UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

A PRELIMINARY EVALUATION OF REGIONAL GROUND-WATER FLOW IN SOUTH-CENTRAL WASHINGTON

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Prepared in cooperation with the
U.S. Atomic Energy Commission

OPEN-FILE REPORT
73-153

Richland, Washington

January 1973

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Abstract

The characteristics of regional ground-water flow were investigated in a 4,500-square-mile region of south-central Washington, centered on the U.S. Atomic Energy Commission Hanford Reservation. The investigation is part of the Commission's feasibility study on storing high-level radioactive wastes in chambers mined in basaltic rocks at a depth of about 3,000 feet or more below the surface. Ground-water flow, on a regional scale, occurs principally in the basalt and in interbedded sediments of the Columbia River Group, and is controlled by topography, the structure of the basalt, and the large streams--the Columbia, Snake, and Yakima Rivers. The ground water beneath the main part of the Hanford Reservation, south and west of the Columbia River, moves southeastward from recharge areas in the uplands, including Cold Creek and Dry Creek valleys, and ultimately discharges to the Columbia River south of the reservation. East and northeast of the Columbia River, ground water flows generally southwestward

and discharges to the river. The Yakima River valley contains a distinct flow system in which movement is toward the Yakima River from the topographic divides. A large southward-flowing ground-water system beneath the southern flank of the Horse Heaven Hills discharges to the Columbia River in the westward-trending reach downstream from Wallula Gap.

Introduction

This study of regional ground-water flow in south-central Washington is part of the U.S. Atomic Energy Commission's research program on managing radioactive wastes stored at the Hanford Reservation, which lies within the 4,500-square-mile region shown in figure 1. It is a phase of an investigation of the feasibility of storing high-level radioactive wastes in chambers mined at a depth of about 3,000 feet or more below the surface. The first phase of this feasibility investigation was centered on the drilling of test well ARH-DC-1 to a depth of 5,661 feet near the present waste-storage areas (fig. 1). Geophysical logging and hydraulic testing in this well indicated that basalt flows of high density and low permeability, and which are therefore possibly suitable for mining of chambers, occurred within the required depth interval (La Sala and Doty, 1971). Of prime consideration in the overall feasibility study is the prediction of the rate and direction of movement of waste radionuclides that may leave the proposed chamber through the ground-water system. This prediction must be based on knowledge of the flow and geochemical characteristics of the ground water in the basalt. For this reason, the drilling of well ARH-DC-1 was followed by the present study with the purpose of making an initial appraisal of the direction of ground-water flow in the basaltic-rock sequence and to identify probable recharge and discharge areas.

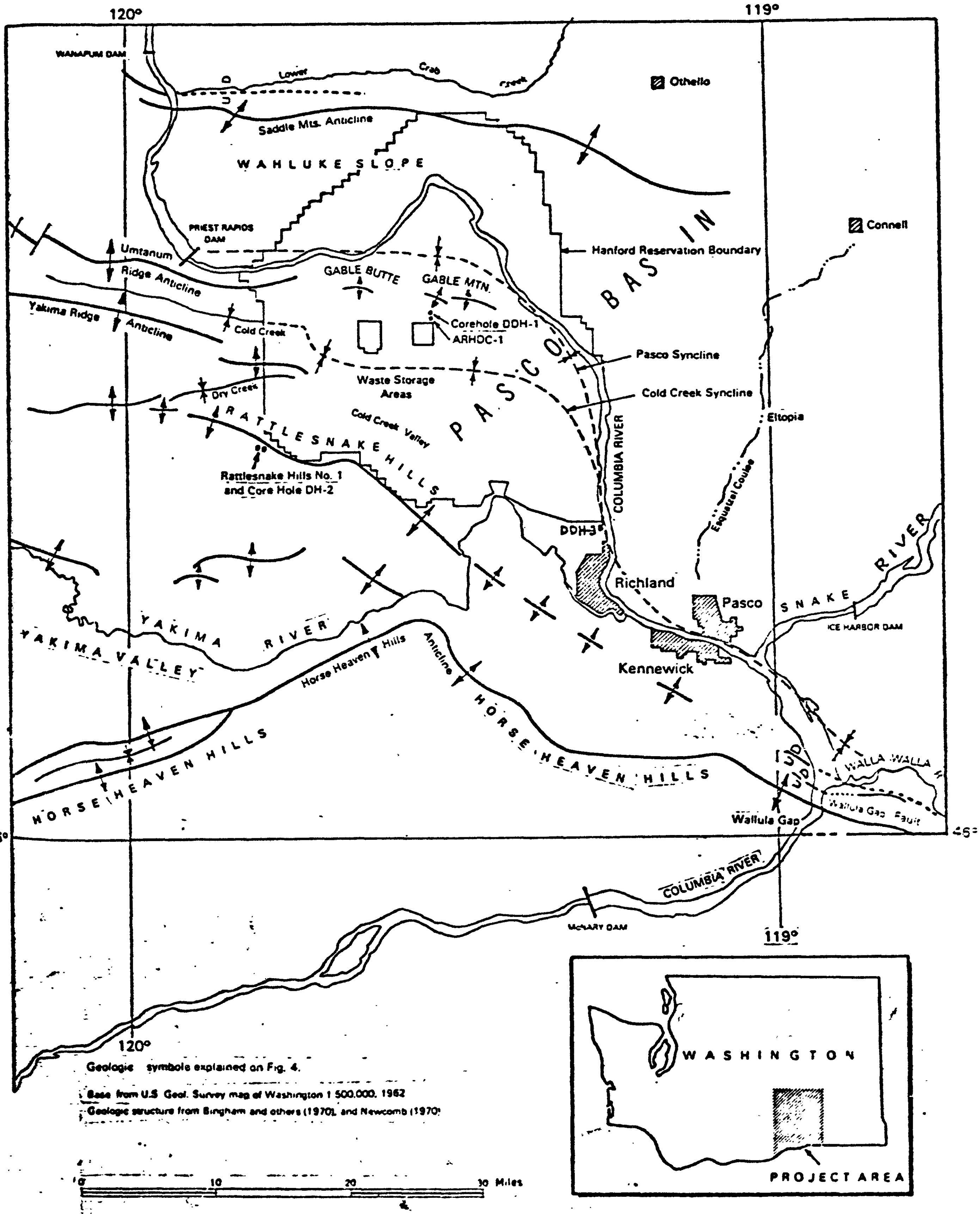

Figure 1 The Hanford R[illegible] on P[illegible] adjacent areas of south-central Wa[illegible]

The specific objectives of the present study are: (1) To assemble and evaluate the hydrologic, geochemical, and geologic information from existing wells tapping the deeper parts of the ground-water system; (2) to develop a hypothesis as to the flow characteristics of the system; and (3) to determine the need for additional data that would be required to describe the system adequately.

Ground-water data on file in various offices were reviewed in detail. Some of these data are available in reports (Walters and Grolier, 1960; Newcomb and others, 1970; Newcomb, 1965; Molenaar, 1968). However, data essential to this study on construction details of the wells, changes in ground-water levels in wells as drilling progressed through deeper water-bearing zones, and other pertinent details generally were not published. The principal sources of these unpublished data are the Tacoma and Portland District offices of the U.S. Geological Survey; Washington State Department of Ecology at Olympia; the Walla Walla District of the U.S. Army Corps of Engineers; and the U.S. Bureau of Reclamation. Mr. R. E. Brown, formerly of the Pacific Northwest Laboratory, Battelle Memorial Institute, also provided data on a number of wells

The data on wells were analyzed to determine (1) the ground-water potential both areally and with depth, (2) the mode of occurrence of ground water in the basaltic rocks, (3) areas of recharge and discharge, and (4) the distribution of chemical constituents in the ground water. The available data were supplemented by the collection of ground-water samples from wells for analyses of isotopic and chemical constituents. The wells were selected for sampling on the basis of location, depth of water-bearing zones, and construction features that would facilitate collection of representative samples. They were inspected to see if their pumping systems were suitable for obtaining unaerated samples and to verify data obtained from file records. Water samples were analyzed for chemical constituents, the radioisotopes tritium and carbon-14, and the stable isotopes of carbon. Field measurements were made of pH, alkalinity, and oxidation-reduction potential.

Physiographic and Geologic Setting

South-central Washington is within the Columbia Plateau and is underlain by basaltic rocks of the Columbia River Group of middle Miocene through early Pliocene age. These rocks have long been the subject of geologic studies, beginning with Russell (1893). They are an accumulation of lava flows, which were so fluid that individual flows spread over large areas of the plateau.

The basalt sequence of the Columbia River Group exceeds 10,000 feet in thickness in the vicinity of the Hanford Reservation. This thickness is known from the drilling record of a petroleum test well, Rattlesnake Hills No. 1 (see fig. 1) drilled in 1958, and from geophysical and lithologic studies made of the well on behalf of the Atomic Energy Commission by Raymond and Tillson (1968). Only the upper part of the Columbia River Group, the Yakima Basalt, is commonly exposed in the region of study. The type section of the Yakima Basalt is more than 2,000 feet thick in the upper part of the Yakima River valley west of the Hanford Reservation (Diery and McKee, 1969). Closer to the reservation, only about the upper 1,000 feet or so of the formation crops out along the surrounding ridges and in the stream valleys. The outcrops contain some significant zones of tuff and water-laid sand between dense basalt flows and also zones of pillow palagonite, flow breccia, and vesicular basalt. Stratigraphic studies of this section of rocks have been made by a number of workers (Bingham and Grolier, 1966; Brown, 1968; Mackin, 1961; and Schmincke, 1967). Further stratigraphic studies in connection with the feasibility investigation are now being made under the direction of R. E. Isaacson of the Atlantic Richfield Hanford Company, prime contractor to the AEC on the deep-mine waste-storage study.

The Yakima Basalt has been warped and folded to form the principal topographic features of the region. The Pasco Basin, in which the Hanford Reservation lies (fig. 1), is an extensive downwarping of the basalt, having two main synclinal segments, the Pasco and Cold Creek synclines (Newcomb, 1970). These synclines are separated by the Gable Mountain anticline, which forms a discontinuous but prominent eastward-trending ridge across the central part of the Reservation. The eastern side of the Pasco Basin merges with an extensive southwestward-dipping homocline that extends northeastward and eastward through the Columbia Plateau. To the west of the Pasco Basin is a broad upland area of folded basalt that extends westward to the Cascade Range. The ridges of this upland area are formed by a series of eastward- and southeastward-trending tightly folded anticlines. The Umtanum Ridge and Yakima Ridge anticlines terminate at the western border of the Pasco Basin. The Saddle Mountains and Rattlesnake Hills anticlines are persistent eastward and form the north and south boundaries of the basin, respectively. In the southeastern part of the region, the Rattlesnake Hills anticline is subdued topographically, and here the northfacing scarp of the Horse Heaven Hills is the boundary of the Pasco Basin. The Horse Heaven Hills are formed by a major linear upwarp of the basalt having an asymmetric anticline along its north side. The Horse Heaven Hills extends from the Cascade Range on the west to the Blue Mountains in Oregon on the east and forms a continuous drainage divide across south-central Washington, except where breached by the Columbia River at Wallula Gap.

Faults in the region (figs. 1 and 4) are described by Bingham, Londquist, and Baltz (1970) and Newcomb (1970). Minor thrust faults associated with folding occur at Gable Mountain, as was demonstrated by trenching, and Umtanum Ridge (fig. 4). Vertical faults are described at Wallula Gap by Bingham, Londquist, and Baltz (1970, p. 67-70) on the basis of field mapping. These workers hypothesized that the faults in Wallula Gap extended northwestward along topographic alinements. Further detailed work is needed in the region to define the extent of known faults and the character of topographic alinements.

Lacustrine and fluvial sediments of Pliocene age partly fill the structural basins formed through folding of the basalt sequence. These sediments consist of laminated silt, fine sand, and clay and of crossbedded sand and gravel. The Ellensburg Formation was laid down in the Yakima River valley and the Ringold Formation in the Pasco Basin. Deposition of these sediments was in part contemporaneous with the folding. The lower part of the Ellensburg Formation is apparently interfingered with the uppermost flows of the Yakima Basalt (Bingham and Grolier, 1966). During the Pleistocene Epoch glacial melt water eroded southwestward-trending coulees in the basalt northeast of the Hanford Reservation and caused considerable erosion along the present course of the Columbia River. The upper part of the Ringold Formation was removed by erosion from the Pasco Basin south and west of the Columbia River. At one time glacial melt water formed a lake in the Pasco Basin in which silt and fine sand comprising the Touchet Beds of Flint (1938, p. 493-495) were deposited. After draining of the lake, glaciofluvial materials consisting mainly of coarse gravel and sand were deposited. Erosion of the glaciofluvial deposits by subsequent melt water produced a series of terraces descending toward the Columbia River. Surficial fine-grained windblown deposits originating in postglacial time are widespread. The combined sedimentary and glacial deposits have a maximum thickness of about 750 feet beneath the Hanford Reservation and probably about 800 feet or more in the Yakima valley.

The broad terraces of glaciofluvial gravel in the central part of the Hanford Reservation lie at altitudes of about 360 to 800 feet above mean sea level. Maximum altitude in the line of ridges formed by the Gable Mountain anticline is 1,085 feet on Gable Mountain. The Horse Heaven Hills have an altitude of about 2,000 feet along the crest of their north-facing scarp. Rattlesnake Mountain has an altitude of about 3,000 feet. The other anticlinal ridges range from about 2,000 to 3,500 feet in altitude, the highest altitudes being in the western part of the area.

The Columbia River, which is the master stream of the region, flows generally southeastward to Wallula Gap and then makes a broad turn through the Horse Heaven Hills and flows westward to the Pacific Ocean. The Columbia River is joined by the Snake and Walla Walla Rivers from the east between Pasco and Wallula Gap and by the Yakima River from the west at Richland. The Columbia and Snake Rivers drain a large part of western United States and Canada. Above their junction they have average annual flows of about 120,000 and 40,000-50,000 cfs (cubic feet per second), respectively. The Yakima and Walla Walla Rivers, which have much smaller drainage areas, have average annual flows of about 2,000-3,000 and 500-600 cfs, respectively.

In its course through the region, the Columbia River is artificially controlled by Wanapum, Priest Rapids, and McNary Dams, above which normal pool altitudes are 570, 486, and 340 feet. Lake Wallula, the pool formed by McNary Dam, extends about 11 miles upstream of Richland. Between this pool and Priest Rapids Dam the river is free flowing, though the flow is controlled by upstream releases. In this reach, the river falls in altitude from 400 feet to the 340-foot normal pool elevation of McNary Dam. Before the dam was constructed, the Columbia River dropped from 340 feet north of Richland to about 250 feet at the present site of the dam.

The average annual precipitation ranges from about 6.3 inches on the Hanford Reservation to about 12 inches on the higher ridges. Perennial surface-water flow does not occur within the area except in the Columbia, Snake, Yakima, and Walla Walla Rivers and in lower Crab Creek, which is north of the Saddle Mountains (fig. 1). The flow in all these streams is considerably regulated and affected by irrigation withdrawals. Springs giving rise to some streamflow occur west of the Reservation in the upper part of Cold Creek valley and on the flanks of the Rattlesnake Hills and Umtanum and Yakima Ridges. The flow from these springs generally sinks into the ground within 1/2 to 1 mile from their sources.

Occurrence and Movement of Ground Water

The ground water of the region occurs in permeable interflow zones and fractures mainly under artesian condition in the basaltic rocks, and in intergranular openings under both water-table and artesian conditions in the unconsolidated deposits. On the Hanford Reservation south and west of the Columbia River, the movement of ground water in the unconsolidated deposits has been intensively studied by the U.S. Geological Survey (Newcomb and others, 1970) and AEC contractors. Ground-water recharge to these deposits occurs by (1) infiltration of surface runoff from the ridges to the west and southwest; (2) discharge of waste water to the ground as part of the processing operations on the Reservation; (3) loss of water from the lower reach of the Yakima River year round, and from the Columbia River during high stages; and (4) direct infiltration where the water table is close to the surface (Newcomb and others, 1970, p. 70). Ground-water discharge from these deposits is to the Columbia River. On the north and east sides of the river, the unconsolidated deposits and the basaltic rocks are recharged by irrigation return water and by surface runoff in coulees and ditches (H. H. Tanaka and J. E. Luzier, U.S. Geol. Survey, oral and written commun., 1971). Ground-water movement is toward the Columbia River.

Water-bearing properties of the rocks.--Information obtained during drilling of numerous irrigation wells in the basaltic rocks consistently show that basalt flows yield little water but that thin zones of rubbly or fractured rock along the contacts of basalt flows yield large quantities of water. Sediments interbedded with basalt flows also yield large quantities of water. This contrast in water-bearing properties of the rocks is very marked and was investigated at well ARH-DC-1. Hydraulic tests of discrete zones of rock penetrated by well ARH-DC-1 allowed the transmissivity of individual rock units within those zones to be estimated (La Sala and Doty, 1971). At this well the basaltic rocks from 362 to 1,200 feet in depth have a transmissivity of about 695 ft^2/day. More than half of this transmissivity value is contributed by a sedimentary unit at a depth of about 830 to 936 feet which has a transmissivity of about 355 ft^2/day. A dense basalt zone from about 960 to 1,090 feet in depth has a transmissivity of only 0.2 ft^2/day. Data from well ARH-DC-1 also indicates that fracture zones of high transmissivity occur between flows that make up thick rock sections that are otherwise low in transmissivity. For instance, from a depth of about 2,100 feet to 3,900 feet there appear to be no significant water-bearing zones, except for a 10-foot-thick zone of fractured basalt at a depth of 3,230 feet which has a transmissivity of about 68 ft^2/day.

The values of transmissivity determined by hydraulic testing in well ARH-DC-1 were used to compute average hydraulic conductivity of rock materials in the various rock units. Average hydraulic conductivity is computed by dividing the transmissivity value by the thickness of the unit. Laboratory methods were also used to determine the hydraulic conductivity of several specimens of basalt. Hydraulic conductivity values can be used to compare the water-transmitting properties of different materials, which characteristically contain different types of water-bearing openings. Indirectly, these data can be used to appraise the water-transmitting properties of various types of water-bearing openings occurring in the basaltic rocks.

The basaltic-rock section contains water in (1) pore spaces and vesicles in the matrix rock of basalt flows, (2) fractures that cut across basalt flows, (3) tabular zones of intense fracturing or concentration of cinders or rubble along the contacts of flows, and (4) the pore spaces of sedimentary rocks interbedded with basalt flows.

The hydraulic conductivity of rocks in basalt flows results only to a small degree from pore spaces and vesicles. Laboratory determination of hydraulic conductivity values for five specimens of cored rock from well ARH-DC-1 range from $1.9X10^{-5}$ to $4.96X10^{-5}$ ft/day (La Sala and Doty, 1971). The smallest value determined was on a specimen of dense basalt having a porosity of 2.1 percent. A specimen of vesicular basalt having a porosity of about 25 percent has a hydraulic conductivity of $3.12X10^{-5}$ ft/day, only about 60 percent greater than that of the dense specimen. Apparently, vesicles in the basalt are not interconnected to an extent that would cause a significant increase in hydraulic conductivity with increasing void ratio.

Fractures in the basalt consist mainly of numerous joints caused by shrinkage during cooling and fewer master joints caused by tectonic forces. Shrinkage joints are of three types (Newcomb, 1965, p. 19). One common type separates the basalt into polygonal (usually hexagonal) columns that are normal to the cooling surfaces of the flow. These columns may range from about 1/2 foot to 5 feet or more in diameter and may extend through the greater thickness of a flow. The upper and lower colonnades of flows owe their characteristic appearance to the development of such joints. A second type of shrinkage joint separates the basalt into smaller more irregular, at places contorted, columns, generally about 6 inches across and commonly cross jointed into a form called "brickbat." This more irregular jointing occurs in the "entablature" of some flows, between the upper and lower colonnades as described by Mackin (1961, p. 14-15). Joints of a third type, which are essentially horizontal, consist of fractures that parallel the flow boundaries. Where the horizontal jointing is well developed, the basalt has a fissile appearance. Mackin (1961, p. 6), referring to the upper part of the Yakima Basalt, states that habits of cooling-contraction jointing differ markedly from flow to flow, and that distinctive arrangements of jointing patterns in a given flow tend to be persistent laterally and to be a means of identification. Master joints arising from tectonic forces are mainly vertical and cut across several flows. Joints of this type can be observed in Wallula Gap where they may be associated with faulting.

The effect of jointing on the permeability of basalt can be appraised from data collected at well ARH-DC-1. From hydraulic test data on competent basalt in place below a depth of 1,000 feet, average hydraulic conductivity values ranging from $1.6X10^{-3}$ to $3.1X10^{-3}$ ft/day were determined. These values are two orders of magnitude greater than the values determined for core specimens in the laboratory. The higher values for rocks in place probably are caused by water-bearing joints. Nevertheless, they are low, probably because many of the fractures contain veinlike fillings of secondary minerals, as was observed in some cores of basalt recovered from test holes on the Reservation, or because fractures are poorly interconnected. A hydraulic test on an 80-foot-thick interval of a basalt flow at a depth of 400 feet gave a greater hydraulic conductivity value of $2.9X10^{-2}$ ft/day. Fractures in a near-surface basalt flow, such as this, probably would tend to remain open to a greater degree than would those in flows that are more deeply buried. The reports of workers in other areas (Newcomb, 1965, p. 29; Garrett, 1968, p. 6-7) indicate that fracturing may result in significantly greater hydraulic conductivity than has been observed on the Reservation to date.

The most permeable water-bearing zones in the basaltic rocks occur along the contacts of some of the flows. These permeable zones are caused by fracturing and weathering of the upper parts of flows, which are particularly effective at producing numerous water-bearing openings if the rock is also vesicular (Foxworthy, 1958, p. 15). Such zones generally are only a few feet thick and make up a small percentage of the total basaltic-rock section. Newcomb (1965, p. 29) stated that the permeable zones comprise about one-tenth of the vertical section of the basalt. In well ARH-DC-1, permeable zones at flow contacts occur at depths of about 1,200; 2,050; 2,600; 3,200; and 4,000 feet. The average hydraulic conductivities of rocks in these zones were indicated from hydraulic tests to be as high as 8.7 ft/day. The zones are generally persistent but do thicken or thin and in places are absent. The water-bearing properties of the zones vary laterally because of changes in thickness and because of changes in the character of the contained material or degree of fracturing.

Other important water-bearing units are beds of sedimentary rocks interlayered with the basalt flows. At well ARH-DC-1, the principal permeable zones above a depth of 1,000 feet are sedimentary units containing beds of sand. These sedimentary units are considerably thicker than the permeable tabular zones along flow contacts. They range from about 25 to 100 feet in thickness and the principal zones occur at depths centering at about 500, 650, and 900 feet. They are considerably thicker than sedimentary beds reported in areas to the northeast and east of the Pasco Basin by Garrett (1968, p. 6) and Newcomb (1965, p. 19-20). The sedimentary unit at a depth of about 900 feet in well ARH-DC-1 consists mainly of well-sorted medium sand of moderate permeability; because of its thickness of about 100 feet, as well as its permeability, it is the most productive aquifer penetrated by this well. The average hydraulic conductivity of this aquifer is about 3.4 ft/day. Part of the water apparently produced from the other sedimentary units penetrated by the well may have come from zones of fractured rock along the contacts of the basalt flows overlying and underlying the sediments.

The effective porosity of the basalt flows, the fracture and rubble zones between basalt flows, and the sediments probably vary considerably. The porosities of the water-bearing units are a factor in the velocity of ground-water movement. The actual velocity of ground-water movement is inversely proportional to the porosity and directly proportional to the transmissivity and hydraulic gradient. (See Hubbert, 1940). If two rock units have identical transmissivities and are subject to the same hydraulic gradient, both will transmit water at the same flow rate. However, if they have different porosities, they will transmit water at different actual velocities, the unit of smaller porosity transmitting water at the higher velocity. In general, fractured basalt and zones of intense fracturing or rubble will have lower porosities than sedimentary beds. Therefore water will generally travel at relatively higher velocities through the fracture or rubble zones of high transmissivity than it will through the sedimentary beds in the basaltic rocks.

Structural control of ground-water movement.--The movement of ground water is strongly influenced by both depositional structure of the rocks and tectonic structures, chiefly folds and faults. As was previously described, the principal water-bearing zones in the basaltic-rock section are (1) thin tabular bodies of fractured or rubbly rocks lying at some contacts of basalt flows and (2) beds of sedimentary rocks. The average permeability of the rock section as a whole is therefore much greater in the direction concordant with the dip than in the discordant or cross-bed direction. In an area uncomplicated by structural features, water will tend to move more readily in a horizontal rather than in a vertical direction. This characteristic of the basaltic rocks tends to greatly restrict cross-bed movement of water into and from rocks that are deeply buried. The effect of the low cross-bed permeability in restricting percolation can be appreciated by viewing some of the contact springs high on the south flank of Umtanum Ridge, west of the Reservation. Water that infiltrates into jointed basalt on the ridge percolates downward to the upper contact of a dense basalt flow that has been exposed by erosion. Downward movement is greatly retarded by the dense basalt, and the water moves laterally along the upper contact of the dense basalt and discharges at springs.

Structural features of tectonic origin cause some considerable effects on the movement of ground water in the basalt. The upward arching and subsequent erosion of rocks in ridges formed by anticlines exposes some of the permeable zones to direct infiltration and facilitates recharge. Due to orographic effect, the ridges have higher precipitation than surrounding areas and this facilitates infiltration. On the other hand, sharp folds and faults generally are barriers or partial barriers to lateral ground-water flow (Newcomb, 1965, p. 31; 1969, p. C20-C21). In addition, Mundorff, Reis, and Strand (1952, p. 23-28) describe the significant effect to the Frenchman Hills (north of the region of study and parallel to the Saddle Mountains) on separating the ground-water systems of the Quincy Basin to the north and the Royal Slope and Crab Creek valley to the south. These authors also point out, but on the basis of fewer data, that the Saddle Mountains similarly separates the flow systems of Crab Creek valley and the Wahluke Slope. It would appear, therefore, that ground-water flow is inhibited at the ridges bounding the structural basins in the region. However, until more information becomes available on the structural character of these ridges, their effects on the hydrologic regime cannot be fully evaluated.

Recharge and discharge.--Recharge to the basaltic rocks occurs by (1) direct infiltration, which is probably small and takes place mainly on the ridges and valleys to the west of the Reservation; (2) seepage from surface runoff into coulees northeast of the Columbia River and into canyons on the anticlinal ridges and Horse Heaven Hills, in which permeable zones are exposed; (3) seepage resulting from irrigation activities, mainly in the area of the Columbia Basin Irrigation Project and in the Yakima River valley. This movement of water into the basaltic rocks may occur either where they are exposed at the surface or where they are covered with unconsolidated deposits. Recharge is enhanced, of course, if the overlying unconsolidated deposits are saturated perennially.

The natural recharge to the basaltic rocks underlying the main part of the Hanford Reservation, south and west of the Columbia River, mainly occurs in the upland valleys and ridges to the west. Only negligible natural recharge occurs on the Reservation, because of the small precipitation and the character and large thickness of the unconsolidated deposits there (Newcomb and others, 1970, p. 63). Considerable waste water enters the ground-water body in the unconsolidated deposits in the vicinity of the waste-storage areas. This waste water has raised the water table in the unconsolidated deposits considerably and has modified the direction and rate of movement of water in them. By analogy with the hydrologic effects produced by irrigation water in the Columbia Basin Irrigation Project, it is possible that waste water has recharged the basaltic rocks of the Hanford Reservation.

In the area of the Columbia Basin Irrigation Project (CBIP), north and east of the Columbia River, natural sources of recharge have been completely overshadowed by recharge from irrigation works. H. H. Tanaka and others, of the U.S. Geological Survey (oral commun., 1971), are studying the ground-water system of the irrigation project area and have estimated the recharge caused by irrigation activities. Tanaka estimates that to the south of Potholes Reservoir, which is near Othello, roughly 4 acre-feet of water for irrigation use is delivered annually per irrigated acre. Of these 4 acre-feet, consumptive use by crops is about 2 acre-feet, surface-water runoff about 0.4 acre-foot, evaporation about 0.6 acre-foot, and ground-water recharge, including that from lateral canals, about 1 acre-foot. In 1969, irrigated land was 457,000 acres and irrigation water supplied at the farms was 1,855,000 acre-feet. If the foregoing estimates are correct, about 450,000 acre-feet of project irrigation water enters the ground-water system in the southern part of the CBIP area during an average year. Part of this water definitely enters the basaltic rocks, as is shown by an increase in head and a change of water quality in the basalt at places. It is possible that water similarly has entered the basalt underlying the Hanford Reservation as a result of waste-water disposal.

Discharge of water from the basaltic rocks occurs by movement of water into streams and into the unconsolidated deposits lying at low elevations in the region and by seepage to the surface, forming springs at places on the flanks of ridges. Water is discharged from the unconsolidated deposits by movement into streams, by evapotranspiration, and by flow from springs occurring along bluffs and in dry streambeds.

Regional Investigations

About 250 records of wells, which contain reliable data on ground-water head in the basalt, were used in an analysis to discern the general ground-water flow patterns. A number of these wells were selected for sampling of ground water on the basis of location in the flow system and on construction details that would facilitate collection of representative samples. Ultimately, 22 wells were sampled in the region including and surrounding the Hanford Reservation. All these wells were in the depth range of about 500 to 1,500 feet. The data on ground-water head in wells could be interpreted only from the standpoint of discerning general flow patterns of the ground water in the basalt. The anisotropy of the basaltic rocks will cause the volume rates and velocities of flow to be unevenly distributed. There is a general lack of knowledge about the stratigraphic position and continuity of water-bearing units which would allow such variations in flow to be appraised. Many wells, especially irrigation wells, tap two or more water-bearing units and may be uncased through thick sections of the basalt. In such wells water may circulate through the uncased portion from one water-bearing unit to another and disturb the natural ground-water heads, even when the wells are not in use. The ground-water heads measured in such wells are composites resulting from cross-formational flow. The investigation was not made in detail sufficient to appraise such features of ground-water flow. The data do show, however, the broad relationships of ground-water head with the movement of ground water.

Chemical characteristics of the ground water.--The general chemical character of ground water sampled during the study is indicated by means of Stiff diagrams in figure 2. The analytical data are given in table 1 and records of the wells are given in table 2. The water from most wells in the basalt has characteristics similar to water from well ARH-DC-1 (fig. 3) at shallow to moderate depth. There is a tendency for calcium, magnesium, and sulfate to decrease and for sodium and chloride to increase with depth in ARH-DC-1.

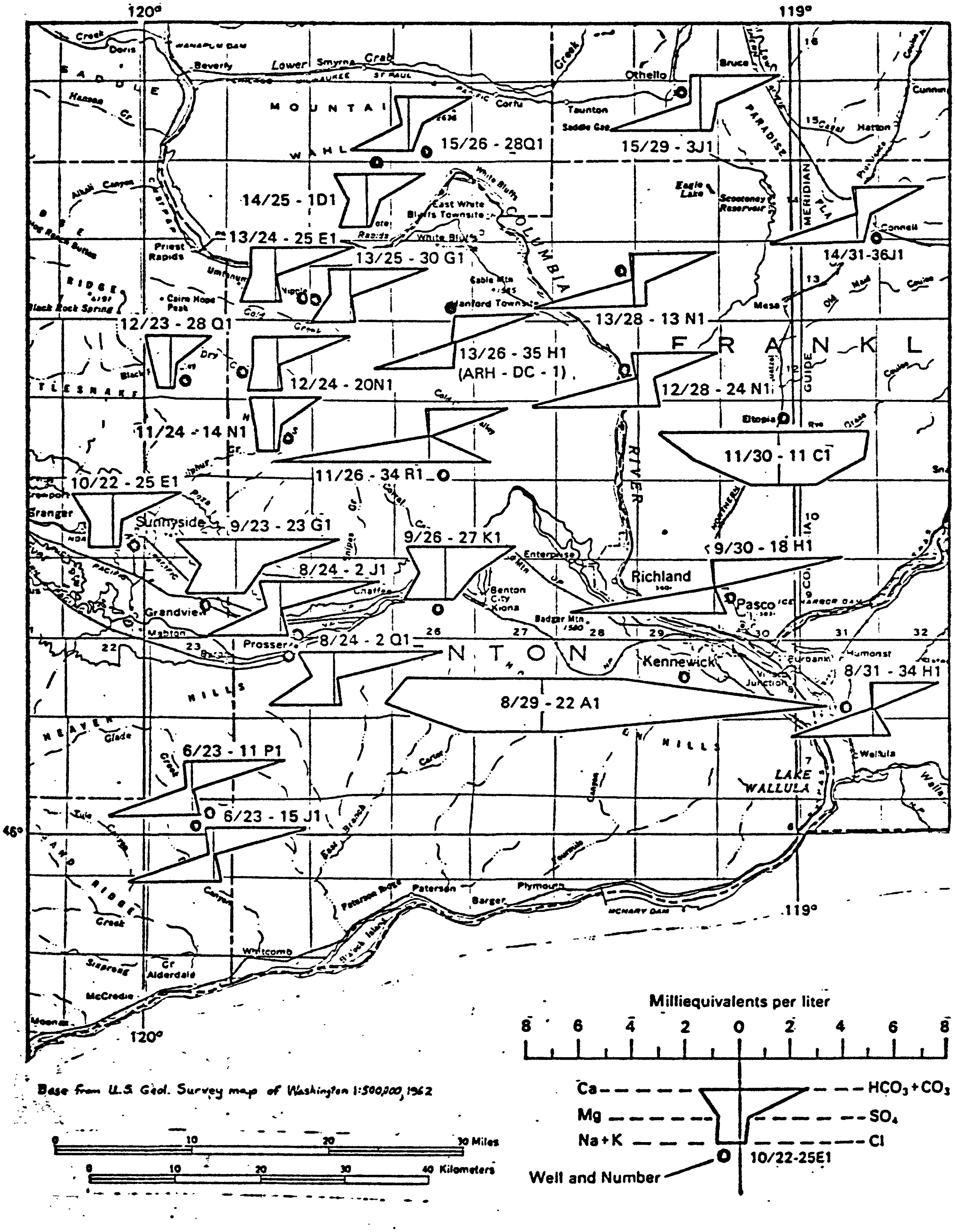

Figure 2. Chemical characteristics of ground water in south-central Washington.

Table 1.--Chemical analyses of ground-water samples from wells drawing water principally from basalt in south-central Washington

Well number	Date collected	Temperature (°C)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Chromium (Cr) (Total)	Nickel (Ni)	Copper (Cu)	Lead (Pb)	Zinc (Zn)	Calcium (Ca)	Magnesium (Mg)	Strontium (Sr)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Orthophosphate (PO_4)	Boron (B)	Dissolved solids: Calculated	Dissolved solids: Residue on evaporation at 180°C	Hardness: As $CaCO_3$	Hardness: Noncarbonate	Specific conductance (micromhos at 25°C)	pH	Color
			Milligrams per liter																													
[illegible]23-11P1	12/11/70	20	52	0.00	0.04	<0.02	<0.03	-----	<0.05	<0.1	<0.01	6.3	2.7	<0.05	64	15	0.04	207	0	0.0	9.2	1.0	0.1	0.07	0.01	252	252	27	0	348	8.1	0
[illegible]/23-11P1	10/21/70	22	56	.00	.03	<.02	<.03	<0.05	<.05	<.1	<.01	6.2	2.4	<.05	64	15	<.02	206	0	.2	9.1	1.0	.0	.09	.13	255	-----	26	0	348	8.1	0
[illegible]/23-15J1	10/22/70	21	57	.00	.03	<.02	<.03	<.05	<.05	<.1	<.01	6.8	2.7	<.05	64	13	<.02	205	0	.2	8.6	1.0	.2	.11	.07	255	-----	28	0	345	7.9	0
[illegible]/24-2J1	10/9/70	18	47	.00	.05	.08	<.03	<.05	<.05	<.1	<.01	16	6.2	<.05	55	11	<.02	222	0	.0	9.1	.9	.0	.03	.15	254	-----	66	0	380	7.4	0
[illegible]3/24-2Q1	9/28/70	16.8	45	.00	.05	.08	<.03	<.05	<.05	<.1	<.01	26	10	<.05	49	11	<.02	255	0	3.8	8.5	.6	.0	.13	.15	279	-----	106	0	429	---	0
[illegible]3/29-22A1 1/	11/17/70	23	53	.02	.27	.20	<.03	-----	<.05	<.1	<.01	103	72	.55	58	17	.03	184	0	512	16	.4	.4	.00	.03	922	1,015	550	400	1,240	7.3	0
[illegible]3/31-34H1	9/9/70	25.4	83	.11	.02	.05	<.03	-----	-----	----	-----	2.1	.2	-----	68	8.2	----	113	18	2.8	22	3.9	.0	.03	.53	272	275	6	0	327	9.0	0
[illegible]/23-23G1	10/7/70	16	52	.00	.03	<.02	<.03	<.05	<.05	<.1	<.01	44	15	.06	38	5.4	<.02	232	0	50	13	.6	.3	.05	.07	332	-----	172	0	484	7.9	0
[illegible]/26-27K1	10/12/70	21.5	59	.00	.03	<.02	<.03	<.05	<.05	<.1	.10	30	12	<.05	32	9.0	<.02	158	0	54	12	.4	.5	.03	.16	287	-----	125	0	405	7.8	0
[illegible]/30-18H1 2/	8/28/70	21	54	.03	.04	<.02	<.03	-----	-----	----	-----	1.9	.5	-----	115	11	----	277	10	.0	15	1.8	.0	.14	.10	350	358	7	0	506	8.6	0
10/22-25F1	10/6/70	20	62	.00	.03	<.02	<.03	<.05	<.05	<.1	<.01	29	9.7	<.05	16	7.4	<.02	157	0	16	4.8	.5	1.1	.04	.02	224	-----	113	0	307	7.6	0
11/24-14N1	11/13/70	15	45	.00	.03	<.02	<.03	<.05	<.05	<.1	.20	18	8.3	<.05	12	4.5	<.02	109	0	15	4.2	.4	.0	.09	.02	161	-----	79	0	219	7.5	0
11/26-34R1	11/19/70	24	75	.35	.05	<.02	<.03	-----	<.05	<.1	<.01	1.0	.0	<.05	122	15	<.02	154	15	.0	81	8.5	.2	.01	.49	400	408	3	0	597	9.8	0
11/30-11C1	12/14/70	14	45	.00	.02	<.02	<.03	-----	<.05	<.1	<.01	90	39	.75	21	4.6	<.02	210	0	158	51	.4	33	.02	.00	545	627	385	213	843	7.7	0
12/23-28Q1	9/21/70	15.4	36	.02	.02	<.02	<.03	-----	-----	----	.8	18	7.9	-----	9.0	1.8	-----	93	0	11	5.1	.4	4.1	.18	.06	139	146	78	2	201	7.2	0
12/24-20N1	9/11/70	26	56	.00	.08	.05	<.03	-----	-----	----	-----	18	11	-----	21	7.7	-----	170	0	.2	3.8	.6	.0	.02	.02	202	204	90	0	276	8.0	0
12/28-24N1	9/15/70	19	56	.14	.05	.10	<.03	-----	-----	----	-----	3.7	.7	-----	94	11	-----	170	8	29	29	4.2	.0	.13	.09	324	329	12	0	468	8.7	0
[illegible]/24-25E1	8/27/70	24.2	56	.09	.09	.10	<.03	-----	-----	----	-----	18	11	-----	26	7.3	-----	130	0	.2	4.4	.7	.0	.03	.09	213	213	90	0	295	8.0	0
3/25-30G1	8/27/70	26.9	56	.08	.07	.05	<.03	-----	-----	----	-----	16	8.9	-----	30	8.6	-----	175	0	.0	4.4	.7	.0	.03	.11	211	220	77	0	287	8.1	0
3/25-30G1	9/8/70	27	57	.08	.08	.05	<.03	-----	-----	----	-----	16	8.8	-----	30	8.3	-----	175	0	.0	4.5	.7	.0	.03	.07	211	216	76	0	288	8.1	0
3/26-35H1	5/8/69	----	46	.1	.10	.00	.00	-----	-----	----	-----	2.1	.3	-----	79	7.8	-----	199	10	.0	4.2	1.0	.1	.11	.06	249	252	6	0	344	8.6	0
3/28-13N1	11/10/70	27.6	67	.04	.04	<.02	<.03	<.05	<.05	<.1	<.01	.8	.4	<.05	78	17	<.02	182	1	19	14	2.2	.0	.26	.12	289	-----	4	0	386	8.6	0
4/25-1D1	9/17/70	26.4	56	.02	.14	<.02	<.03	-----	-----	----	-----	24	8.6	-----	17	11	-----	141	0	24	5.0	.4	.0	.03	.03	215	222	96	0	291	8.1	0
4/31-36J1	9/24/70	25	70	.00	.03	<.02	<.03	-----	-----	----	-----	3.1	.3	-----	72	9.0	-----	139	10	27	11	1.7	.0	.03	.07	267	269	9	0	352	8.8	0
5/26-28Q1	5/15/69	----	54	.0	.06	.00	.00	-----	-----	----	-----	11	3.3	-----	4.1	17	-----	139	3	24	4.3	.3	.2	.04	.04	226	220	41	0	303	8.4	0
5/29-3J1	10/27/70	20.4	56	.00	.03	<.02	<.03	<.05	<.05	<.1	<.01	7.6	4.8	<.05	70	13	.02	184	0	30	14	1.8	.2	.06	.06	288	-----	39	0	406	8.2	0

1/ A developed [illegible].

2/ [illegible] from the depth [illegible] well.

Table 2.--Records of wells in south-central Washington from which water samples were collected

Well number	Altitude of land surface (feet)	Depth of well (feet)	Depth of continuous unperforated casing (feet)	Static water level	
				Depth (feet)	Date
6/23-11P1	1,020	892	155	+81	3/18/70
6/23-15J1	1,050	633	128	1	6/18/67
8/24-2J1	650	768	525	24	--------
8/24-2Q1	645	744	493	----	--------
8/29-22A1	760	802	295	400	1950
8/31-34H1	456	385	130	115	10/21/68
9/23-23G1	798	1,148	248	127	7/7/44
9/26-27K1	1,472	670	450	450	1944
9/30-18H1	410	1,033	194	70	6/9/58
10/22-25F1	746	1,576	1,203	80	1945
11/24-14N1	2,860	407	-----	220	1970
11/26-34R1	1,212	1,000	739	802	1958
11/30-11C1	700	614	40	355	9/17/51
12/23-28Q1	2,200	2	-----	----	--------
12/24-20N1	1,060	1,200	400	+92	1924
12/28-24N1	430	755	-----	19	--------
13/24-25E1	924	777	625	+36	11/28/51
13/25-30G1	836	1,110	-----	+172	11/28/51
1/13/26-35H1	572	5,661	964	166	5/8/69
13/28-13N1	953	1,119	1,029	488	10/28/70
14/25-1D1	660	938	891	183	6/9/58
14/31-36J1	850	1,100	-----	415	1970
15/26-28Q1	770	892	860	317	9/1/53
15/29-3J1	1,096	905	550	225	1/30/65

1/ Well ARH-DC-1. Water level given is that for the depth interval of 540-620 feet measured during construction of the well.

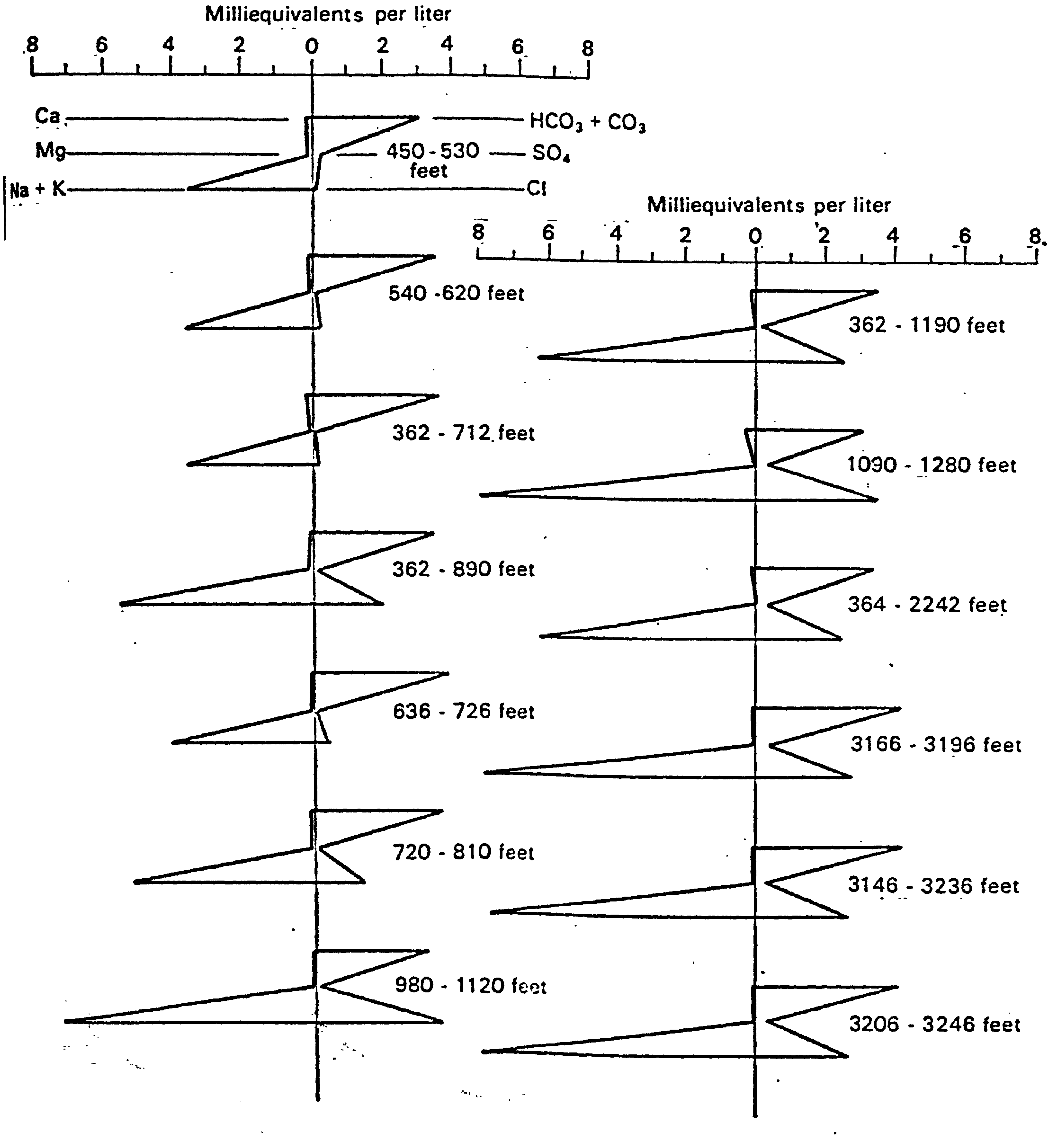

Figure 3. Chemical characteristics of ground-water samples from well ARH-DC-1 (13/26 - 35 H1)

The calcium and magnesium content is higher in the ground water of the Yakima River valley and somewhat higher on the Wahluke Slope than in typical ground water from the basalt. The chemical data also clearly show that irrigation water has entered the basalt at Eltopia through Esquatzel Coulee which receives irrigation return water. The sample from well 11/30-11C1 at Eltopia contained 33 mg/l (milligrams per liter) of nitrate, which is probably indicative of contamination by fertilizer, in addition to being high in other constituents. The high concentrations of calcium, magnesium, sulfate, and total solids in the sample collected south of Kennewick from well 8/29-22A1 appear to indicate contact with an evaporite deposit. It is not known if an evaporite deposit does occur interbedded with the basaltic rocks in this area. An alternate explanation for the high dissolved solids in the ground water is that chemical constituents are concentrated due to the character of the ground-water flow and the geologic features. This well is on a structural trend marked by a line of tightly folded anticlines and a fault in Wallula Gap. The water may have obtained its chemical character (1) due to its coming in contact with mineralized rock along this structure or (2) ground water may be extremely slow moving adjacent to this structure, which would allow the mineral content of the water to build up.

Radioisotope characteristics.--The radioisotopes, carbon-14 and tritium, were used to appraise the reliability of samples and to estimate the age of the water where possible. Results of the analyses are shown in table 3. This table is divided into four parts. Part A shows the data from wells believed to be representative of the ground water moving through the basaltic rocks on the main part of the Hanford Reservation, west and south of the Columbia River. Part B shows data believed to be representative of ground water in the basaltic rocks, but outside the area mentioned in part A. Part C gives data for the Yakima River valley. Part D gives those results for water not representative of or not interpretable in terms of the general characteristics of the water moving through the system.

Table 3.--Radioactive isotope characteristics and ages of ground water

Well number	Total dissolved carbonate as mg HCO_3^-/l 1/	Tritium TU ± 1σ	Carbon-14 percent modern ±1σ	Apparent age, years 1/	Adjusted age, years 1/
Part A	Samples representative of water moving through main part of Hanford Reservation, south and west of Columbia River.				
2/ 12/23-28Q1	132	1.7±0.3	97.2±0.9	200	0
12/24-20N1	171	<0.8	10.2± .4	18,000	16,000
13/24-25E1	187	<0.9	13.6± .6	16,000	13,000
13/25-30G1	187	<0.5	6.8± .3	22,000	19,000
13/26-35H1 (ARH-DC-1; interval 540-620 ft)	219	3/ 2.2±0.3	13.4± .4	16,000	12,000
11/26-34R1	174	<1.9	1.7± .5	33,000	30,000
Part B	Samples similar to but outside the area of those in Part A.				
6/23-11P1	210	<1.7	3.4±0.3	27,000	
6/23-15J1	207	<1.2	3.8± .3	26,000	
8/31-34H1	143	<0.8	1.8± .5	32,000	
9/30-18H1	300	<1.0	<0.6	>41,000	
12/28-24N1	179	4/ 2.8±0.4	5.1±0.6	>24,000	
13/28-13N1	183	<1.1	<1.3	>35,000	
14/31-36J1	162	<0.8	6.4±0.4	22,000	
15/29-3J1	184	<1.8	3.4± .3	27,000	
Part C	Samples from Yakima River valley wells. Relatively high tritium and low carbon-14 contents suggest mixed waters. Thus no age calculations can be made.				
8/24-2J1	229	25.9±1.5	--------		
8/24-2Q1	267	49.0±2.7	56.8±0.5		
9/23-23G1	250	53.8±2.9	63.2± .5		
10/22-25F1	170	<2.1	18.9± .4		
Part D	Samples from wells not indicative of the general character of water in flow systems. (See text.)				
8/29-22A1	192	8.1±0.5	10.4±0.4		
9/26-27K1	159	<1.5	14.6± .3		
11/24-14/N1	117	0.8±0.3	38.7± .5		
11/30-11C1	220	100±5	89.6±1.0		
14/25-1D1	151	<1.2	--------		

1/ See p.40.

2/ A developed spring.

3/ Tritium residual from drilling fluid. (See text.)

4/ Tritium presence shows admixture of recent water, as from casing leakage. Carbon-14 is therefore probably also too high, so only lower limit age reported.

The tritium content of the water samples has been used to appraise the reliability of the samples. Those tritium values preceded by less-than signs (<) are within two standard deviations of the detection limits of the analytical apparatus, and mean that no measurable quantity of tritium was present. The range in these values arises from normal variations in laboratory procedures. The lack of measurable tritium means the water was in the ground long enough for its tritium content to decay. Those tritium determinations reported in terms of a standard error of plus or minus one standard deviation indicate the presence of measurable tritium. If the tritium content exceeds 10 tritium units, the water entered the ground in recent years following the testing of nuclear weapons which raised the tritium content of the meteoric water significantly above the former background level of a few tritium units. In some parts of the Hanford Reservation, shallow ground water contains tritium derived from plutonium manufacture. This shallow water was cased off in well ARH-DC-1. The tritium content of the sample from a depth of 540-620 feet in well ARH-DC-1 shows that some drilling fluid, which was made up with water from the Columbia River, is residual in the sample. Wells 8/24-2J1, 8/24-2Q1, and 9/23-23G1 are probably inducing some infiltration from the Yakima River or irrigation ditches. Well 12/28-24N1 possibly has a leaky casing which is allowing some near-surface water to enter the well.

The carbon-14 content of the water sample is also given in table 3. As with tritium, the less-than (<) values are within two standard deviations of the analytical detection limits, whereas the remainder show measurable carbon-14, plus or minus one standard deviation. The total dissolved carbonate values in table 3 represent the sum of all carbonate species (dissolved CO_2, HCO_3^-, and $CO_3^=$) in the sample and were calculated from pH and alkalinity measurements made at the sampling site. Because field data were used in calculations, these values of total carbonate may differ from the laboratory-determined values of HCO_3^- plus $CO_3^=$ in table 1. The alkalinity and pH of a bottled water sample commonly change after collection. The field measurements generally are more representative of the ground water.

Carbon-14 ages on normal samples are calculated using the expression

$$\frac{A}{A°} = \exp\ (-8033t)$$

where A/A° is the ratio of sample carbon-14 activity to the activity of a standard of age zero years, t is the sample age, in years, and 8,033 the mean life of carbon-14 based on the conventional half-life of 5,570 years. In table 3, the values of carbon-14 are reported as percentages of modern values, and apparent ages given were calculated using the expression

$$A/A° = \%\ \text{Modern}/100.$$

An underlying assumption in the use of the equation given above is that there has been no net gain or loss of carbon-14 from the sample throughout its history except by radioactive decay. This assumption is often untrue for ground-water samples, for the carbonate they contain is usually a mixture of carbonate present at the time of recharge and carbonate dissolved from the aquifer. The latter is carbon-14 free because of its age, and it acts to lower the net carbon-14 content of the water and hence give an apparent age greater than the real age.

A method given by Pearson and Hanshaw (1970) was applied as follows to account for the dilution of C-14 by carbonate dissolved from the aquifer. A spring (12/23-28Q1) high in Cold Creek valley is assumed to represent the carbonate content (128 mg/l) of the principal recharge to the ground-water system in the main part of the Hanford Reservation. Carbonate contents in excess of the value found in the spring water are assumed to be from solution of aquifer carbonate containing no carbon-14. To correct for this dilution of C-14 by the aquifer carbonate, the measured carbon-14 activity is multiplied by the ratio of the sample carbonate content to the initial recharge carbonate content. That is

$$\text{Activity}_{\text{adjusted}} = \text{Activity}_{\text{measured}} \times \frac{\text{Total carbonate}_{\text{sample}}}{\text{Total carbonate}_{\text{recharge}}} .$$

The adjusted activity is then substituted for "A" in the exponential equation given previously to calculate an adjusted age. Ages adjusted by this method were calculated only for those samples from the system in the main portion of the Reservation because data were not available on the character of the recharge water elsewhere in the region.

Characteristics of the Regional Flow System

The general pattern of ground-water flow in the region was appraised from water-level data for wells and test holes in the region, the water-chemistry reconnaissance, the structural features of the rocks described by Newcomb (1970) and Bingham and others (1970), and the detailed data on well ARH-DC-1. Figure 4 shows the inferred direction of ground-water flow and altitudes of ground-water levels in the wells that were sampled. Water-level data from about an additional 200 wells were considered in preparing this map. There is a general consistency of ground-water levels, chemical character of the water, and age of the ground water with the flow regime as presented in figure 4.

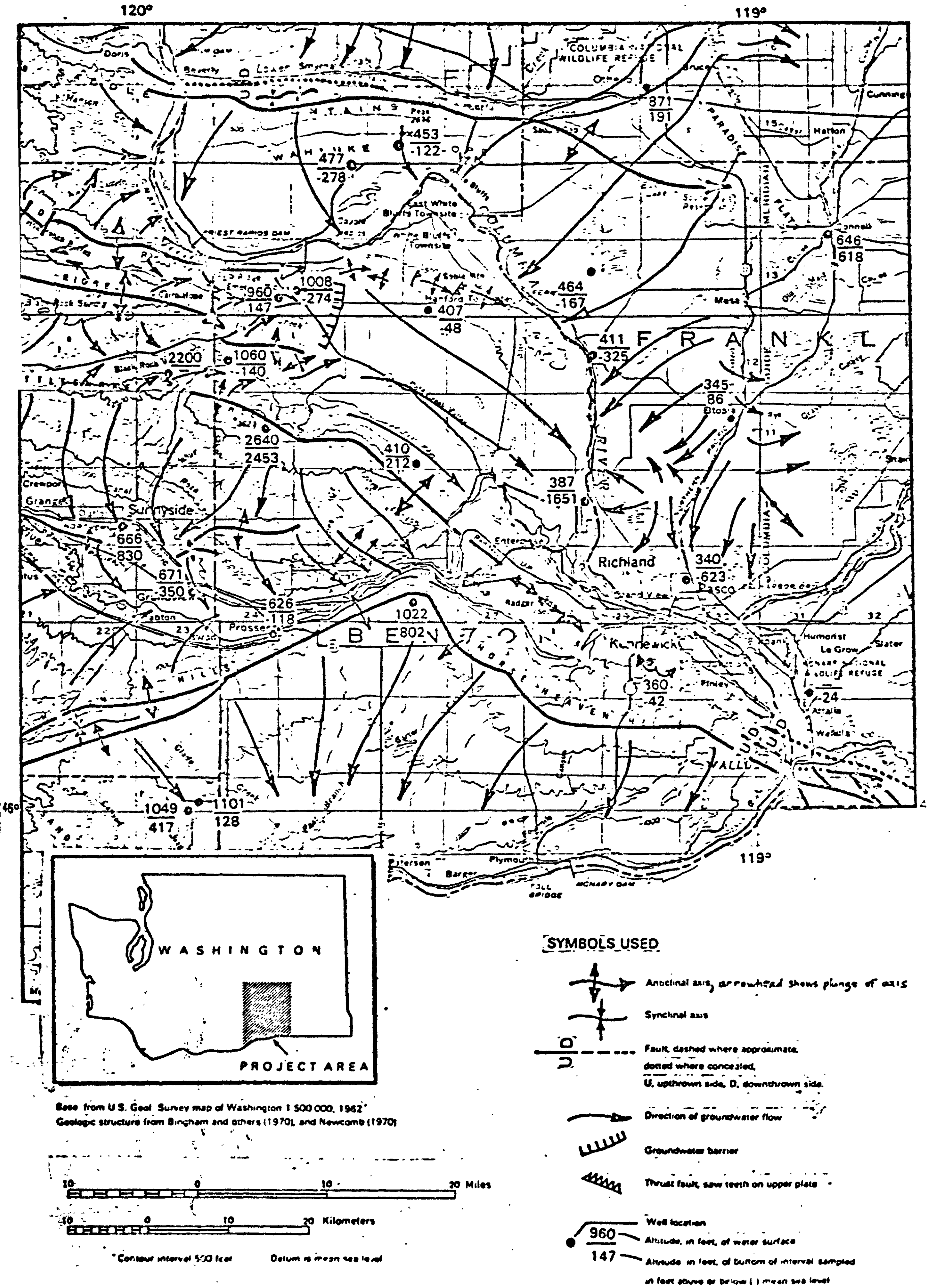

Figure 4. Inferred direction of ground-water flow in the basaltic rocks of south-central Washington

A comparison of the data on water samples and the information on ground-water flow in the Columbia Basin Irrigation Project provided by H. H. Tanaka of the U.S. Geological Survey (written commun., 1971), indicates that the carbon-14 ages and chemical characteristics of ground water are generally consistent with the flow pattern described by Tanaka. A piezometric map prepared by Tanaka shows that ground water moves generally southeasterly toward the Columbia River through a large regional flow system. Superimposed on this large system are smaller systems mainly arising from recharge produced by irrigation activities, such as the large southward trending ground-water mound along Esquatzel Coulee, west of Eltopia.

The creation of Lake Wallula doubtless has affected the flow system by raising the water-level elevations in a long reach of the Columbia River. Water levels in deep wells between Pasco and Eltopia, for instance, were at or close to the present normal pool level prior to filling of the lake. The water-level altitudes of about 340 to 345 feet in figure 4 for wells 9/30-18H1 and 11/30-11C1, respectively, were measured prior to filling of the lake or extensive irrigation activity. Presumably, hydraulic gradients presently are adjusting to creation of the lake as well as to recharge from irrigation waters. Samples collected in this flow regime show an increase in the age of the ground water from Othello and Connell to the wells near the Columbia River, generally consistent with the ground-water flow pattern. The sample from well 11/30-11C1 at Eltopia is high in both nitrate and tritium as would be expected where the basaltic rocks were recharged with irrigation water. Another exception was found in the water from the well at Ringold (12/28-24N1) which has a tritium content (2.8 ± 0.4 TU), possibly indicating leakage of young water around the casing, but it nevertheless has a low C-14 content (5.1 ± 0.6) percent of modern. This indicates that a mixture containing young water was obtained and that relatively old water probably occurs at depth at Ringold. Carbon-14 contents below the two standard-deviation detection limits were found in the samples obtained north of Pasco (well 9/30-18H1) and also north of Ringold (well 13/28-13N1) near the Columbia River.

On the Hanford Reservation west and south of the Columbia River, the isotope analyses also appear to be consistent with hydraulic gradients. The ground-water ages in this area were adjusted to a carbon content giving spring 12/23-28Q1 an adjusted age of zero years. This spring probably is the best available representation of the character of the recharge water in the two synclinal valleys of Cold Creek and Dry Creek. The results from the closely spaced flowing wells 13/24-25E1 (adjusted age 13,000 years) and 13/25-30G1 (adjusted age 19,000 years) may appear anomalous. However, well 13/25-30G1 taps deeper water-bearing zones having higher heads than does well 13/24-25E1 and has intercepted older water. A ground-water barrier which was hypothesized by Newcomb and others (1970) and which may be related to a sharp decrease in altitude of the bedrock surface east of the wells, causes an abrupt change in the ground-water gradient in the basalt between the wells in Cold Creek valley and well ARH-DC-1. The average ground-water head is about 1,000 feet in altitude in Cold Creek valley, but the head is only about 407 feet in altitude in the upper aquifer penetrated by well 13/26-35H1 (ARH-DC-1). The ground-water heads at well ARH-DC-1 decrease abruptly at a depth of about 3,600 feet. The lowest head measured in this well has an altitude of 365 feet and occurs in a water-bearing zone of relatively high transmissivity at a depth of 4,000 feet (La Sala and Doty, 1971). This head is nevertheless higher than the normal pool elevation of Lake Wallula which is 340 feet above mean sea level. About 18 miles southeastward from well ARH-DC-1, a core hole DDH-3 is completed with a piezometer set at a depth of 2,025 feet. The head measured in this piezometer is about 386 feet in altitude. At well 11/26-34R1, about 12 miles south of well ARH-DC-1, the head is about 410 feet above sea level. These water-level data indicate that ground-water flow is southeastward through this part of the Reservation. The carbon-14 age determinations are not inconsistent with this conclusion, considering that the water sample from well ARH-DC-1 was obtained from a shallow depth compared to those samples from other wells. The relatively young age of the ARH-DC-1 sample (12,000 years) probably reflects some vertical diffusion of young water with ground-water moving from the recharge areas.

The decrease in head with depth at well ARH-DC-1 indicates that there is a downward vertical component of ground-water flow to the water-bearing zone at 4,000 feet. The altitude of the ground-water head in this zone is higher than the normal pool elevation of Lake Wallula, which indicates that the water can move to the Columbia River in that reach. However, this discharge to the river would have to occur south or southeast of core hole DDH-3. The relatively old water occurring at well 11/26-34R1 (fig. 2; table 3) is indicative that flow is southeastward and probably parallels Rattlesnake Mountain.

The wells in the Yakima Valley, and possibly well 9/26-27K1 (fig. 2), are part of a separate flow system. The chemical character of these ground waters is different from those occurring elsewhere in the region and the ground-water levels are considerably higher than those occurring on the Hanford Reservation.

Wells 6/23-11P1 and 6/23-15J1 in the Horse Heaven Hills contain water having chemical characteristics typical of other moderately old water from the basalt. The ground-water levels in these wells are considerably higher than those in the Yakima Valley yet the water is older. On the basis of this information, it is inferred that a separate system in which flow is generally southward is tapped by these wells. The recharge area is probably to the north in the upper part of Glade Creek valley (T. 7 E., R. 22 N.) where it parallels the crest of the Horse Heaven Hills (fig. 4) and lies in a minor syncline/ which has been breached by erosion.

Conclusions

The data are indicative of characteristics of regional ground-water flow systems with superposed local systems that have been widely recognized by many hydrologists and were systematically formulated by Tóth (1962; 1963). The authors cannot yet sufficiently describe the characteristics of the flow in the region as to direction and velocity, particularly at depths below 1,000 feet, for purposes of this feasibility study. However, the following conclusions seem logical:

1. The main part of the Hanford Reservation contains a large flow system originating in recharge areas in the uplands to the west, which include Cold Creek and Dry Creek valleys. The flow is southeasterly, and discharge is to the Columbia River. The relatively low heads that occur with depth in well ARH-DC-1 indicate a downward component to ground-water flow at that site. Downward flow there may be caused by (1) recharge occurring locally in the vicinity of the waste-storage areas and arising from the discharge of waste water to the unconsolidated deposits; (2) movement of water locally in a direction opposite to the dip of the basaltic rocks, because of the strong anisotropy of the rock section; and (3) the existence of a higher order flow system at a depth below 3,600 feet having different flow characteristics. The water occurring below a depth of 3,600 feet at well ARH-DC-1, if circulating in the same direction as the shallower ground water, must discharge ultimately to the Columbia River southeast of the Reservation but north of the Horse Heaven Hills.

2. A regional flow system northeast of the Columbia River discharges to the river. This regional flow system extends much outside the area of study to the northeast. Superimposed on it are local shallower flow systems having the ground-water movement directed toward a few small drainage basins or directed away from areas of irrigation recharge.
3. The Yakima River valley, bounded north and south by topographic highs, contains a local ground-water flow system with higher water levels than the system at the Reservation.
4. The southern flank of the Horse Heaven Hills include part of a separate ground-water system in which flow is southward.
5. Ground water circulating through the flow systems that have been identified does not cross the major topographic divides formed by anticlines. This may be caused partly by the closures on the structures and, at places, by associated faults.

Recommendations for Further Studies

The hydrologic factors involved in determining the feasibility of deep-cavern storage of wastes cannot be evaluated adequately with the data thus far obtained. More information is needed on the direction of movement and time of travel of ground water to discharge areas. Future studies should include test drilling on the main part of the Reservation to ascertain in detail the character of the flow system. It is proposed that two deep test wells be drilled near the western and southern boundaries of the waste-storage areas. These wells should be tested to determine heads, transmissivities, and water chemistry of discrete zones. These wells, along with well ARH-DC-1, should allow a determination of the hydraulic gradients, stratigraphy, and ground-water movement in the immediate area. A second triangle of three wells more widely spaced should then be drilled farther southeast on the Reservation, with the most southerly well located near core hole DDH-3 so as to take advantage of data from that hole and to determine the flow patterns and hydrologic characteristics of the system as far south on the Reservation as possible. Also, more water samples from existing wells should be taken south of the Reservation and near the Columbia River to determine if the chemical characteristics of the water can be used to identify the discharge area of the system. More samples should also be obtained from springs in upland areas so that better appraisals can be made of the carbon-14 age of ground water and the chemical changes occurring in the water as it flows through the system.

Acknowledgments

The authors would like to thank their colleagues in the Geological Survey, who provided support and encouragement. P. C. Benedict, regional research hydrologist, supervised the study, and Robert Schneider and C. V. Theis provided much valuable advice and reviewed this report. Other colleagues who reviewed the report are R. K. Blankennagel, Alfred Clebsch, Jr., J. H. Robison, B. L. Foxworthy, W. W. Dudley, and Robert Schoen.

Within the Richland Operations Office of the AEC, Messrs. O. J. Elgert, director, Production Programs Division, and E. B. Jackson, chief, Waste Management Branch, requested that this study be made and obtained financial support for it. They and Mr. David J. Squires maintained a continual interest in it and provided various support services through their own offices and through AEC contractors.

In the Atlantic Richfield Hanford Company, Messrs. Raymond E. Isaacson, manager, Advance Process Development Section, and Donald J. Brown, assisted the authors in obtaining data and provided laboratory services in making up reagents needed for field use.

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