The effect of the barrier on the lowering of the water level at both the pumped well and the outcrop of the aquifer is computed from that equation and adjustments derived from the laws governing the drawdown of the water level in image wells (Ferris, 1949).

Under the assumed conditions of a producing-well system such as is shown in figure 12, and on the basis of conservative coefficients of transmissibility and storage, a withdrawal of 1,000 gpm for 120 days would result in a drawdown of about 140 feet at the producing well and of 50 feet at the outcrop of the aquifer. In these calculations the coefficient of transmissibility was assumed to be 25,000 gallons per day per foot and the coefficient of storage to be 0.0001.[1]

If there is 50 feet of drawdown at the outcrop of the aquifer, the ground-water surface would have a generally downstream gradient of 20 feet per mile by the end of 120 days. Theoretically, this drawdown at the outcrop should induce infiltration ranging from 10 gpm at the beginning of the pumping season to 250 gpm at its end. Because the calculated 140 feet of drawdown exceeds the 100 feet of hydrostatic pressure at the beginning of the test, this well would need to be pumped near the end of the season or the flow be reduced to a seasonal average of about 700 gpm. So many unknowns and assumptions based on scant data are included in these calculations that their only significance is that they show general quantitative agreement with the results estimated from a qualitative approach.

ESTIMATED COST OF A PROPOSED TEST INSTALLATION AND TEST PROCEDURE

The necessary test wells should include both shallow and deep wells, both of which are foreseen as the ultimate outlets of water from barrier reservoirs.

Assuming that each reservoir will ultimately be developed by at least one well 300 to 400 feet deep paired with a well 600 to 700 feet deep, the depth of 4 test wells is estimated to total 2,000 feet. When completed with proper casing and sealing, each of these wells, of 14-, 12-, and 10-inch diameter, may cost about $25 per foot. Valves, meters, aeration trays (for absorption of oxygen, where needed), and other appurtenances are estimated to cost $2,000 per well. Observation wells of 8- to 4-inch diameter located about midway between producing wells and the outcrop of the aquifer should be planned near 2 of the 4 well sites. Each would cost about one-fourth as much as a producing well.

A station for accurate gaging of the nearby stream is estimated to cost an average of $5,000, which includes the cost of the installation and the first year's operation. Such a gaging station would serve one barrier-reservoir installation, whether single, twin, or triple wells are used, but even if only one test well is drilled at each barrier tested, the cost of one stream-gaging station will need to be included in the cost of development for each barrier reservoir.

On the basis of 1959 prices, the estimated cost of testing four barrier reservoirs with single producing wells is:

Drilling casing, and completing 4 wells, total length 2,000 feet, at $25 per foot	$50, 000
Appurtenances	8, 000
Observation wells, 4	12, 000
Stream-gaging station (including cost of first year of test), 4	20, 000
Total	$90, 000

Thus, the cost of testing 1 barrier reservoir on a single-well basis would be about $22,500.

The estimated annual operating cost at 1 test reservoir thereafter is about $1,000, on the assumption that the operation would be under the supervision of a county watermaster or similar official. It is assumed that most of the cost is that of gathering the hydraulic data, and at any reservoir this cost would be about the same,

[1] The coefficient of transmissibility is defined as the number of gallons of water that will pass in 1 day, under prevailing conditions, through a vertical strip 1 foot wide extending the height of the aquifer under a hydraulic gradient of 1 foot in 1 foot. The coefficient of storage of an aquifer is the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

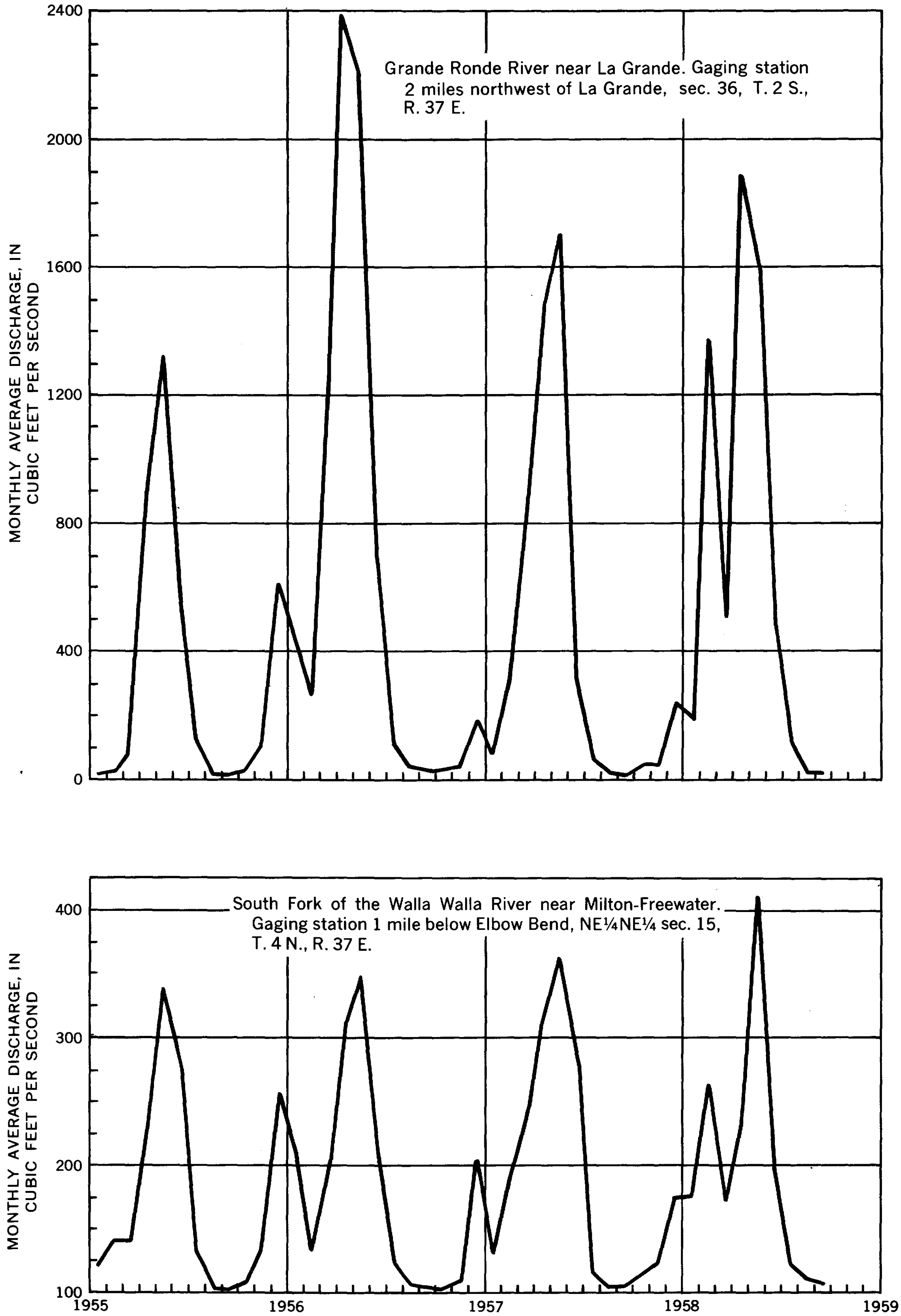

FIGURE 11.—Average monthly discharge in two rivers where structural reservoirs of ground water are believed present for artificially augmenting the annual low flow.

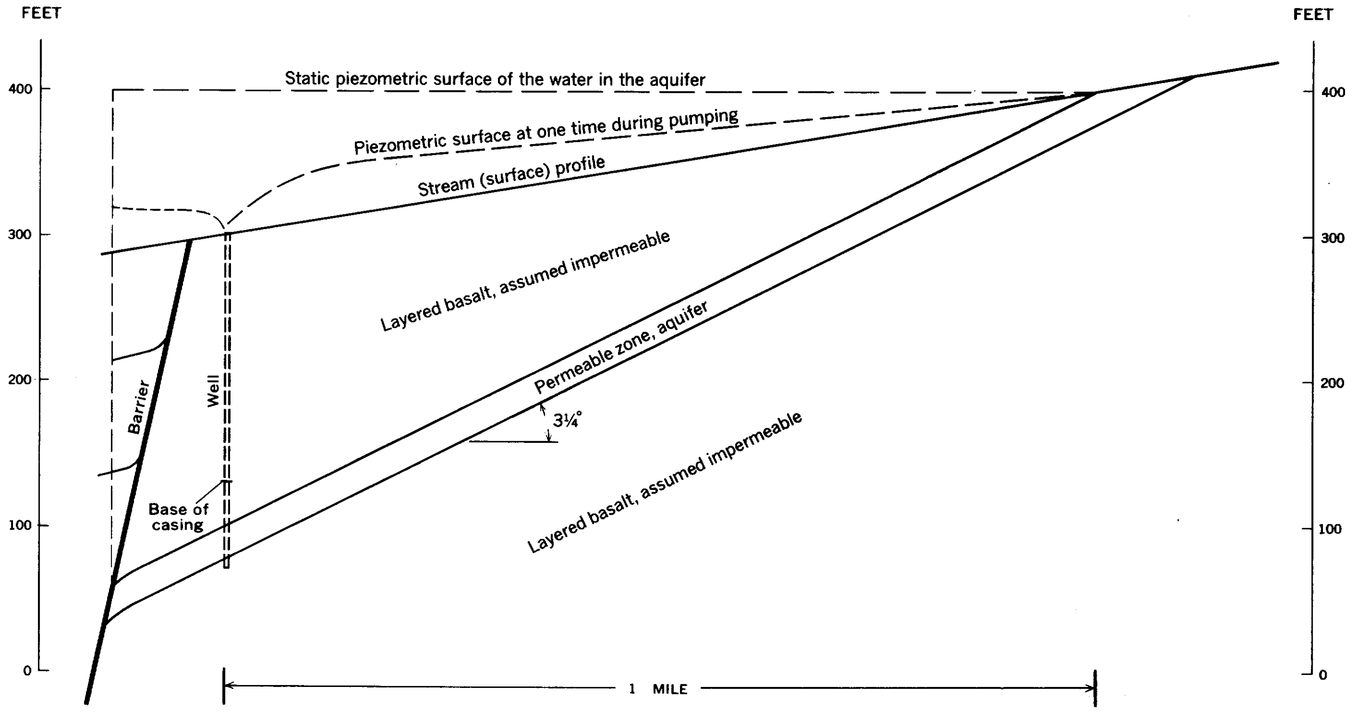

FIGURE 12.—Cross section of a hypothetical ground-water-withdrawal system utilizing an aquifer of a barrier reservoir.

regardless of the number of wells used. Thus, ultimate full production at each reservoir may not entail an average operational cost of much over $1,000 per year.

In these estimates the cost of pumping is omitted, because one objective in the location of the test sites would be to secure free-flowing wells where pumping costs would be avoided.

VALUE OF THE BENEFITS DERIVED

By continuing a hypothetical average well yield of 1,000 gpm over 120 days and assuming that 80 percent is new water previously unavailable, a total of 425 acre-feet of new water would be made available by each well. At $8 per acre-foot, the value of this water for irrigation purposes would be about $3,400 per year.

At some sites, where a hydroelectric plant would use the water at 200 feet gross head, this 1.75 cubic feet per second of new water in 120 days of the low-flow period would generate 67,000 kilowatt hours of electricity, which, at $0.007 per kilowatt hour, would have a value of $470 per year.

It is difficult to compute the value of the new water for fish culture, especially for the improvement of otherwise good spawning reaches that lack an adequate summer flow, as does the Grande Ronde River between Starkey and La Grande, Oreg. The value of the new water for such uses as recreation, public and domestic supply, abatement of pollution, and watering of livestock is also difficult to assess at this time.

These conservative estimates show that the wells would yield new water that annually would exceed in value the operating costs and at least 5 to 10 percent of the capital investment.

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