O-22053

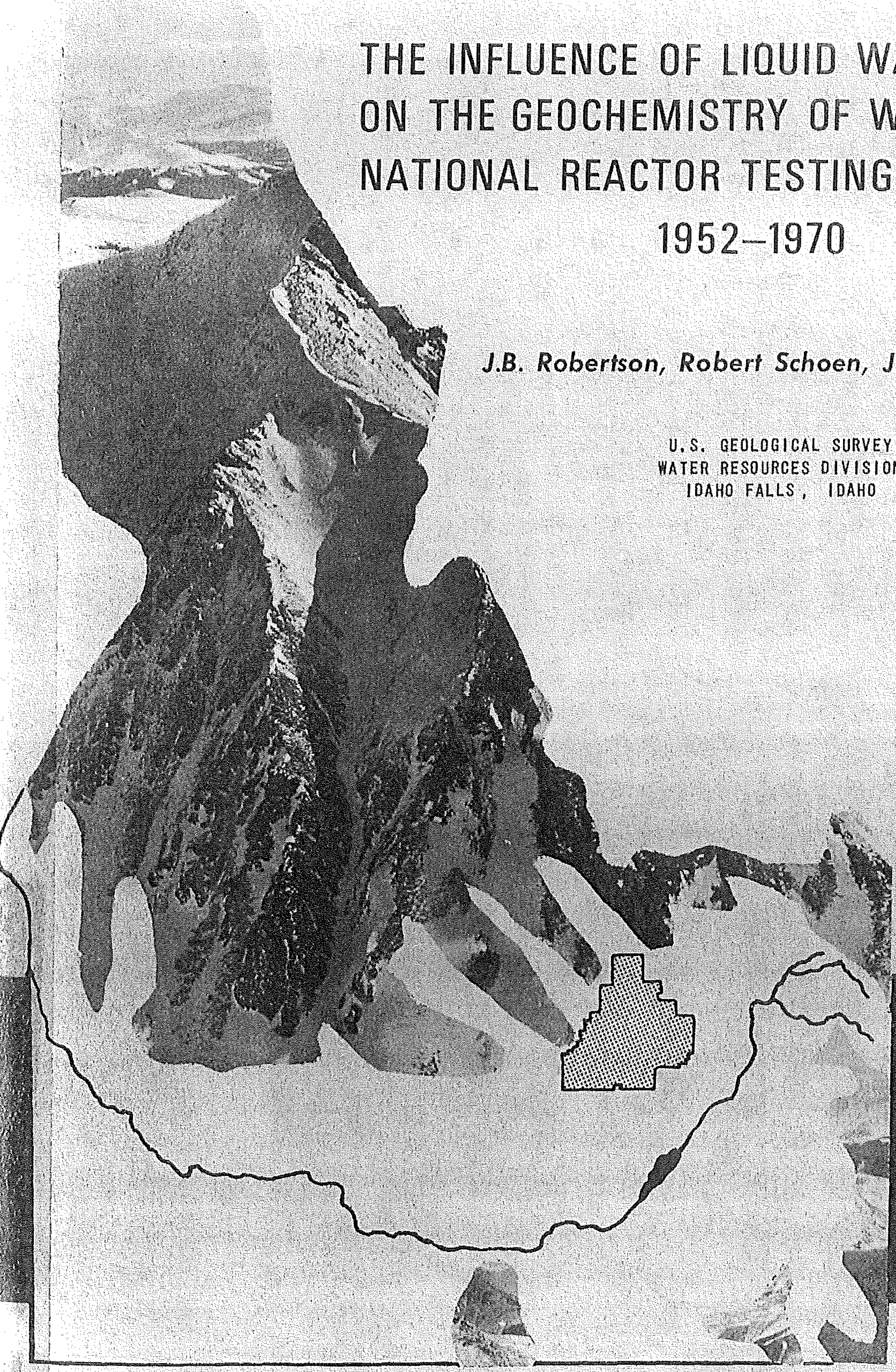
~~F.A. Kohout~~ UC-70

DEPARTMENT OF THE INTERIOR
March 3, 1849

THE INFLUENCE OF LIQUID WASTE DISPOSAL ON THE GEOCHEMISTRY OF WATER AT THE NATIONAL REACTOR TESTING STATION, IDAHO: 1952–1970

J.B. Robertson, Robert Schoen, J.T. Barraclough

U.S. GEOLOGICAL SURVEY
WATER RESOURCES DIVISION
IDAHO FALLS, IDAHO



PREPARED IN BEHALF OF
THE
U.S. ATOMIC ENERGY
COMMISSION

USGS Open-File Report
IDO-22053
Waste Disposal and Processing
TID-4500
Issued: February 1974

THE INFLUENCE OF LIQUID WASTE DISPOSAL ON THE GEOCHEMISTRY OF WATER AT THE NATIONAL REACTOR TESTING STATION, IDAHO: 1952-70

by

J. B. Robertson, Robert Schoen,
and J. T. Barraclough

U. S. Geological Survey

Prepared in cooperation with
The United States Atomic Energy Commission

ABSTRACT

This report describes studies at the National Reactor Testing Station (NRTS), Idaho by the U. S. Geological Survey, which were sponsored by the U. S. Atomic Energy Commission. It presents a summarized evaluation of the geology, hydrology, and water geochemistry of the NRTS and the associated influences of subsurface liquid-waste products discharged from the NRTS facilities. The progressive buildup, distribution, and changes of both radioactive and chemical wastes are analyzed for the total disposal period -- 1952-70. Of principal concern is the fate of wastes discharged from the NRTS in the Snake River Plain aquifer, an extremely large and productive groundwater system underlying the vast eastern Snake River Plain.

A review of the available evidence for the geologic formation and structure of the plain indicates that it is most likely a large graben structure with several thousand feet of displacement, filled with a thick sequence of basalt flows and interbedded sediments. In some areas (Twin and Big Southern Buttes) silicic volcanism has been important. The formation of the plain and associated volcanism began about 7 million years ago (Pliocene time) and has continued to recent time, no more than 1,600 years ago. These conclusions are supported by new geochemical data gathered from thermal springs around the fringes of the plain.

Runoff from the mountainous fringes of the plain (such as the Big Lost River) recharges groundwater in the Snake River Plain aquifer, which flows southwestward toward the American Falls and Hagerman Valley areas of discharge into the Snake River. Groundwater beneath the NRTS is of exceptionally good quality with low dissolved solids (generally about 250 milligrams per liter) due to the abundant precipitative recharge in surrounding mountains, the high permeability of the aquifer and short residence time of most groundwater, the relative inertness of the basaltic matrix, and the mildly alkaline composition of recharge to the aquifer. The composition of the groundwater generally reflects the composition of rocks in the surrounding mountains and valleys rather than the composition of Snake River Plain basalts. Deep groundwater beneath the NRTS contains appreciably greater amounts of sodium, fluoride, and silica than shallow groundwater and is inferred to reflect the presence of silicic volcanic rock beneath the basalts and sediments of the Plain as well as longer groundwater residence periods. Irrigation recharge water can be readily distinguished from ordinary groundwater by its higher content of dissolved solids, higher nitrate, and warmer temperature. Due to the near-saturation of groundwater beneath the NRTS with calcite and dolomite, care must be used in its utilization to avoid precipitation of solids.

Since 1952, the NRTS facilities (primarily the Test Reactor Area -- TRA, Idaho Chemical Processing Plant -- ICPP, and the Naval Reactor Facility -- NRF) have discharged

1.6×10^{10} gallons of liquid waste containing 7×10^4 curies of radioactivity and about 1×10^8 pounds of chemicals to the subsurface. The discharge has been disposed in wells and seepage ponds. The principal waste products include tritiated water, strontium-90, cesium-137, cobalt-60, sodium chloride, chromates, and heat. Wastes at the NRTS have been distributed in the Snake River Plain aquifer and overlying bodies of perched groundwater according to hydrologic and geochemical controls.

Expansion of the plume of waste products in the aquifer from the ICPP disposal well has been traced over the years. Chloride and tritium in this plume are most widely distributed, detectable over about 15 square miles of the aquifer. Migration of cationic waste products, especially strontium-90 and cesium-137, has been greatly retarded by sorption. Radioactive decay is a significant influence on the spreading and dilution of wastes as they move down-gradient in the aquifer. No detectable wastes have been found close to or beyond the southern boundary of the NRTS. Materials and heat balances calculated for the ICPP wastes indicate that the interpretive subsurface distributions are valid and that the wastes generally remain in the upper 250 feet of the aquifer. The balances indicate that heat and tritium are maintaining an equilibrium (nearly constant) inventory. Waste plumes from TRA and NRF are poorly defined because of insufficient observation wells.

CONTENTS

FIGURES

TABLES

THE INFLUENCE OF LIQUID WASTE DISPOSAL ON THE GEOCHEMISTRY OF WATER AT THE NATIONAL REACTOR TESTING STATION, IDAHO: 1952-70

I. INTRODUCTION

1. LOCATION AND DESCRIPTION OF THE NATIONAL REACTOR TESTING STATION

The National Reactor Testing Station (NRTS) covers 572,000 acres (894 square miles) of sagebrush land in southeastern Idaho (Figure 1). The NRTS is located near the central part of the semiarid eastern Snake River Plain and has an average altitude of about 4,900 feet. The eastern Snake River Plain is a structural basin about 200 miles long, 50 to 70 miles wide, an area of about 12,000 square miles. It extends from the north-eastern corner of Idaho, near Yellowstone Park, southwest toward the Hagerman-Twin Falls area. The eastern Snake River Plain consists of a thick sequence of basalt lava flows and sediments, perhaps in excess of 5,000 feet thick.

The eastern Snake River Plain is underlain by a vast body of groundwater contained in the Snake River Plain aquifer, sometimes called "Snake Plain aquifer" (Mundorff and others, 1964), which is the major aquifer in Idaho. The NRTS obtains its water supply from this aquifer. The Snake River Plain aquifer is defined here as the continuous groundwater system underlying the eastern Snake River Plain, generally contained within the basalts and interlayered sediments of the Snake River Group.

The NRTS was established in 1949 for the construction, operation, and testing of various types of nuclear reactors by the U. S. Atomic Energy Commission (AEC). It is one of the principal centers for developing peacetime uses of atomic energy. It has the world's largest and most varied collection of reactors, including research, testing, power, and propulsion reactors. Forty-eight reactors have been constructed; of which 22 are presently operable.

In 1949, the AEC requested the U. S. Geological Survey (USGS) to investigate and describe the water resources of the NRTS and adjacent areas. A continuing program of investigations serves to determine natural changes in the geohydrology and also to determine changes brought about by activities at the station.

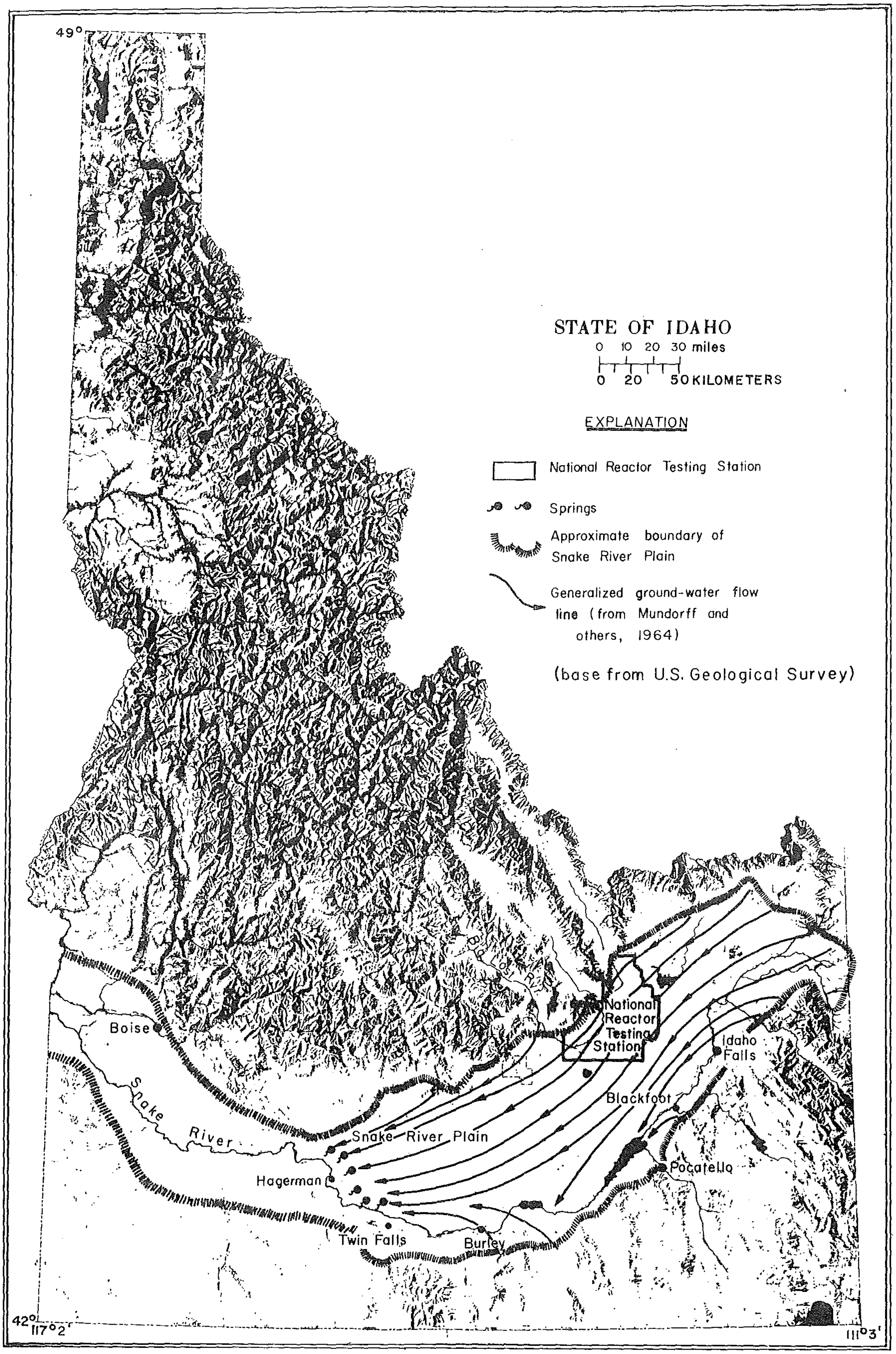


Fig. 1 Relief map of Idaho showing the location of the NRTS, the Snake River Plain, and inferred groundwater flow lines of the Snake River Plain aquifer (base from U. S. Geological Survey).

During recent years, the USGS has investigated the subsurface movement of low-level radioactive wastes and the chemical and radiochemical changes that accompany such waste movement in terms of the geologic, hydrologic, and geochemical factors that influence the changes. Study of the hydrology of subsurface waste disposal at the NRTS requires, among other things, knowledge of: geology of the Snake River Plain, flow patterns in the aquifer, locations and quantities of waste disposed, and methods of disposal.

2. HISTORICAL DEVELOPMENT: 1949-70

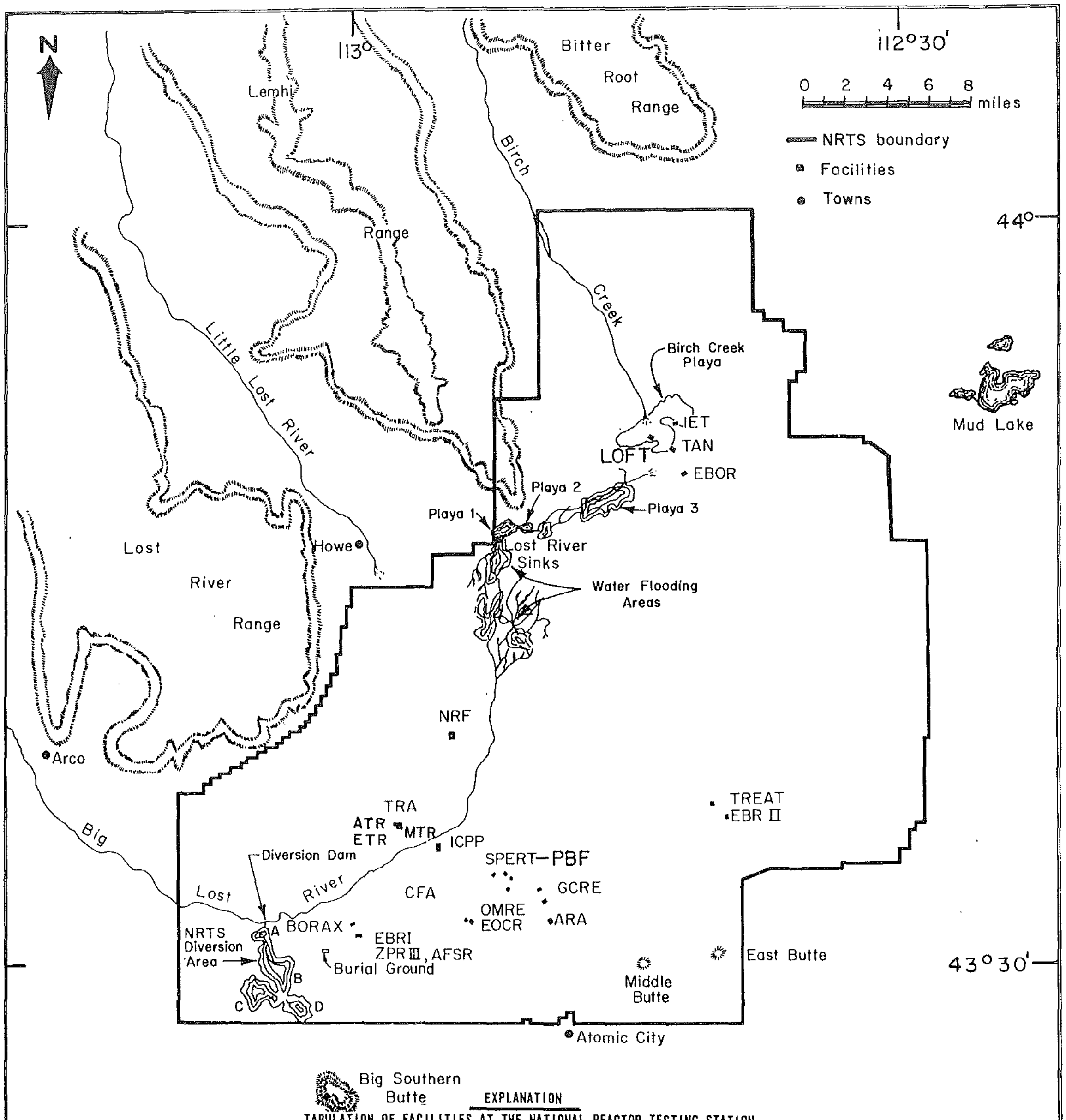
Construction of the first reactor on the NRTS, Experimental Breeder Reactor-I (EBR-I), was completed in 1951. The first electric power was generated at EBR-I on December 20, 1951 and the feasibility of breeding nuclear fuel was demonstrated. The number of facilities constructed to date at the NRTS has greatly exceeded early estimates. Names, abbreviations, and locations of the facilities mentioned in this report, as well as other important installations at NRTS, are shown on Figure 2.

The Materials Testing Reactor (MTR) was completed in 1952 at the Test Reactor Area (TRA). Contruction of the Submarine Thermal Reactor (STR) at the Naval Reactor Facility (NRF) started in 1950 and was completed in 1953. The Idaho Chemical Processing Plant (ICPP) was constructed from 1950 to 1953. Used nuclear-fuel elements are dissolved at the plant, and unused fissionable material is extracted for reuse in new fuel elements.

These four installations provided the initial program for the NRTS. The principal operations and tests concerned with breeding nuclear fuel, nuclear propulsion for ships, test irradiations on various materials, and processing nuclear fuel elements have continued. In many cases, facilities have been expanded and concepts changed. A considerable number of additional facilities and programs have also been initiated, such as Test Area North (TAN) and Experimental Breeder Reactor-II (EBR-II). However, three of the four primary installations mentioned above (TRA, ICPP, and NRF) are the principal waste contributors and will therefore receive most of the attention in this report.

3. PURPOSE AND SCOPE OF REPORT

Since 1952, the AEC has disposed of several thousand curies of low-level, liquid radioactive waste at the National Reactor Testing Station, Idaho. The principal results and effects of this disposal on the environment have been under study by the USGS and AEC since disposal began. However, the data and results of these individual studies are dispersed through many reports or have never been published. In addition, the entire body of information has not been analyzed comprehensively. Because of increasing national concern over the effects of waste disposal, a comprehensive analysis is needed to present the results



EXPLANATION

TABULATION OF FACILITIES AT THE NATIONAL REACTOR TESTING STATION

Name	Abbreviation	Name	Abbreviation
Advanced Test Reactor	ATR	Idaho Chemical Processing Plant	ICPP
*Argonne Fast Source Reactor	AFSR	*Initial Engineering Test Facility	IET
Auxiliary Reactor Area	ARA	Loss of Fluid Test Facility	LOFT
*Boiling Water Reactor	BORAX	Materials Testing Reactor	MTR
Central Facilities Area	CFA	Naval Reactors Facility	NRF
Engineering Test Reactor	ETR	*Organic Moderated Reactor Experiment	OMRE
*Experimental Beryllium Oxide Reactor	EBOR	Special Power Excursion Reactor Test	SPERT
*Experimental Organic Cooled Reactor	EOCR	Test Area North	TAN
*Experimental Breeder Reactor No. 1	EBR-I	Test Reactor Area	TRA
Experimental Breeder Reactor No. 2	EBR-II	Transient Reactor Test Facility	TREAT
		Zero Power Reactor No. 3	ZPR-III
*Gas Cooled Reactor Experiment	GCRE	Power Burst Facility	PBF

Fig. 2 Map showing major facilities and surface water features in the vicinity of NRTS. Asterisk indicates facilities which are no longer operational.

of the disposal system. Such an analysis would constitute a case history for this geohydrologic environment, involving extremely anisotropic groundwater flow conditions in a basalt aquifer, high groundwater velocities, and wide lateral dispersion. The analysis might be applicable, to some extent, to other terranes with similar hydrologic conditions, for instance, fractured rocks or cavernous limestone.

Data in this report illustrate past and present conditions related to the disposal of liquid waste to the subsurface environment. These data also provide a key for evaluating possible future effects of waste disposal and will be useful in evaluating accidental waste releases, should they occur.

Many of the earlier studies covered conditions for only small areas of the NRTS or for brief time spans. This report attempts to amalgamate these available data into a total NRTS picture for the entire period of record, and to provide new and more comprehensive interpretations. The authors as well as other concerned people felt a special need for a current geologic summary of the Snake River Plain and surrounding area. The summary shows the geologic controls on water chemical composition and points to areas where additional geologic information is required.

The principal object of this report is to analyze radiometric and geochemical effects on the environment resulting from liquid waste disposal from late 1952 through 1970. Emphasis is placed on the processes responsible for changes in groundwater quality and the implications of those changes with regard to future disposal operations. The study is based primarily on previous data and information. Rates of movement and dispersion patterns of tritium, strontium-90, sodium, chloride, chromium, temperature, and specific conductance are analyzed and compared for various times. Processes affecting the waste distribution changes include radioactive decay, sorption or ion exchange, oxidation-reduction and other chemical reactions, hydraulic dispersion, and horizontal and vertical head distributions.

A prerequisite for evaluating the influence of NRTS operations on the subsurface environment is a detailed understanding of the natural or background chemical composition of the groundwater. This report contains considerable data on the groundwater chemistry prior to NRTS operations. The apparent relationships of groundwater compositions to minerals in the enclosing rocks are also discussed.

Some concern is also directed toward water-quality changes due to agricultural practices adjacent to NRTS. It is important that such outside influences be distinguished from NRTS effects.

Although the Solid Waste Burial Ground is an important NRTS waste management facility, it has not been included in the scope of this report, which is directed solely to liquid wastes. A separate investigation of the Burial Ground and the possible migration of radioactive wastes from it was completed in 1972. The final report is not yet available but is expected to be released in 1974.

4. ACKNOWLEDGMENTS

Grateful appreciation is expressed to the many individuals who provided a variety of helpful contributions to this investigation. Walter G. Belter, former Chief, Environmental and Sanitary Engineering Branch, Division of Reactor Development and Technology, U. S. Atomic Energy Commission, and members of his staff, Harold Bernard, William P. Gammill, and I. Craig Roberts, provided guidance, goals, and encouragement for this study.

Geological Survey investigations at the NRTS were coordinated by AEC personnel of the Health Services Laboratory at the NRTS. Charles A. Pelletier, former Chief of the Environmental Branch, Health Services Laboratory, and his successor, Adrian H. Dahl, have provided helpful guidance throughout the study. George L. Voelz, former Director, and Donald I. Walker, Director of the Health Services Laboratory, provided staff support which greatly facilitated our work.

The detailed chemical and low-level radiometric analyses were performed by the staff of the Analytical Chemistry Branch, Health Services Laboratory, Claude W. Sill, Chief. These numerous data provided a very important part of the waste migration study. Joseph H. Osloond, Environmental Branch, furnished considerable waste disposal data. Bruce L. Schmalz, AEC, made helpful suggestions during the early part of the study. Wilfred L. Polzer, Environmental Branch, furnished useful data and suggestions on ion exchange.

The supervision, guidance, and assistance provided by Paul C. Benedict, Robert Schneider, George DeBuchananne, and Alfred Clebsch, Jr., of the U. S. Geological Survey were invaluable. Donald E. Trimble, Don R. Mabey, and Robert L. Christiansen of the U. S. Geological Survey provided stimulating advice and counsel on geologic and geophysical problems. Numerous other Geological Survey personnel have been helpful in various phases of the study, including Charles V. Theis, Raymond L. Nace, Franklin H. Olmsted, Elmer H. Baltz, Jr., and Emerson G. Crosthwaite. Particularly significant were the contributions of Rodger G. Jensen, who collected and tabulated most of the samples and field data, ran geophysical logs, plus many other contributions too numerous to mention.

Aerojet Nuclear Company provided the following: cover design by Doyle W. Elison and his staff, Graphic Arts, Research and Engineering; layout and final typing by the Technical Editing Section, R. T. Struhs, Supervisor, report reproduction by the Printing and Reproduction Department, Vern E. Wagner, Chief.

II. GENERAL HYDROLOGY OF THE NRTS AND VICINITY

(J. B. Robertson, J. T. Barraclough)

Knowledge of the general geology and hydrology of the NRTS and vicinity is needed in order to evaluate the effects of waste disposal. This is especially important at the NRTS because the subsurface formations are hydraulically quite heterogeneous and anisotropic. The geometry of the aquifer has a very pronounced influence on groundwater flow. Sedimentary beds contained within the volcanic rocks alter flow patterns, especially vertically. Information on amounts and locations of aquifer recharge and seepage from surface streams is needed to help understand the dynamics of the flow system.

1. METEOROLOGY

The National Oceanic and Atmospheric Administration (NOAA), by agreement with the Reactor Development Division of the Atomic Energy Commission, established a weather station with a staff of meteorologists and technicians at the NRTS in 1949. This station has the responsibility of providing meteorological support for operations at the NRTS and of conducting studies of the transport, diffusion, and deposition of airborne effluents. The information in this section of the report is adapted primarily from NOAA data (Yanskey and others, 1966).

The location of the NRTS in a broad, rather flat valley with the surrounding mountain ranges, its altitude above sea level, and its latitude, all have a definite effect upon the climate as well as on the day-to-day weather. All air masses entering the Snake River Plain must cross over mountains and, in so doing, lose much of their moisture outside the plain. The yearly rainfall is generally 8 to 10 inches and the region has semidesert characteristics. The local northeast-southwest orientation of the eastern plain and its mountain range walls tend to channel the prevailing west winds so that a southwest flow predominates. The relative dryness of the air and the sparse low cloudiness permit intense solar heating of the surface during the day and rapid radiational cooling at night, which give a large diurnal range of temperature.

The Centennial and Beaverhead Mountains to the north act as an effective barrier and keep most of the shallow, but intensely cold, winter air masses that push southward from Canada over the Great Plains from entering the Snake River Plain. Occasionally, however, the cold air can spill over the mountains.

Since 1950, the average annual precipitation at the Central Facilities Area (CFA) (Figure 2) was 8.54 inches. The maximum annual precipitation was 14.40 inches in 1963 and the minimum was 4.50 inches in 1966. At Test Area North (TAN) the average annual precipitation is 7.85 inches. The maximum annual precipitation was 15.60 inches in 1963 and the minimum annual precipitation was 4.37 inches in 1956.

The two wettest months on the average are May and June with about 2.5 inches of total precipitation. The average precipitation for each of the other 10 months ranges from 1/3 of an inch to almost an inch. July is the driest month, on the average. Normal annual snowfall is about 26 inches. The maximum annual snowfall is 41 inches and the minimum is 11 inches. The maximum snow depth on the ground is 24 inches. Snowfall accounts for about 30% of the annual precipitation.

The annual average temperature at CFA is 42.4°F. January is normally the coldest month with an average temperature of 15.4°F and July the warmest, averaging 69.0°F. The lowest daily minimum temperature of record at CFA is -40°F and the highest is 101°F.

2. SURFACE WATER

Surface water at the NRTS consists mainly of streams draining through intermountain valleys to the northwest -- Big Lost River, Little Lost River, and Birch Creek (Figure 2). Local spring runoff in other parts of the station can also be significant at times. Most of the NRTS lies within the Pioneer Basin, a closed topographic depression into which the three above mentioned streams drain. The termination for the three drainages is the Birch Creek Playa in the north-central part of the Station (Figure 2).

The Big Lost River is by far the most important element of the surface water hydrology. Flow from the Little Lost River and Birch Creek very seldom reaches the NRTS, whereas the Big Lost River has carried a significant discharge onto the Station during most of the past 10 years. Except during years of extremely high runoff, all flow from the Little Lost River and Birch Creek is diverted for irrigation before it reaches the NRTS or the terminating playas. The average discharge of Little Lost River, 7 miles northwest of Howe, is about 50,000 acre-feet per year or 70 cubic feet per second (cfs). The average discharge for Birch Creek is about 57,000 acre-feet per year (79 cfs) near Reno, Idaho. For comparison, the Big Lost River discharges an average of 208,000 acre-feet per year (289 cfs) below Mackay Dam, 30 miles northwest of Arco. The flow of Birch Creek is remarkably uniform, as shown in Figure 3, because it is primarily fed by groundwater inflow. During periods of extremely rapid thawing and runoff, such as early spring of 1969, water from the Birch Creek drainage can become a flood threat to facilities at TAN. Otherwise, Birch Creek and Little Lost River have a negligible effect on NRTS hydrology. Therefore most of the interest in surface water at NRTS is directed toward the Big Lost River.

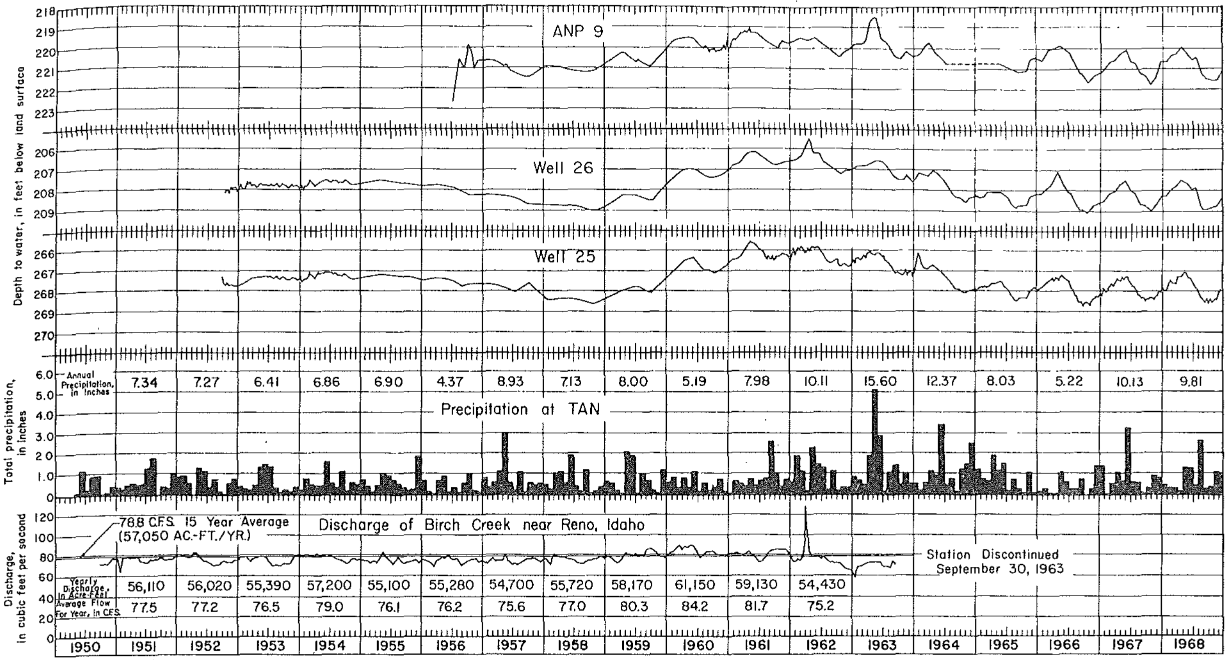


Fig. 3 Hydrographs of three wells in the northern part of the NRTS, precipitation at TAN, and discharge of Birch Creek near Reno, Idaho.

The Big Lost River flows southeastward down the Big Lost River valley past Arco and out onto the Snake River Plain, and then turns northward through the NRTS to its termination in playas 1, 2, and 3 (Figure 2). After entering the Plain, the river continually loses water by infiltration through the channel bottom. Therefore the distance to which flow is carried in the channel depends on the discharge and infiltration conditions. At times flow does not even reach the NRTS, and at others it continues as far as playa 3. If playa 3 ever fills to capacity, it will overflow into Birch Creek Playa. As flow approaches playas 1 and 2, the channel branches into many distributaries and the flow spreads over several flooding and ponding areas.

The maximum discharge of the Big Lost River occurred in water year 1965 (397,000 acre-feet below Mackay) and the average for 54 years of record is 208,000 acre-feet per year (Figure 4). The effects of the 1965 record flow are discussed in detail by Barraclough, Teasdale, and Jensen (1967). The second highest discharge occurred in 1969 and nearly equaled the 1965 record.

Two major artificial controls affect the river in addition to irrigation diversions. These are Mackay Dam, 30 miles above Arco, and the NRTS flood-diversion system in the southwestern part of the Station (Figure 2). The NRTS flood-control diversion system was constructed in 1958 to reduce the threat of floods on the NRTS from the Big Lost River. The diversion dam can divert flow out of the main channel to spreading areas A, B, C, and

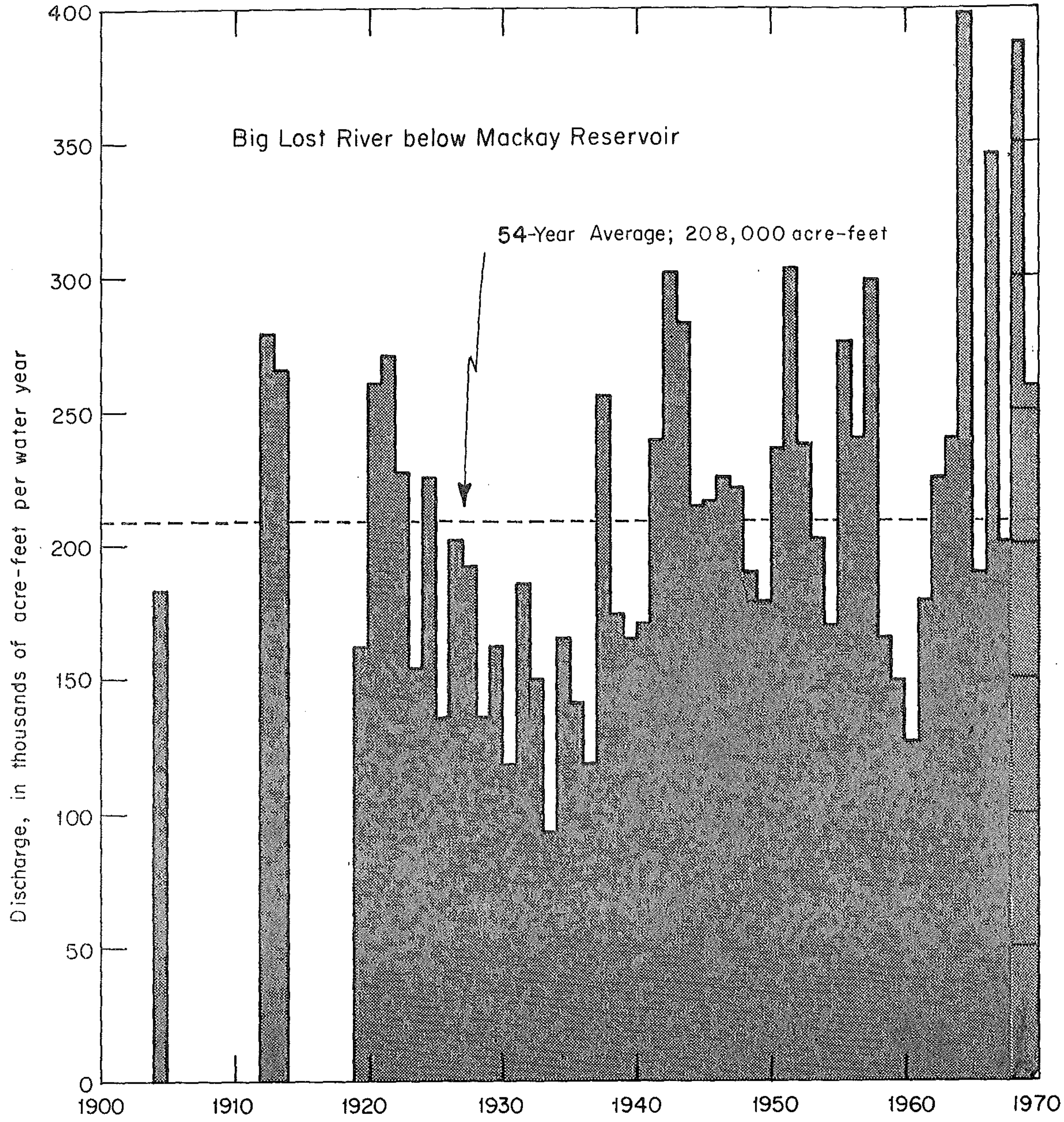


Fig. 4 Graph showing the yearly discharge of the Big Lost River below Mackay Reservoir.

D. During winter months nearly all flow is diverted to avoid accumulation of ice in the main channel downstream on the Station. Also during periods of high discharge much of the flow is automatically diverted to the spreading areas (as occurred in the summers of 1965 and 1969). Details of the channel regimen and hydraulics of the river on the Station are discussed by Lamke (1969). The lower hydrograph on Figure 5 shows an example of the

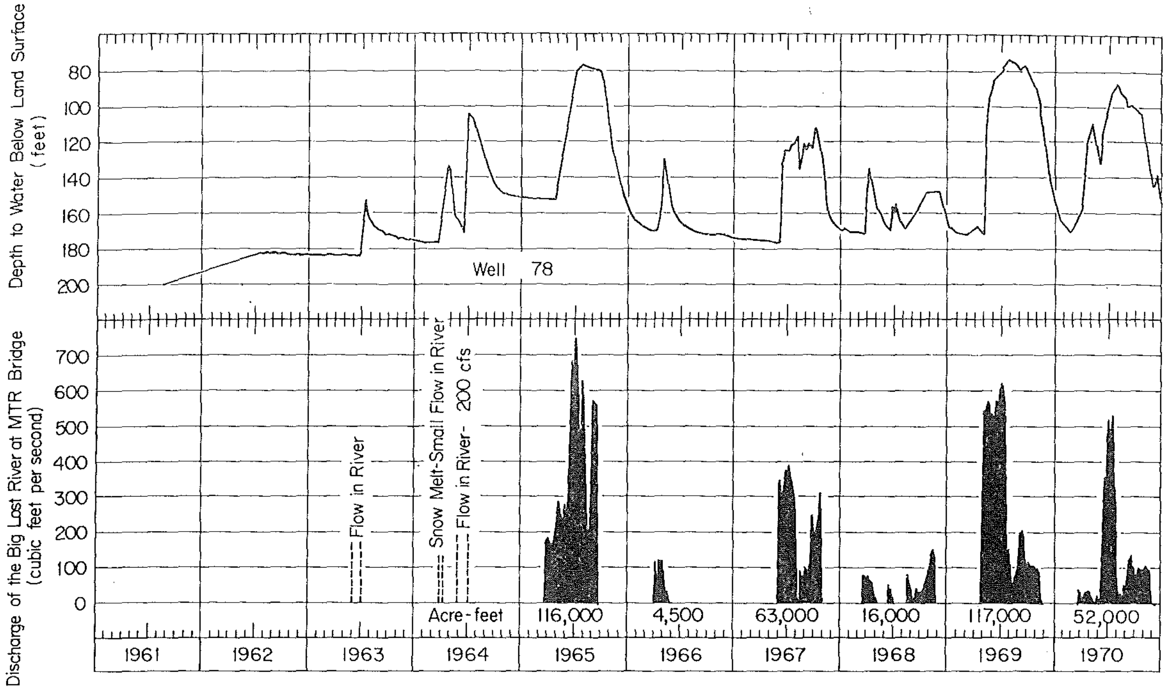


Fig. 5 Hydrographs of the Big Lost River at the Lincoln Blvd. bridge near the TRA and perched water level in Well 78.

discharges on the Station downstream from the diversion structure at the bridge where Lincoln Boulevard crosses the river between ICPP and TRA (Figure 5). As indicated by the hydrograph, 1969 was the record high discharge with 117,000 acre-feet.

All flow of the Big Lost River that enters onto the Snake River Plain is recharged to the subsurface, except for evaporation losses. Recharge effects from the Big Lost River are very pronounced in the Snake River Plain aquifer and in perched water beneath the river. These effects are discussed in more detail in the following section on groundwater.

Many NRTS facilities are located on the floodplain of the Big Lost River, within 2.5 miles of the river. These include the Solid Waste Burial Ground and the ICPP, TRA, NRF, and TAN facilities (Figure 2). An unusually large flood (such as one which would occur only once in 300 years on the average) could theoretically be damaging to some facilities. For this reason, much attention has been focused on Big Lost River hydrology. Carrigan (1971) has done a detailed analysis of the probability and potential effects of rare catastrophic floods on the Big Lost River, in relationship to the NRTS.

3. GROUNDWATER

Groundwater, which serves as the sole NRTS water supply source, is the most important factor of NRTS hydrology. Although the Snake River Plain aquifer is the principal groundwater body, in some areas of the Plain, including NRTS, local bodies of perched groundwater may be important. Only a summarized description of the groundwater resources at NRTS is presented here; more comprehensive information (particularly regarding the Snake River Plain aquifer) can be found in published reports (Mundorff and others, 1964; Norvitch and others, 1969; and R. L. Nace, J. W. Steward, and W. C. Walton, written communication, 1959).

3.1 Snake River Plain Aquifer

The Snake River Plain aquifer is referred to here as the continuous body of groundwater underlying nearly all of the eastern Snake River Plain which is outlined on Figure 1. Mundorff and others (1964) referred to this aquifer as the "Snake Plain aquifer". The aquifer is about 200 miles long by 30 to 60 miles wide and comprises an area of about 9,600 square miles. Lithologically, the aquifer is composed of a series of thin basalt flows, generally 10 to 75 feet thick, with interbedded layers of fluvial, lacustrine, windblown, and pyroclastic sediments. Most of the aquifer permeability occurs along the upper and lower contacts of successive basaltic flows which have large and irregular fractures, fissures, and other voids. This leads to a large degree of heterogeneity and anisotropy in the hydraulic properties of the aquifer.

The thickness of the aquifer is not known because no wells have been drilled deep enough to pass through it. Most evidence indicates that the aquifer is between 1,000 and 10,000 feet thick. Seismic and deep resistivity data indicate that the aquifer may be about 5,000 feet thick in the NRTS region. The deepest well is only 1,500 feet. R. L. Nace (written communication, 1959) believed that effective thickness of the aquifer is on the order of only 1,000 feet and that it may contain 2×10^9 acre-feet of water, of which 5×10^8 acre-feet might be recoverable. Even though the basalt-sediment sequence which fills the Snake River Plain depression may be 5,000 feet or more thick, evidence (page 148) indicates that the upper part of the sequence, perhaps the upper 500 feet, may be considerably more permeable and thus the most effective part of the aquifer.

Groundwater generally flows southwestward through the aquifer from the north and northeastern recharge areas to the south and southwestern discharge areas (Figure 1). According to Norvitch, Thomas, and Madison (1969), about 6.5 million acre-feet (2.12×10^{12} gallons) are discharged by the aquifer annually. Most of the discharge occurs as springs near the Hagerman area and a region west of Pocatello and as irrigation well withdrawals. The water table in the Snake River Plain aquifer slopes from northeast to southwest at an average gradient of about 10 feet per mile. The depth to the water table ranges from zero in some of the spring discharge areas to about 1,000 feet a few miles southwest of NRTS.

The transmissivity of the aquifer generally ranges from 1×10^6 to 100×10^6 gallons per day per foot (gpd/ft) with 5×10^6 gpd/ft being in the normal range (Norvitch and others, 1969). Measured storage coefficients (S) of the aquifer are highly variable both spacially and temporally, ranging from 0.001 to 0.2. Norvitch and others used an average value of S = 0.15 for an electrical analog model of the aquifer.

Average flow rates in the aquifer are difficult to assess. Tracer studies at the NRTS indicate natural flow rates in the range of 5 to 20 feet per day with an average near 10 feet per day. However, these local measurements are not necessarily representative of velocities throughout the aquifer. Indirect estimates of general flow rates were made by assuming certain properties of the aquifer. Studies at the NRTS (Barraclough, Teasdale, Robertson, and Jensen, 1967 and data presented later in this report) indicate the effective (water-transmitting) porosity of the aquifer is in the range of 5 to 10%. If a value of 8% is assumed together with an effective aquifer thickness of 2,000 feet, an average flow rate can be calculated. An average of about 70 cfs flows through the aquifer per mile width in the central part (southern-NRTS), based on a generalized flow net analysis (Mundorff and others, 1964). This is equivalent to 1,200 ft^3 (cubic feet) per day per foot of aquifer width. If the aquifer is 2,000 feet thick, this would be 0.6 ft^3 per day per square foot of aquifer cross section normal to the flow direction. For an 8% porosity, this is an actual velocity of eight feet per day which is certainly in good agreement with the NRTS measurements. Actual velocities, of course, would vary greatly from place to place in the aquifer because of its heterogeneity, but it appears that the average velocity is on the order of 5 to 10 feet per day. Using a different approach, flow rates of 10 to 20 feet per day were calculated using transmissivities of 5×10^6 to 10×10^6 gpd/ft, an assumed thickness of 2,000 feet, and an average hydraulic gradient of 10 feet per mile.

3.2 Snake River Plain Aquifer at the NRTS

The part of the Snake River Plain aquifer beneath the NRTS is typical of the aquifer in general. Depth to the regional water table (Snake River Plain aquifer) at the NRTS varies from about 200 feet in the northeast corner to 900 feet in the southeast corner. Depth to water in the TRA-ICPP area is about 450 feet. The average hydraulic gradient is about 5 feet per mile to the southwest (Figure 6). Data from Mundorff and others (1964) indicate that about 2,000 cfs flow beneath the NRTS at its widest point. Aquifer pumping tests performed on 20 different NRTS production and test wells indicate transmissivities ranging from 3×10^4 to 1.8×10^7 gpd/ft (Walker, 1960, and Walton, 1958). Lowest values were generally at the northern end of the site (TAN) and the highest were for wells in the TRA. A normal or average transmissivity for the NRTS might be 2×10^6 to 3×10^6 gpd/ft. Storage coefficients range from 0.01 to 0.06.

In 1970, the entire NRTS water supply was provided by 24 production wells which tapped the Snake River Plain aquifer. The wells pumped a total of 2.6×10^9 gallons for the year. About half (1.2×10^9 gallons in 1970) of the volume pumped is returned to the subsurface by waste disposal operations. An additional unknown amount also returns

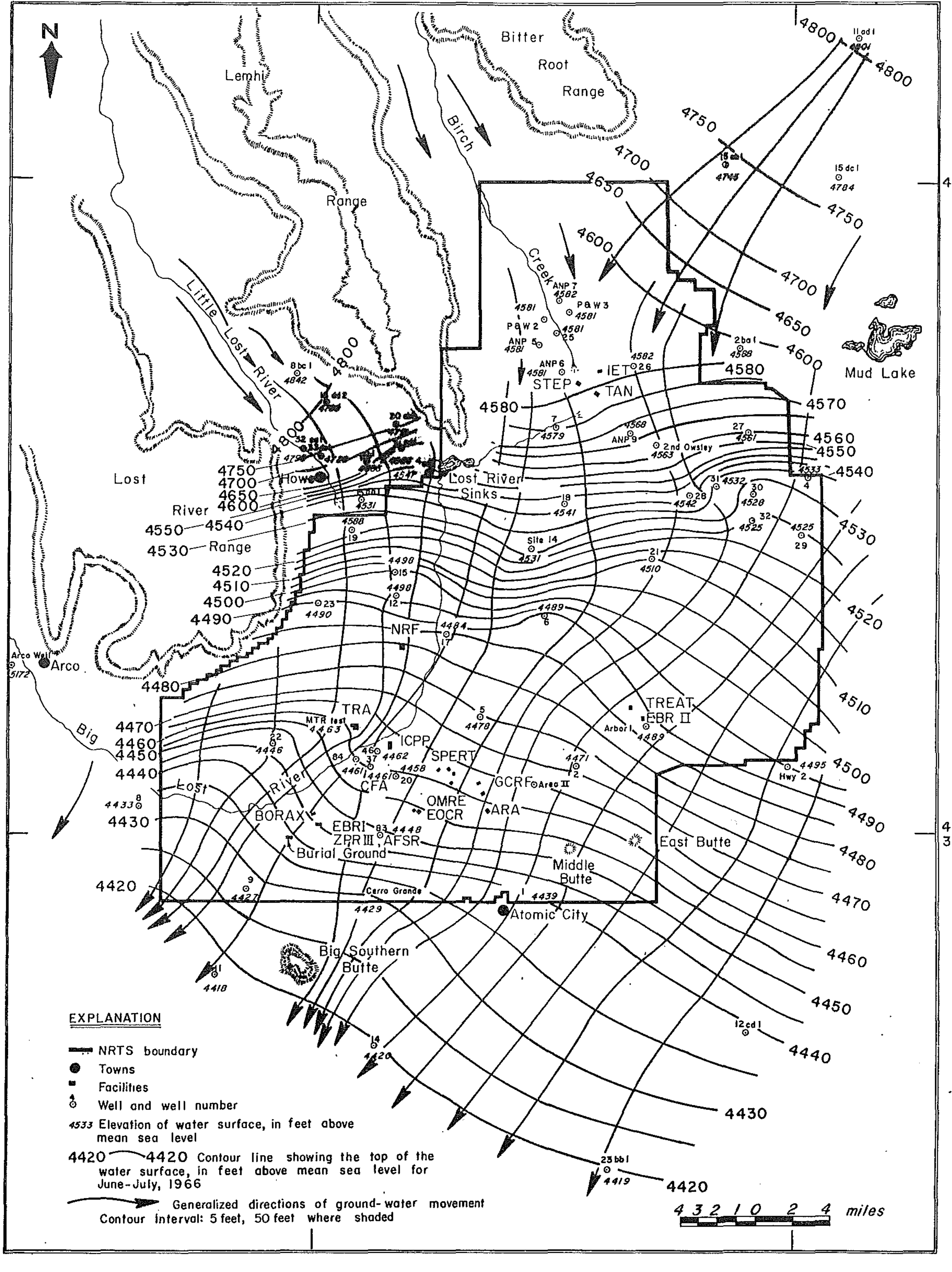


Fig. 6 Map of the NRTS vicinity showing contours on the regional water table and the inferred directions of groundwater movement, June-July 1966.

underground by infiltration from lawn irrigation and other water uses. A significant amount (nearly half) of the pumped water is consumed by evaporation and transpiration to the atmosphere, principally from reactor cooling towers and lawn irrigation. The calculated underflow of 2,000 cfs beneath the NRTS is equivalent to 4.7×10^{11} gallons per year. Therefore, if NRTS operations consume 1.3×10^{9} gallons per year, the consumption is less than 1% of the NRTS underflow and less than 0.1% of the total annual aquifer discharge.

The only significant natural recharge to the aquifer in the NRTS vicinity is from the Big Lost River. A small amount of recharge occurs from infiltration of precipitation directly on the Station and in some years of high runoff, Birch Creek water flows onto the Station and seeps underground. The Big Lost River drains into a closed basin terminating at the northern end of the Station (described in the foregoing surface water discussion). Therefore, all Big Lost River water entering the NRTS is recharged to the Snake River Plain aquifer (minus evaporation losses).

Hydrographs of the wells penetrating the Snake River Plain aquifer have different characteristics from place to place, but all reflect natural recharge variations as well as irrigation influences. Figures 3 and 8 through 12 show hydrographs of various wells in the NRTS vicinity (locations on Figure 7) for a period of several years, through 1968. Detailed discussion of these hydrographs is presented in Appendix A.

3.3 Perched Groundwater

When the Big Lost River flows on the Station, water infiltrates the channel bottom and percolates downward toward the aquifer. Layers of fine-grained sediments with low permeability tend to retard the downward percolation, forming perched groundwater beneath the River. This is vividly demonstrated by the hydrograph of Well 78 (Figure 5). Well 78 is only 235 feet from the river and 203 feet deep (does not penetrate the Snake River Plain aquifer). Changes in the flow of the River are rapidly reflected in the perched water-level in the well, as shown in the figure. The sections shown in Figures 34, 56, and 70, discussed later in the report, show schematically how the perched river water occurs in relation to other subsurface features. Perched water undoubtedly occurs beneath other parts of the Big Lost River system where there are high seepage losses, such as the NRTS diversion areas. However, there are very few wells available for monitoring such perched water.

The most significant body of perched water resulting from waste disposal occurs at TRA beneath the waste seepage-ponds. That system is discussed in detail in a following section of this report describing TRA waste disposal (Figure 43). Minor perched zones resulting from waste disposal at other areas are also discussed later in the report.

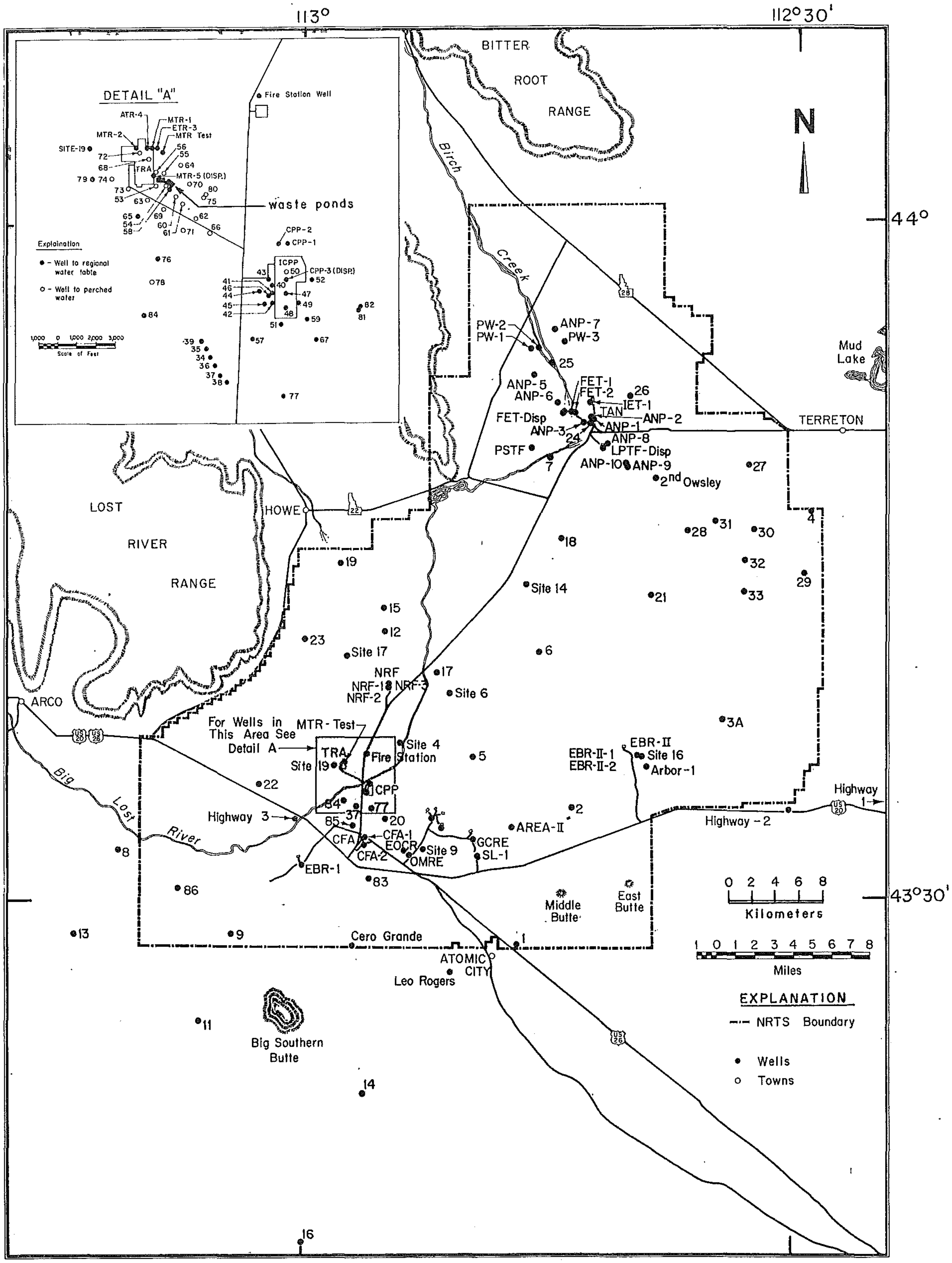
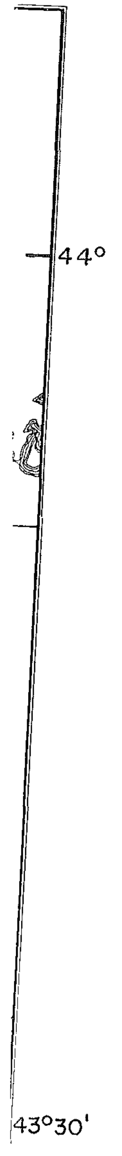


Fig. 7 Map of the NRTS vicinity showing the numbers and locations of NRTS production and observation wells.



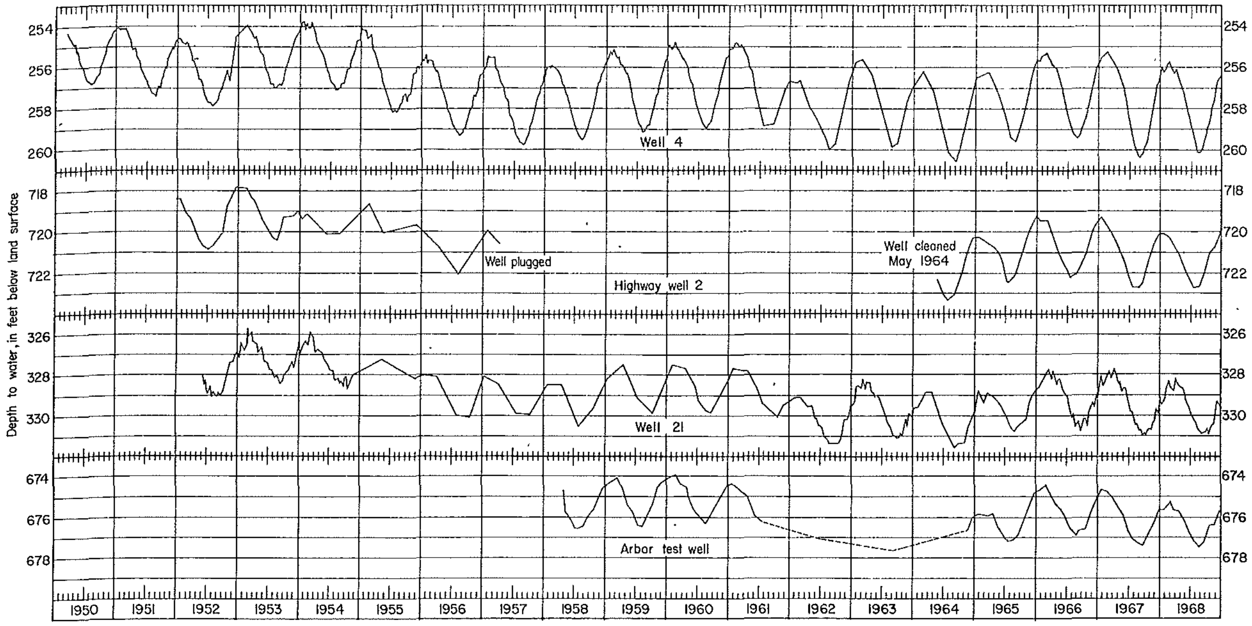


Fig. 8 Hydrographs of four wells in the eastern part of NRTS.

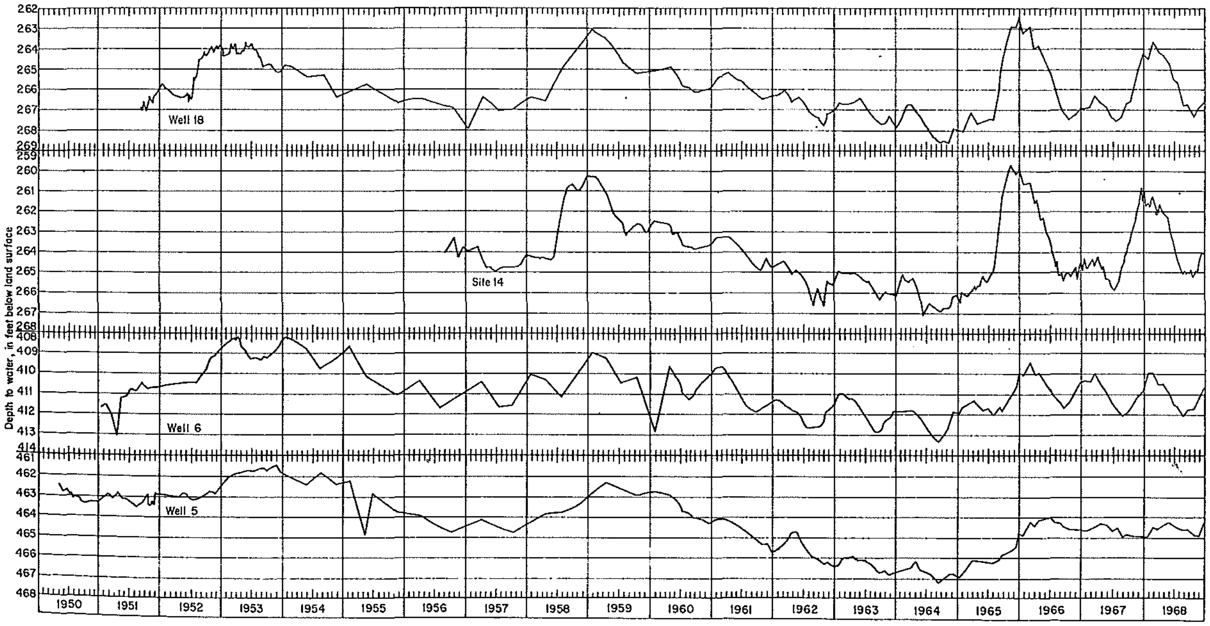


Fig. 9 Hydrographs of four wells in the central part of NRTS.

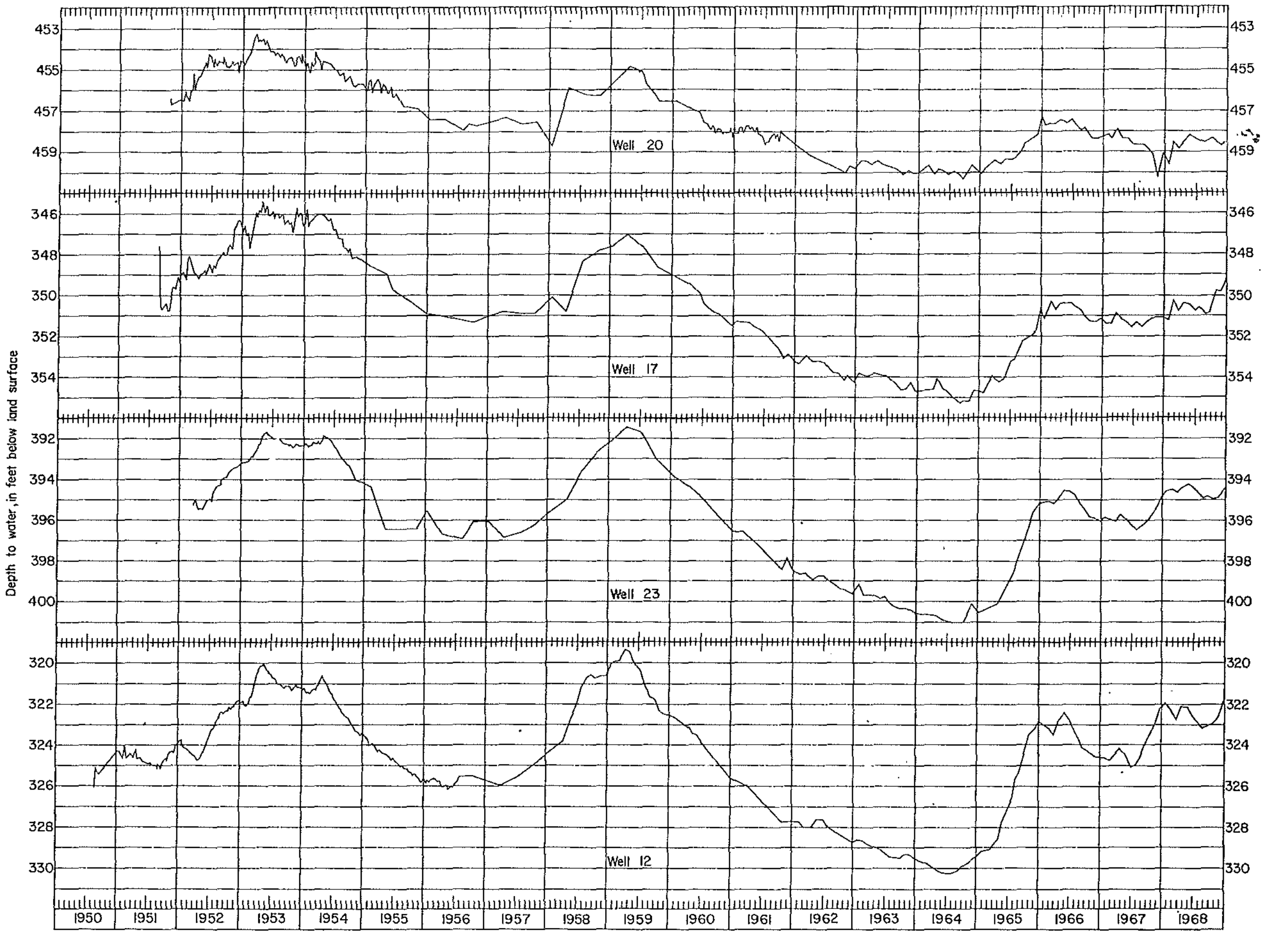
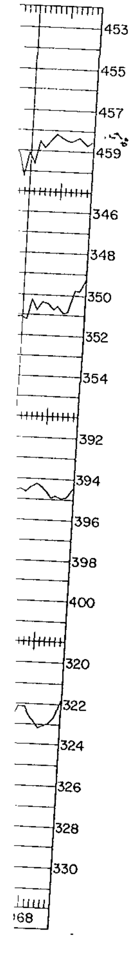


Fig. 10 Hydrographs of four wells in the western part of NRTS.



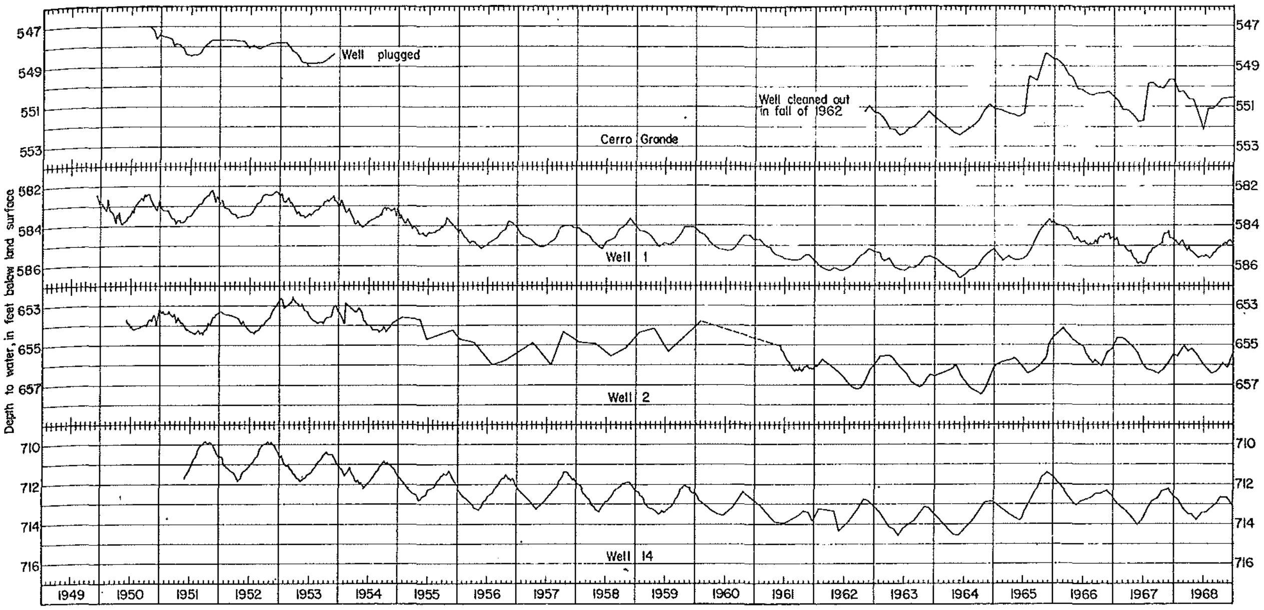


Fig. 11 Hydrographs of four wells in the southeast corner of NRTS.

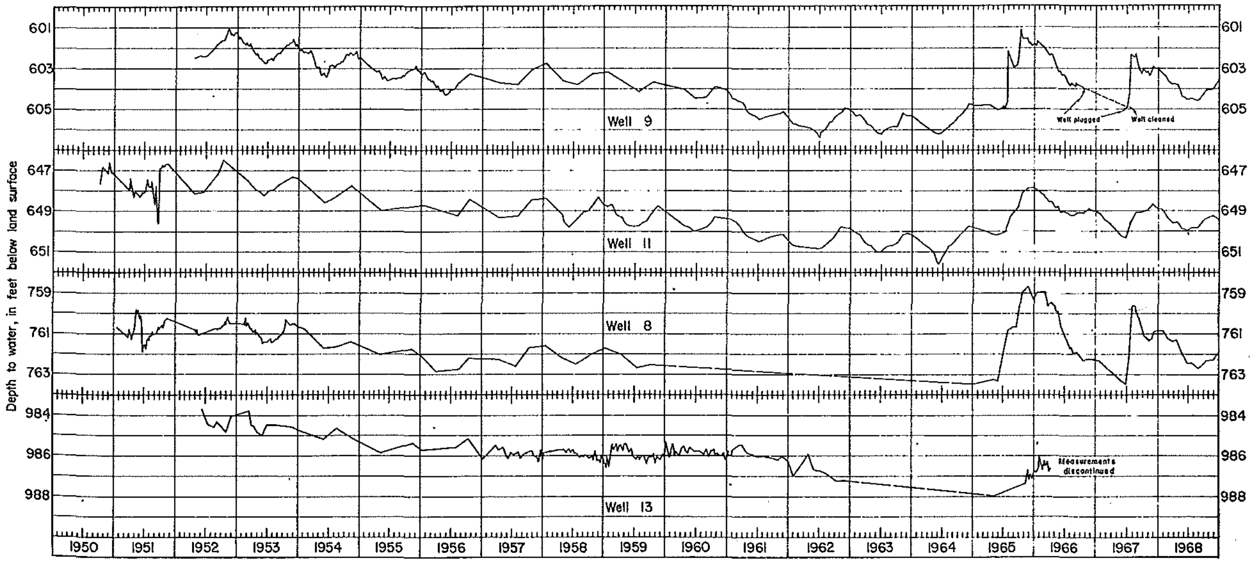


Fig. 12 Hydrographs of four wells in the southwest corner of NRTS.

III. GEOLOGY

(Robert Schoen)

The Snake River Plain cuts a 50- to 100-mile-wide swath through the Rocky Mountains across the State of Idaho. In contrast to altitudes in excess of 12,000 feet in the adjacent snow-tipped mountains, the plain rises gently from 2,300 feet in the west to 6,000 feet in the east. Bordering ranges consist of Paleozoic and Mesozoic miogeosynclinal rocks folded during Laramide orogenesis and later uplifted along normal faults during basin and range tectonism. These ranges terminate abruptly against both sides of the low-lying, basalt- and sediment-filled Snake River Plain. Except for a narrow strip of green along the banks of the Snake River where irrigation makes farming practicable, clumps of dry gray sage cover the plain, interrupted by hummocks of glistening black basalt flows. Located entirely on the eastern Snake River Plain, the National Reactor Testing Station (NRTS) adjoins mountains to the northwest that provide the northern boundary of the plain. Formation of the plain and filling to an unknown depth with tuffs, lavas, and sediments began in middle Pliocene and apparently continues at present. The last volcanic eruption at Craters of the Moon, 13 miles southwest of the NRTS, occurred about A.D. 400 (Stearns, 1963; Bullard and Rylander, 1970).

The geology of the NRTS provides the framework within which the hydrologic environment exists. An adequate understanding of the local geology is necessary in order to relate the natural chemical composition of groundwaters to reactive minerals in rock units associated with the groundwaters; to determine potential aquifers and confining beds that may direct or contain discharged waste; and to aid in evaluating potential geologic hazards to long-term storage of waste, such as seismicity, volcanism, and land subsidence.

In spite of these basic requirements for an understanding of local geology, the Snake River Plain of Idaho, on which the NRTS is located, constitutes one of the most poorly known geologic areas in the United States. The major reason for this is a lack of economic incentive for deep exploration coupled with rather shallow natural rock exposures. Few published geologic studies deal with the Snake River Plain, and almost none attempt to synthesize the available data into a working hypothesis. With these deficiencies in mind, the following analysis of previous geologic work and synthesis are designed to prepare a conceptual geologic framework for the geochemical and waste disposal parts of this report, as well as point out major gaps in geologic knowledge of the Snake River Plain.

1. GEOLOGIC HISTORY OF SNAKE RIVER PLAIN REGION

In late Precambrian time, a north-south geosyncline lay across most of the Snake River Plain region, apparently covering much of the same area as the ensuing Cordilleran geosyncline. Rocks consisting largely of sandstone and shale formed in this geosyncline followed by nearly continuous deposition of similar lithologies during the Cambrian and Early Ordovician (Crittenden and others, 1971). In the region north of the NRTS, the Skull Canyon Disturbance (Scholten, 1957) folded and subjected to erosion rocks older than Middle Ordovician, leaving an angular unconformity. But in southeastern Idaho the rock sequence from Precambrian into the Cambrian remains unbroken, and the base of the Paleozoic is difficult to identify.

The eastern edge of the Cordilleran geosyncline lay approximately along the Idaho-Wyoming border. West of this line subsidence resulted in deposition of about 50,000 feet of Paleozoic rocks and 35,000 feet of Mesozoic rocks (Armstrong and Oriel, 1965). To the east, on the stable shelf, only thin equivalent units formed. The miogeosynclinal portion of the geosyncline lay over the eastern part of the present Snake River Plain and here, except for sandstones in the Middle Ordovician and Pennsylvanian, thick sections of carbonate rocks formed. This dominantly carbonate section reflects the great distance to sources of detritus in the west and the low topography on, and east of, the Wyoming shelf.

Cambrian rocks today, on the west and north sides of the Teton Mountains, correlate readily with similar rocks in the Centennial Mountains on the north side of the Snake River Plain. Although this matching at the extreme northeastern end of the plain is easy, matching becomes increasingly difficult to the southwest where greater distances across the plain separate the Cambrian outcrops. Trimble and Carr (1962) describe over 7,000 feet of Cambrian rocks near Pocatello that thicken northward toward the Snake River Plain. Yet on the northwest side of the plain where a continuation of this thick Cambrian section would be expected, the stratigraphy is less clear. Cambrian rocks on the northwest side of the plain, studied only by reconnaissance and involved in large structural distortions, have been described as thin or absent (Scholten, 1957) as well as in excess of 2,200 feet thick (Hobbs and others, 1968). Similar great apparent changes in some subsequent Paleozoic systems, across the eastern Snake River Plain, may reflect only the difficulty of measuring true thicknesses in faulted and folded rocks rather than gross changes in the environment of deposition (Paull and others, 1971).

In Permian time, volcanics became abundant in the eugeosynclinal region west of Challis, Idaho, and phosphate-rich carbonates formed along the eastern edge of the geosyncline and on the shelf. Through Triassic, Jurassic, and Cretaceous time, the axis of the basin of marine deposition shifted eastward and the basin became narrower, reflecting apparent uplift in the west (Armstrong and Oriel, 1965). Many continental units formed, including some with evaporites signifying restricted marine conditions locally.

The post-Pennsylvanian rock record indicates the beginnings of tectonism culminating in the late Cretaceous Laramide orogeny. In the region of the Snake River Plain, the immediate source for Mesozoic tectonism may have been the forcible uplift of rocks by the Idaho batholith, whose emplacement must have consumed a long period prior to its solidification in the Cretaceous. Erosion of those rocks covering the rising batholith provided detritus for Mesozoic rocks to the east. And in the final stages of orogeny, layers of rock may have slid eastward off the flank of the batholith forming many of the thrusts now seen in western Wyoming and western Montana (Scholten, 1968).

Erosion dominates the early Cenozoic history of the region except near the Idaho batholith where Challis Volcanics (andesitic to rhyolitic flows and tuffs and fluvial and lacustrine sediments) formed during Eocene and early Miocene. In the Miocene, basin and range faulting began and evidently culminated in late Miocene time, about 7 to 12 million years ago. Basin and range structures since the Miocene have undergone partial erosion of horsts, partial filling of grabens, and relatively minor movements along the faults. By the beginning of the Pliocene, 7 million years ago, southern Idaho consisted of a rugged mountain mass with the Idaho batholith on the west, perhaps extending south to the Nevada border, and on the east, basin and range horsts and grabens exhibiting about 10,000 feet of relief.

Onto this scene came the unknown process that formed the great depression of the Snake River Plain. Effusion of sialic rocks accompanied the earliest foundering of the plain in early to middle Pliocene. Following this, the volcanism was entirely basaltic. Fluvial and lacustrine sediments formed in disconnected basins constructed by coalescing flows, yielding a thick succession of basalt and interbedded sediments. Sialic volcanism recurred briefly along an east-trending zone immediately south of the NRTS with intrusion and partial extrusion of rhyolitic rocks. Recent basalt flows, some only 1,600 years old, crop out along a rift zone crossing the plain southeastward from Craters of the Moon.

1.1 Rocks of the Snake River Plain

Russell (1902) made the first estimate of the age of rocks underlying the Snake River Plain. He felt that the upper rocks must be much younger than the Miocene and Pliocene Columbia River basalts that lie immediately to the west in Oregon and Washington but conjectured that the basal Snake River basalts might correlate with the upper part of the Columbia River basalts. This is the first suggestion in print that late Tertiary basaltic volcanism may have moved progressively eastward from the Pacific Coast toward the Yellowstone Plateau.

Detailed work by Malde and Powers (1962) in the western plain confirms the general correctness of Russell's estimate. The Idavada volcanics, a series of predominantly sialic ash flows, dip beneath the Snake River Plain on both flanks and show thickening associated with northwest trending faults that outline the western plain. Consistent dating of the Idavada Volcanics as early to middle Pliocene places the first indication of a Snake River Plain structure in the middle Pliocene. The Idaho Group, made up of basalt flows and lacustrine sediments ranging in age from early Pliocene to middle Pleistocene, overlies the

Idavada Volcanics. These rocks show progressively greater plainsward dips with increasing age (Kirkham, 1931). The present extrapolated sub-sea-level altitude of some of the continental sediments indicates a slow regional subsidence at least through the middle Pleistocene. The youngest rocks, the Snake River Group, occur principally in the eastern plain and consist of basalt flows with minor interbedded fluvial and lacustrine sediments. These rocks range in age from late Pleistocene through the Holocene and include flows at Craters of the Moon National Monument dated by tree rings at about A.D. 400 (Stearns, 1963) and others dated by radiocarbon at about 2,000 years before present (B.P.) (Bullard, 1971). Recent K-Ar dating in the western Snake River Plain indicates that rocks of the Snake River Group are less than 0.54 million years (m.y.), whereas the underlying Idaho Group ranges from 0.6 to 10 m.y. (Armstrong, 1971).

On the eastern Snake River Plain (Figure 13), silicic volcanic rocks, stratigraphically equivalent to Idavada Volcanics of the western plain, present several unique problems. Stearns and others (1939) described rhyolitic flows and tuffs all around the northeastern end of the plain from Lidy Hot Springs, along the Centennial Mountains, to Island Park. In 1938, Stearns and others traced rhyolitic tuffs along the Snake River between American Falls and Massacre Rocks, named them, and assigned a possible Pliocene age to them. Stearns and others (1938) also noted that when these rhyolites are traced toward the Challis Volcanics of central Idaho (Eocene to early Miocene in age) they seem to correlate with the upper part of the Challis. Carr and Trimble (1963) refined the subdivision of silicic rocks at American Falls, renamed and dated them more closely, and noted that their thickening toward the plain implied both a plainsward source and persistence of the rocks across the plain. They also suggested a correlation with lithologically similar rocks near Idaho Falls. K-Ar dates on the Idavada Volcanics are 9 to 13 m.y. in the western plain, 8 to 10 m.y. in the central part of the Snake River Plain, and 4 to 5 m.y. in the eastern plain (Armstrong, 1971).

Subsurface indications of the silicic volcanics are rare on the plain because of the great thickness of overlying basalt and sediments. For instance, a 1,600-foot well at Idaho Falls, presumably close to the edge of the plain, bottomed in basalt. Well 15 at the NRTS bottomed in basalt at 1,497 feet though Paleozoic rocks crop out only 6 miles to the west (Figure 7). South of Burley and close to the south edge of the plain, however, silicic volcanics occur in a 714-foot well. In the Cerro Grande well, about 4 miles northeast of Big Southern Butte, the gamma-ray log suggests silicic rocks beneath about 400 feet of basalt. And in the Leo Rogers well, 2 miles southwest of Atomic City, the gamma-ray log suggests 250 feets of silicic rocks between 100 feet of basalt below and 368 feet of basalt and sediments above[a].

---

[a] Preliminary results of an electrical resistivity survey run recently from Blackfoot to Arco indicate rocks interpreted as silicious volcanics from a depth of 2,000 feet to 12,000 feet beneath the western part of the NRTS (A. A. R. Zohdy and W. O. Stanley, written communication, 1971).

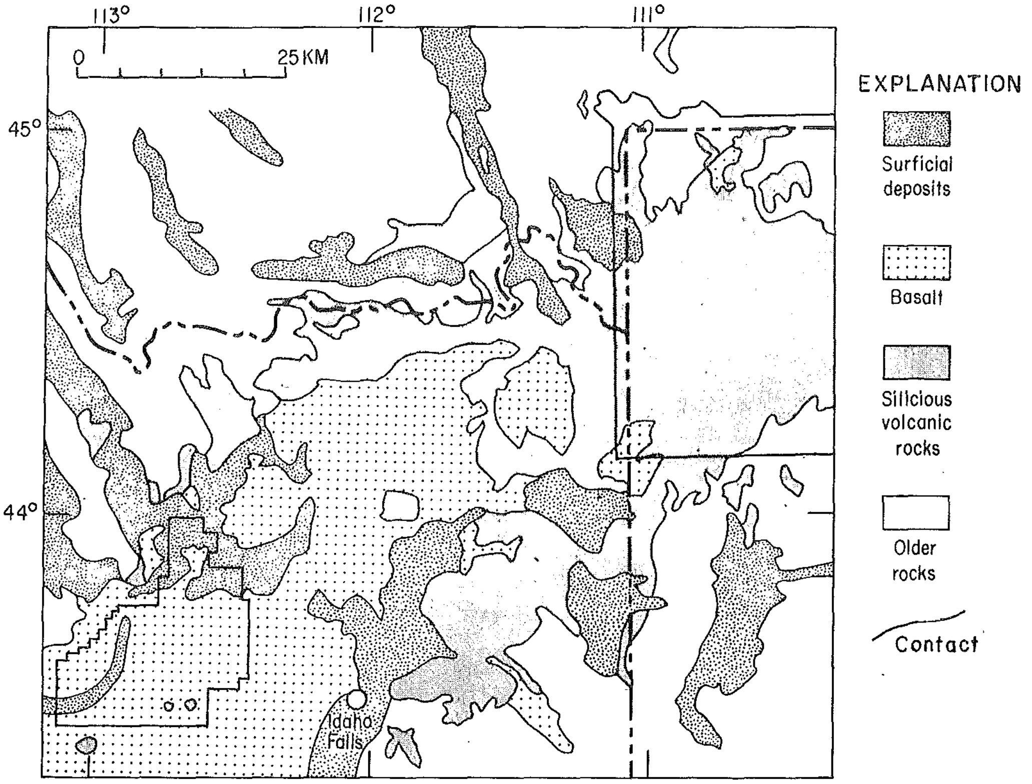


Fig. 13 Generalized geologic map of the eastern Snake River Plain, Idaho, and vicinity. Surficial deposits and basalts are Quaternary. Silicious volcanic rocks are Tertiary and Quaternary. Older rocks principally consist of Paleozoic and Mesozoic sedimentary rocks. Boundaries of the NRTS are indicated.

The last two subsurface indications of silicic volcanics lie between silicic outcrops at Big Southern Butte and East Butte, south of the NRTS, and imply a subsurface connection (Figure 14). The origin of these buttes has long been controversial. They appear as remnants surrounded by basalt, and their sialic composition readily associates them with the older silicic volcanics. Russell (1902) believed they were ancient rhyolitic volcanoes in a sea of basalt (steptoes). Stearns and others (1938) felt they were fault blocks of older rock, uplifted and uncovered.

An alternative explanation, however, is that these silicic buttes represent relatively young rock that punched up as viscous intrusive plugs and domes. Flow banding at East Butte indicates extrusion and downflank flow that covers presumably up-arched basalt along the feeder dike (Figure 15). The 250 feet of silicic rock in the Leo Rogers well, sandwiched by basalt, implies intrusive or extrusive emplacement rather than a fault. The tilted basalt flow capping Middle Butte presents more convincing evidence of the youth of the silicic buttes. Gravity studies indicate that the core of Middle Butte consists of rocks less dense than the capping basalt. In addition to this evidence for a presumed silicic core, the closest outcrop of basalt at the same altitude as the cap on Middle Butte (6,410 feet) lies 80 miles to the northeast on the south flank of the Centennial Range. Thus, it is unlikely that

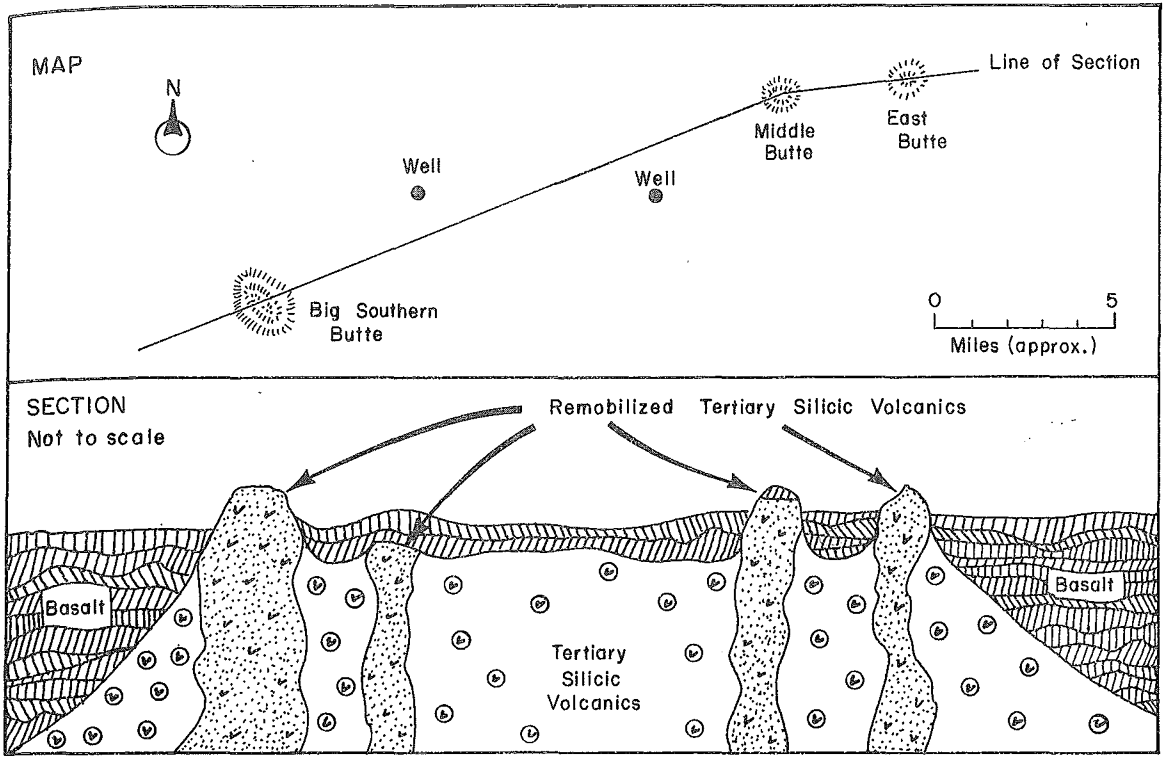


Fig. 14 Interpretation of geology of silicic buttes, NRTS.

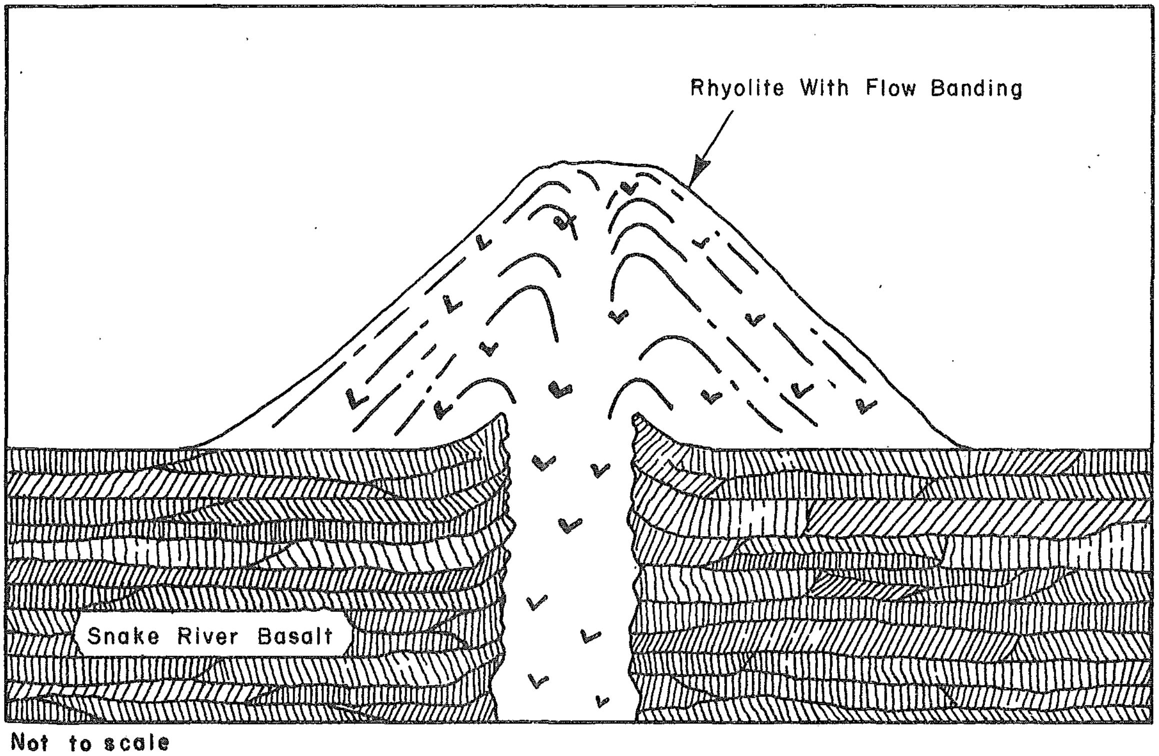


Fig. 15 Interpretation of geology of East Twin Butte.

the basalt on Middle Butte is a remnant of a basalt flow extruded at its present altitude and almost entirely removed by erosion. Rather the cap on Middle Butte most likely represents a plate of Snake River Group basalt pushed up above its level of extrusion and tilted by a concealed plug of younger silicic rocks. R. L. Armstrong (oral communication, 1971) obtained K-Ar dates on the silicic rock of Big Southern Butte and East Butte that indicate they are very young, 0.29 ± 0.03 m.y. and 0.51 ± 0.1 m.y., respectively. G. H. Chase (written communication, 1967) reported K-Ar ages of 0.7 ± 0.2 m.y. and 1.0 ± 0.4 m.y. for the same two localities; however, Armstrong's numbers are considered more reliable. Because the extensive bordering outcrops of Pliocene silicic volcanics imply burial of similar rocks beneath the plain, the young silicic rocks of the buttes may represent remobilized silicic volcanics, recently intruded and extruded.

2. STRUCTURAL ORIGIN OF SNAKE RIVER PLAIN

The obvious magnitude of the forces involved in transecting the Rocky Mountains with the Snake River Plain structure, as well as the youth of this structure, have important implications for the environmental geology of the region. Though our knowledge of the rocks of the Snake River Plain may now be regarded as usable, our understanding of the process that formed the great depression in which these rocks accumulated remains uncertain. Three currently viable hypotheses of origin are:

(1) Graben -- The idea that the Snake River Plain is a simple downfaulted graben structure inundated by flood basalts that now conceal the fault traces occurred to many geologists. Probably the first to say so in print was Lindgren (1898). Russell (1902) added some evidence for large-scale faulting between Tertiary rhyolite and Cretaceous granite north of Boise. Nace, Voegeli, and Deutsch (in press) summarized this hypothesis and added that although most of the faulting was old, the progressively less steeply dipping younger lava flows and lacustrine sediments indicate some movement on these faults as recently as Pleistocene. Malde (1959) found evidence for 1,800 feet of displacement by normal faults on the north side of the western plain, and inferred at least 9,000 feet of total throw.

(2) Downwarp -- Kirkham (1931) proposed that the Snake River Plain is a giant downwarp of the adjacent rocks. He based this hypothesis principally upon the pervasive plainsward dip of the rocks, both volcanic and lacustrine, on both flanks of the plain and, additionally, on the fact that the dip increases in older rocks and is greatest at the borders of the Snake River Plain tending to flatten at the axis.

Though Kirkham believed that small fractures and faults must occur at the hinge zones, he did not envisage more than a few feet displacement on them. On the contrary, he proposed large breaks on the floor of the depression along which copious quantities of Snake River basalt rose. Kirkham believed that the Snake River basalt and interbedded lacustrine rocks accumulated to a thickness of 2,000 to 4,000 feet, and he suggested that the downwarp might be a response to the deep-seated flowage of magma, part of which periodically erupted to slowly fill the basin.

Additional evidence for a lack of faulting at the margins of the basin, Kirkham thought, was the paucity of hot springs along the margins. He recognized only two, Lidy and Heise, and ascribed both to northwest trending faults transverse to the Snake River downwarp.

(3) Tensional Rift -- Hamilton (1963), probably impressed by the large size of the Snake River Plain and its disregard for local or even continental structures, proposed a radically new hypothesis for its origin. "The Idaho batholith is drifting slowly northwestward as an unbroken mass, in the lee of which the Snake River depression is produced by tensional thinning of the crust." Making use of supportive geophysical evidence, Hamilton (1965) elaborated, "This hypothesis requires that the silicic crust beneath the plain has been thinned by tension and implies that, to account for the considerable altitude of the region above sea level, the underlying intermediate crust has been thickened by igneous processes." In 1966, Hamilton and Meyers attempted to fit the genesis of the Snake River Plain into a general tectonic evaluation of the western United States with these additional details, regarding seismic velocity layers "...low-velocity ('granitic') continental crust is probably wholly lacking beneath at least the western part of the plain, which has a thick but high-velocity ('basaltic') crust ..." To the long straight northwest-trending zones bounding the western plain, interpreted by Malde (1959) as normal faults, Hamilton and Meyers (1966) ascribed strike-slip movement, similar to that on the Hope and Osborne faults to the north (Hamilton, 1963), to accommodate the northwestward drift of the Idaho batholith. They continued, "The continental plate has probably been completely sundered in the western part of the plain but only thinned by tension in the eastern part." And further on, "The Centennial and Teton blocks which bound the eastern end of the plain may be sliding gravitationally into it, causing the collapse of the grabens beyond."

Hamilton and Meyers (1966) envisaged continental sialic blocks drifting over the simatic crust and mantle because of inertial forces involving changes in the earth's rotation. The breaking away of the massive Idaho batholith and surrounding rocks from rocks of southern Idaho left a void perhaps 20 kilometers deep which had been occupied by sialic rocks. In the eastern plain, thinning and foundering of the sialic rocks rather than breaching is proposed.

> Filling of this chasm by volcanic rocks derived from the earth's mantle accounts for the present aspect of the Snake River Plain. The tensional rift hypothesis visualizes the Snake River Plain as a sort of megajoint where most of the movement has been perpendicular to the surfaces of the joint which has been filled with material from the mantle. This concept closely resembles the jointing and joint-filling that produces (or is a result of) sea-floor spreading from volcanic, seismically active, oceanic features like the Mid-Atlantic Ridge.

Selection of a working hypothesis for genesis of the Snake River Plain, to use in this and other scientific studies, necessitates evaluation of all the sparse data available. Especially pertinent to an evaluation of the three proposals are geophysical data, extension of basin and range trends onto the Snake River Plain, and fracture patterns including evidence for bounding faults.

2.1 Geophysics

Recent gravity surveys over the Snake River Plain and adjoining mountains to the north and south show broad isostatic compensation of the region (Hill and others, 1961; La Fehr and Pakiser, 1962; Hill, 1963). La Fehr and Pakiser (1962) suggested that the crust under the eastern plain might be 6 kilometers (4 miles) thinner than the adjoining crust of 40 kilometers (25 miles) thickness beneath the mountains, to account for isostatic compensation. In other mountain ranges a deep crustal root generally compensates for the excess mass of the mountains relative to adjoining lowlands. Mabey (1966) found that the gravity field over the eastern plain and adjoining mountains could be explained purely by regional topography without any large-scale mass anomalies. This indicates that the rocks underlying the eastern plain are similar in density to those underlying the mountains.

Additional evidence for the existence of sialic rocks beneath the eastern plain comes from unpublished magnetic and gravity data by D. R. Mabey and D. L. Peterson (written communication, 1965). Fairly definite gravity and magnetic anomalies trend northwest across the Snake River Plain in the vicinity of the NRTS. This northwesterly trend, at right angles to the trend of the plain, matches the structural grain of the basin and range mountains to the northwest and southeast and implies their presence beneath the Snake River basalt. Northwest trending magnetic highs appear to be extensions of the sediment-filled graben valleys, northwest of the NRTS, whose large gravity lows do not extend onto the plain. A logical explanation of this pattern is that basin and range horsts and grabens extend southeasterly beneath the plain and that the grabens became filled with volcanic rocks, thus forming much thicker sections of magnetic rock over the grabens than over the horsts. The generally similar density of the Paleozoic sediments of the horst blocks and the Cenozoic volcanics filling the grabens accounts for our inability to distinguish northwest-trending gravity features on the plain.

Study of seismic waves generated by the destruction of large amounts of World War II explosives on the NRTS (Carder, 1948) showed a velocity of 6,600 feet per second (fps), or 2 kilometers per second (km/sec), in the basalt and sediment sequence above the water table, 9,900 fps (3 km/sec) below the water table, and 22,000 fps (6.7 km/sec) below the basalt. Carder interpreted the deep high velocity layer as compact limestone (presumably Paleozoic) at a depth of 5,000 feet.

J. O. Parr Jr. (written communication, 1964) reported similar velocities in the basalt and sediments above and below the water table. Near Well 33 in the northeast corner of the NRTS, a 14,700 to 16,500 fps (4.5-5 km/sec) layer appeared at a depth of about 5,000 feet with apparent relief of about 1,000 feet.

Recent gravity, seismic, and resistivity studies in the sediment-filled basin and range valley of the Big Lost River, just west of the NRTS, provide additional details about the kinds of structures to be expected beneath the plain if basin and range structures do, indeed, extend across the plain (Crosthwaite and others, 1970). Valley-fill approaches thicknesses of 5,000 feet but northeast-trending cross faults, probabaly younger than the basin and range faults, bring Paleozoic rocks to the surface at Mackay Narrows. A test hole 760 feet deep just north of Arco encountered 150 feet of basalt at a depth of 425 feet. This lava flowed northward from the Snake River Plain up the valley of the Big Lost River and became interbedded in detritus shed from the adjoining mountains. A similar study of gravity and magnetic fields over Gem Valley, a basin and range structure in southeastern Idaho 30 miles east of Pocatello, showed about 9,000 feet of basin-fill (Mabey and Armstrong, 1962).

The geophysical evidence on which Hamilton (1965) based his tensional rift hypothesis consisted of an unreversed seismic profile from Nevada northward to Boise that showed the crust to be 10 kilometers (6 miles) thicker under the Snake River Plain than in Nevada (Pakiser and Hill, 1963). The intermediate velocity layer, 22,000 fps (6.7 km/sec), interpreted as sima and lying 20 kilometers (12 miles) below the surface in Nevada, thickens and rises to within 5 or 10 kilometers (3 or 6 miles) of the surface under the western plain (Figure 16). Hamilton and Myers (1966) interpreted this unusual situation to mean that no sialic rocks, like those in the adjoining highlands, underlie the western plain. Instead only dense rocks (sima) underlie the plain to account for the isostatic compensation of a lowland underlain by thicker crust.

These data, and the consequent postulated absence of sialic rocks beneath the western plain, constitute the principal support for Hamilton's tensional rift hypothesis. The quality of the data, however, and consequently the conclusions based on it, is not optimal. Although later reversal of some segments of the seismic profile generally corroborate the earlier work (Hill and Pakiser, 1967), the additional details raise questions of interpretation. For instance, a zone of surficial rocks 1 to 2 kilometers (3,300 to 6,600 feet) thick with low seismic velocitites of about 6,600 fps (2.0 km/sec) is underlain by about 7 kilometers (4

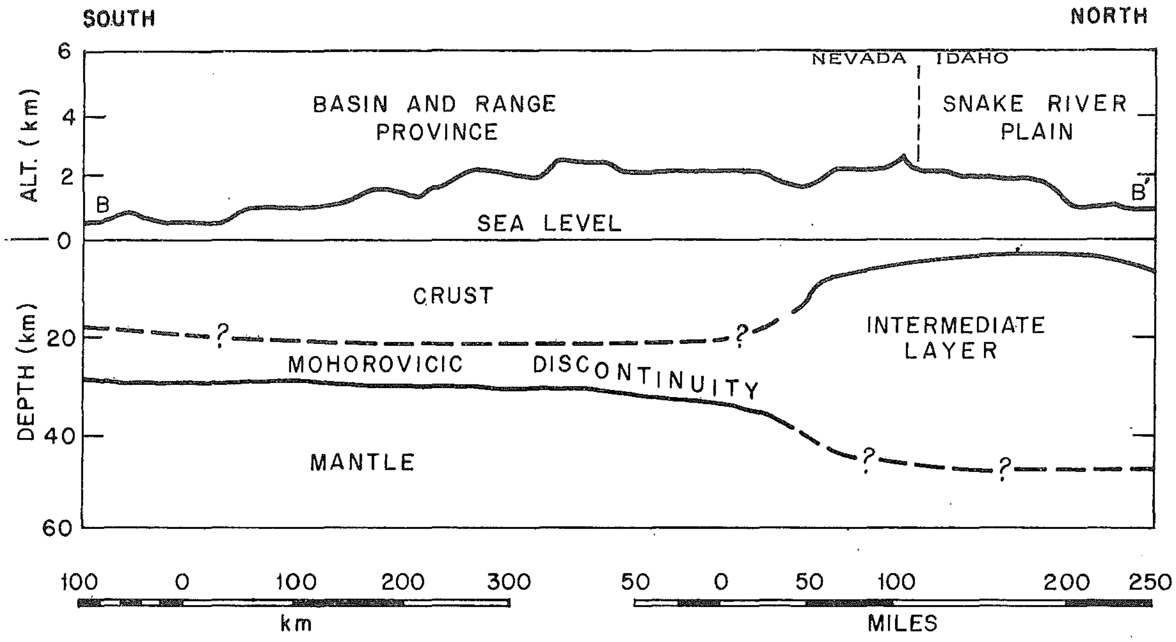


Fig. 16 Generalized north-south cross section showing relative positions of seismic velocity layers beneath the western United States (from Pakiser, 1963).

miles) of rock with seismic velocities of 17,000 fps (5.2-5.3 km/sec). The so-called intermediate velocity layer extending down from about 8 kilometers (5 miles) to the Mohorovicic discontinuity (Moho) at 42 to 46 kilometers (26 to 29 miles) possesses seismic velocities increasing from 22,000 fps (6.6 km/sec) at the top to 23,000 fps (7.0 km/sec) just above the Moho.

In attempting to interpret just what these seismic velocities mean in terms of rock types, the most critical unknown is the relationship between seismic velocity and density. For example, intense fracturing of the upper 8 to 10 kilometers (5 to 6 miles) by tectonic movements within the plain may have lowered the seismic velocities to 17,000 fps (5.2 km/sec) without appreciably affecting density. And the effect of temperature on the velocity-density relation is virtually unknown but probably significant. Recent laboratory studies at low confining pressures [0.5to 2 kilobars (kb)] show seismic wave velocities in basalt and metabasalt of 15,000 to 19,000 fps (4.5 to 5.7 km/sec) and in granodiorites of 20,000 to 21,000 fps (6.0 to 6.4 km/sec) (Fox and Schreiber, 1970). Therefore, the upper 5 to 10 kilometers (3-6 miles) of western Snake River Plain rocks could be primarily basalt, and the upper part of the intermediate zone rocks could be granodioritic as far as the seismic evidence is concerned. As Hill and Pakister (1967) aptly state: "These rationale can be combined in several ways to reconcile the 45-km-thick (28-mile) crust of the Snake River Plain with the 32-km-thick (20-mile) crust of the basin and range province. They, of course, remain speculative and make no pretense of being the final explanation of isostatic mechanism."

2.2 Basin and Range Trends

One of Hamilton's (1965) challenges of the downwarp and graben hypotheses was the apparent lack of continuation of basin and range faulting out into the Snake River Plain. This led him to believe that these structures must be absent from beneath the plain. To examine the validity of this supposition it helps to review briefly the geologic history of the basin and range province.

The basin and range physiographic province extends north from the interior of Mexico in two separate belts that merge near Tucson, Arizona. The eastern belt abuts the south side of the Colorado Plateau, and the western belt extends northward into southern Oregon and southern and eastern Idaho. The mountain ranges northwest of the NRTS, extending to the vicinity of Salmon, appear to be the northern limit of the basin and range physiographic province.

Hypotheses for the origin of basin and range structures vary but currently involve crustal tension induced by various large-scale movements of crustal plates. Christiansen and Lipman (1970) believe this tension began in early and middle Miocene simultaneously with a change in volcanism from largely andesitic to basaltic or bimodal basalt-rhyolite. All this they correlate with the "intersection of North America with the East Pacific rise, mutual annihilation of sectors of the rise and continental-margin trench, and initiation of a transform fault system in their place." Others have envisaged the continent as overriding the rise and point to the predominant tension in the basin and range province as well as the abnormally high heat flow (Kistler and others, 1971, p. 865) as evidence of the existence of an active continuation of the East Pacific rise beneath the basin and range province. Whatever the origin of the tensional forces that produced the basin and range physiographic province, the mountain ranges resulting from them disappear just a short distance north of the Snake River Plain.

Although some geologists find evidence of basin and range tectonism from the Eocene down to the present, most would agree with Christiansen and Lipman (1970) that it began in early to middle Miocene and reached a climax in late Miocene (R. K. Hose, oral communication, 1970), and that the movements that occur at present represent minor readjustment. In a study of basin and range faults in southern Nevada, Ekren and others (1968) found that most of the movement occurred between 11 and 7 m.y. ago. Since 7 m.y. ago, total vertical displacements have averaged less than 100 feet.

Recent seismic monitoring and historical records show that the "interior of the basin and range is essentially devoid of areas with a high incidence of seismic activity except for occasional earthquake swarms" (Smith and Sbar, 1970). A zone of high seismicity traces out a narrow belt from northern Arizona to northwestern Montana along the eastern boundary of the basin and range province. The cause of this narrow belt of energy release remains speculative with proposals ranging from interaction of two major continental plates to localization along the line of maximum bending on the edge of the Cordilleran geosyncline. Whatever its cause, modern major seismic activity seems to avoid the interior of the basin and range province. Because basin and range movements die out in time after the Miocene, and in space in eastern Idaho, the lack of Basin and Range structures on the surface of the post-middle Pliocene Snake River Plain cannot be used as evidence for absence of such structures at depth.

Limited evidence does exist, however, for minor tectonic movements with basin and range orientations on the Snake River Plain (Malde, 1971). The Ferry Hollow graben, near American Falls, exhibits about 50 feet of displacement along northwesterly trending faults that may project to the west side of the basin and range, Deep Creek Mountains (Carr and Trimble, 1963). The faults cut rocks ranging in age from early or middle Pliocene to early Pleistocene but not younger. The Ferry Hollow graben lies about 2 miles plainsward from the trace of a fault, proposed by Carr and Trimble (1963) to bound the Snake River Plain, thus indicating extension of basin and range movements onto the plain.

Ham (1968) mapped a fault along the bold escarpment trending northwest onto the plain in the vicinity of Heise, Idaho, that appears to be a continuation of basin and range structures to the southeast. This fault, and two small faults on the east side of the city of Rexburg, displace Snake River basalt, thus indicating their relative youth. Prinz (1970) describes extensions of the southeast trending Great Rift in Craters of the Moon National Monument and traces these breaks across the plain to Kings Bowl and possibly farther south through the Wapi lava field to just a few miles north of the southern boundary of the Snake River Plain. The orientation of this rift zone across the plain coincides with the basin and range trends on the adjoining blocks. The youth of the lavas along the rift zone (2,000 years B.P.) implies that the rift system is very young. Future eruptions of Snake River basalt will probably conceal this rift system until new basin and range movements rejuvenate it.

2.3 Fracture Patterns

In the tensional rift hypothesis proposed by Hamilton (1963), drifting of the Idaho batholith toward the west-northwest takes place along several large strike-slip faults such as the Hope and Osburn on the north. Hamilton and Meyers (1966) suggest that, to the south, the long straight fault zone north of Boise may have a substantial strike-slip component.

The proposed movement of the batholith toward the west-northwest should produce maximum pull-apart to the east-southeast in the lee of the batholith, that is, in the eastern Snake River Plain. Relatively less separation of the silicic crust should occur in the western Snake River Plain where stike-slip movement accommodates the westerly drift of the batholith against the stable plate of southern Idaho and Nevada. On the basis of seismic evidence, however, Hamilton and Myers (1966) propose that the largest crustal separation, as much as 80 miles, occurred in the western Snake River Plain, and only a tensional thinning of the crust occurred in the east.

Obviously, major mechanical difficulties occur in attempting to explain the proposed tensional rift with west-northwest motion of the Idaho batholith. Major crustal separation should occur in the eastern plain, yet geologic and geophysical evidence indicate little separation. The lack of modern tensional features parallel to the Snake River Plain is very puzzling if the Idaho batholith drifts northwestward with the constancy of the San Andreas fault or oceanic transform faults as Hamilton and Myers (1966) propose. And the proposed northwestward drift of the batholith should actuate strike-slip movement on the old northwest trending basin and range faults that bound Lost River, Lemhi, and Bitterroot Ranges. No such displacement occurs.

2.4 Bounding Faults

If the Snake River Plain structure is a tensional rift or a graben, major breakage of rock at the boundaries of the plain would be expected. Except for the large fault zone with stratigraphic throw in excess of 9,000 feet described by Malde (1959), little direct evidence for boundary breaks exists. This may be because they do not exist or because traces of the breaks were recently inundated and concealed by lava and detritus which may break during future periods of subsidence or rifting. Much indirect, and some direct, evidence exists, however, for the presence of bounding faults.

Concerning the southern border of the western Snake River Plain, Stearns and others (1938) noted the apparent downthrow to the north of a series of welded tuffs and ash beds later designated the Idavada Volcanics (Malde and Powers, 1962). R. R. Coats (oral communication, 1970) noted a rapid steepening of northward dip of the Idavada Volcanics near the Idaho-Nevada border, beyond which they became concealed by the Banbury basalt. The Banbury basalt flowed south from sources on the Snake River Plain reaching as far as the Jarbidge quadrangle in Nevada. Here a normal fault that trends N75E, north side down, cuts the chilled lower part of the Banbury basalt, most of which, in turn, intrudes along the fault plane (Coats, 1964). This relationship dates the fault as early to middle Pliocene and approximately contemporaneous with formation of the Snake River Plain. The similar trend of this fault with the nearby southern border of the plain implies that the border may also be a fault.

Lindgren (1898) proposed the presence of a fault north of Boise at the mountain front along the northern border of the western plain. Russell (1902) enumerated the evidence: alignment of the steep contact between mountains and plain, branching faults extending from the contact into rhyolite flows, recent faults near the border of the plain north of Mountain Home, and hot springs along the base of the mountains. On the basis of geologic mapping and drilling records, Malde (1959) inferred at least 9,000 feet of throw on this fault zone. He observed faults displacing upper Pliocene and lower Pleistocene rocks about 1,800 feet.

On the eastern Snake River Plain, a northeasterly trending normal fault (southeast block relatively down) parallels U.S. highway 20-26 in Craters of the Moon National Monument (Stearns and others, 1938, plate 13). The extreme youth of volcanic rocks cut by this fault (some dated as A.D. 400), argues for very recent movement on the fault which, judging from its location and trend, must be related to a Snake River Plain bounding fault. Northeasterly trending faults and dike swarms occur in the White Knob Mountains, 10 to 20 miles northwest of Craters of the Moon (Nelson and Ross, 1968; 1969). Though these faults are contemporaneous with rocks tentatively correlated with the Eocene Challis Volcanics, the possibility remains that part of these rocks may correlate with the Pliocene Idavada Volcanics on the south side of the plain. If the northeast faults and dikes are of Pliocene age, they would indicate regional tension at the time subsidence of the plain is inferred to have begun.

Carr and Trimble (1963) found a northeast trending set of small faults in the American Falls quadrangle that they believe relates to a N45E fault zone along which the plain subsided. Along with some tenuous evidence of major faulting, they find the most northwesterly outcrop of Paleozoic rocks highly brecciated and silicified.

Some of the gravity anomalies found at the NRTS by D. R. Mabey and D. L. Peterson (written communication, 1965) led them to propose that the boundary between basin and range structure to the northwest and Snake River Plain structure trends east-northeast from Arco Hills to Circular Butte. If this interpretation is correct, it may indicate a series of bounding faults, east of the most recent fault, deeply buried beneath basalt and sediments.

Personal observation indicates that the outcrop of silicic volcanics on the southeast nose of the Lemhi Range, south of the roadcut on state highway 22-28, exhibits N40E fractures dipping steeply to the east. The frequency of these fractures increases toward the plain. About 100 yards from the plain the last outcrops show slickensided fractures a quarter-inch apart indicating a large-scale break toward the plain.

One of the most persuasive indirect arguments for bounding faults is the frequency of hot springs along the borders of the Snake River Plain versus their general absence out on the plain. The vast amount of volcanic material filling the plain came from vents on the plain and some of it is quite young. This points to a large heat source at depth beneath the plain, yet the intercalated flows and sediments effectively seal off this heat from the surface. Only on the borders of the plain are hot springs formed that indicate deep penetration of groundwater and deep permeability. A downwarp cannot provide this permeability but a recurrently breaking fault can. The linearity and narrowness of this zone of deep permeability are shown by the similar chemical compositions and temperatures of Lidy Hot Spring and Condie Hot Spring (Table I), approximately 90 miles apart, and the discovery of

TABLE I

CHEMICAL ANALYSES OF HOT SPRINGS IN THE VICINITY OF EASTERN SNAKE RIVER PLAIN, IN mg/1, EXCEPT AS INDICATED

(milliequivalents per liter in parentheses)

	Lidy Hot Springs 9N 33E 2, SW1/4 Feb. 16, 1970	Green Canyon Hot Springs 5N 43E 6, NW1/4 Feb. 17, 1970	Heise Hot Springs 4N 40E 25, SE1/4 Feb. 17, 1970	Lava Hot Springs 9S 38E 21 "Fountain of Youth" Feb. 18, 1970	Frazier boiling well 15S 26E 23, NW1/4 600 feet west of gravel road between Almo and Bridge, Id. 400 ft deep Feb. 18, 1970	Banbury Hot Springs 8S 14E 33 Feb. 19, 1970	Condie Hot Springs 1S 21E, 13, SW1/4 Feb. 19, 1970
Silica (SiO_2)	34	24	33	44	80	97	27
Calcium (Ca)	90 (4.49)	133 (6.64)	430 (21.46)	150 (7.48)	51 (2.54)	1.0 (0.05)	55 (2.74)
Magnesium (Mg)	16 (1.32)	31 (2.55)	85 (6.99)	30 (2.47)	0.2 (0.02)	0.01 (0)	11 (0.90)
Sodium (Na)	28 (1.22)	3.9 (0.17)	1530 (66.56)	311 (13.53)	541 (23.53)	106 (4.61)	63 (2.74)
Potassium (K)	15 (0.38)	4.4 (0.11)	192 (4.91)	71 (1.82	20 (0.51)	1.5 (0.04)	22 (0.56)
Bicarbonate (HCO_3)	169 (2.77)	164 (2.69)	1080 (17.70)	730 (11.96)	47 (0.77)	127 (2.08)	364 (5.97)
Carbonate (CO_3)	1.1 (0.04)	0.5 (0.02)	0.7 (0.02)	2.9 (0.10)	0.5 (0.02)	16 (0.53)	1.6 (0.05)
Sulfate (SO_4)	184 (3.83)	314 (6.54)	756 (15.74)	144 (3.00)	56 (1.17)	28 (0.58)	25 (0.52)
Chloride (Cl)	7.7 (0.22)	1.0 (0.03)	2360 (66.58)	361 (10.18)	869 (24.51)	25 (0.71)	13 (0.37)
Fluoride (F)	4.5 (0.24)	1.6 (0.08)	3.1 (0.16)	1.1 (0.06)	7.8 (0.41)	15 (0.79)	1.6 (0.08)
Nitrate (NO_3)	0 (0)	0.4 (0.01)	2.6 (0.04)	1.4 (0.02)	1.5 (0.02)	0 (0)	0.2 (0.00)
Specific Conductance (micromhos at 25°C)	687	839	9190	2410	3020	479	652
pH (pH units)	7.84	7.52	6.67	7.56	7.94	9.14	7.68
Calculated Residue	470	595	5950	1480	1650	358	401
Temperature (°C)	48.2	42.2	47.8	48.9	95.6	59.4	50.0
Aluminum (Al)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Iron (Fe)	0.08	0.04	0.10	0.05	0.00	0.00	0.27
Manganese (Mn)	0.05	0.01	0.22	0.02	0.02	0.00	0.00
Lithium (Li)	0.05 (0.01)	0.02 (0)	2.3 (0.33)	0.47 (0.07)	1.4 (0.20)	0.04 (0.01)	0.08 (0.01)
Ammonia (NH_4)	0.26 (0.01	0.32 (0.02)	5.2 (0.29)	0 (0)	0.24 (0.01)	0.13 (0.01)	0.80 (0.04)
Hydroxide (OH)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2.4 (0.14)	0 (0)
Phosphate (PO_4)	0.02	0.03	0.06	0.06	0.01	0.07	0.02
Boron (B)	0.09	(0)	4.6	0.95	0.20	0.20	0.26
Sulfides as H_2S	0.8	---	6.5	---	1.2	0.7	0.5

---

* Data on pH and alkalinity obtained in the field. Samples collected to preserve constituents of interest. Analyses in the U. S. Geological Survey, Water Resources Division laboratory in Menlo Park, California by R. Barnes and C. E. Roberson.

hot water in a shallow municipal well at Butte City about midway along this zone. Unfortunately, no sample was taken for analysis before Butte City sealed off the hot zone.

2.5 Origin of Snake River Plain -- Conclusion

The tensional rift hypothesis as advanced by Hamilton and Myers (1966), while containing certain appealing features such as subcrustal processes and the currently attractive plate tectonics, fails to accord with several lines of detailed evidence. Perhaps most serious is the absence of tensional breaks within and parallel to the eastern Snake River Plain. Although young flows might conceal such fractures, the constant drifting envisaged in the hypothesis necessitates very recent fractures, which do not exist. Equally difficult to reconcile with the slowly opening chasm of tensional rifting is the distribution of oldest Snake River Plain rocks (the Idavada Volcanics) over the entire present-day width of the plain. If rifting had occurred, the oldest rocks should be confined to a narrow strip that represents the width of an early to middle Pliocene Snake River Plain and be overlain by successively younger, more widespread, deposits. The stratigraphy does not indicate this relationship. The seismic quietude of the Snake River Plain argues persuasively against it being an active center for spreading of continental plates. Evaluation of the tensional rift hypothesis to certainty requires the evidence of deep drillholes that completely penetrate Snake River Plain rocks.

A consideration of the merits of the graben versus downwarp hypothesis hinges on the presence of major breaks in rocks at the boundaries of the Snake River Plain. As shown, the sparse evidence does indicate the existence of bounding faults, thus the graben hypothesis remains as presently most tenable.

The geophysical evidence cited by Hamilton and Myers (1966) for a thickening crust beneath the western Snake River Plain requires an explanation compatible with the graben hypothesis. Many geologists suspect that granitic rocks of the Sierra Nevada in California may be continuous at depth with those of the Idaho batholith (Taubeneck, 1971). The gravity low associated with the low-seismic-velocity root of the Sierras diverges from the Sierras toward their northern end and trends northeastward across Nevada through a zone of small masses of Cretaceous granite which intrudes metamorphic rocks. These scattered outcrops extend to the south edge of the Snake River Plain in the Owyhee Mountains southwest of Boise and eastward along the Idaho-Nevada border almost to longitude 113°30’W. Chronologically and petrographically these rocks resemble those of the Idaho batholith (Coats and others, 1965) and the Sierra Nevada batholith (McKee and Silberman, 1970; Smith and others, 1971).

A fairly continuous mass of the Idaho batholith may lie beneath the western Snake River Plain and give way farther south and west to isolated roof pendants or fault-bounded slices of a once continuous batholith. According to this hypothesis, the 10-kilometer

(6-mile) depression of the Moho beneath the plain, indicated by geophysics, may be the beginning of the root zone that presumably lies beneath the Idaho batholith. This hypothesis proposes that in late Miocene the granitic terrain of the Idaho batholith extended southward to the south edge of the present plain where it either thinned considerably or was displaced westward. Tension during the early Pliocene, probably due to subcrustal forces similar to those envisaged by Hamilton and Myers (1966), produced the present Snake River graben into which the southern tip of the batholith subsided.

Along with subcrustal tension directly responsible for the grabening, magma developed in the subcrust, perhaps fractionated from a tholeiite into immiscible rhyolite and olivine basalt (Hamilton, 1965), and erupted along tensional openings in the overlying rocks. Sialic volcanism occurred first and covered the floor of the graben as well as much of the surrounding region with tuff and flows (Idavada Volcanics). Effusive removal of subcrustal material from beneath the graben allowed downfaulting to continue and the Snake River Plain crustal block settled into the mantle. By middle Pliocene time all the rhyolite was gone from the magma chamber and eruption of olivine basalt began. Basalt flows were restricted to filling the graben though some flowed short distances up valleys in the adjoining blocks (Crosthwaite and others, 1970). It is the addition of this subcrustal material to the top of the Snake River graben that accounts for the maintenance of isostasy. Figure 17 depicts these stages in the hypothetical grabening of the Snake River Plain.

Throw on faults bordering the Snake River graben may be as little as 3 kilometers (1.9 miles) (Malde, 1959) or as much as 10 kilometers (6.2 miles). If the 6.7 km/sec (22,000 fps) seismic layer at a depth of 8 to 10 kilometers (5 to 6 miles), found by Hill and Pakiser (1967), is the top of batholithic rocks, the greater throw is indicated. High seismic velocity may simply indicate a relatively simatic granodiorite under pressures appropriate for its present depth of burial that merges downward into a layer of sima at the base of the crust. Some of the lower velocity (5.2 to 5.3 km/sec or 17,000 fps) rocks in the upper 8 to 10 kilometers (5 to 6 miles) may, however, be relatively sialic granite fractured as suggested by Hill and Pakiser (1967) to yield a lower seismic velocity. Thus, the throw on the graben could be less than 10 kilometers (6 miles).

A recent chemical analysis of a hot spring provides evidence that the tip of the Idaho batholith may lie buried beneath the western plain. Banbury Hot Spring near Hagerman (Table I) is strikingly similar in composition to hot-spring waters issuing from granitic rocks north of the Snake River Plain (Ross, 1970). Table II shows that, excluding carbonate and bicarbonate, the only constituents that differ by appreciably more than one standard deviation from an "average" Idaho batholith hot spring are sodium and chloride, the higher dissolved solids being caused by the excess sodium and chloride. The potentially rapid variability of carbonate and bicarbonate values, shown by the large standard deviations in Table II, render these constituents less useful in tagging waters. The source of the excess sodium and chloride is unknown.

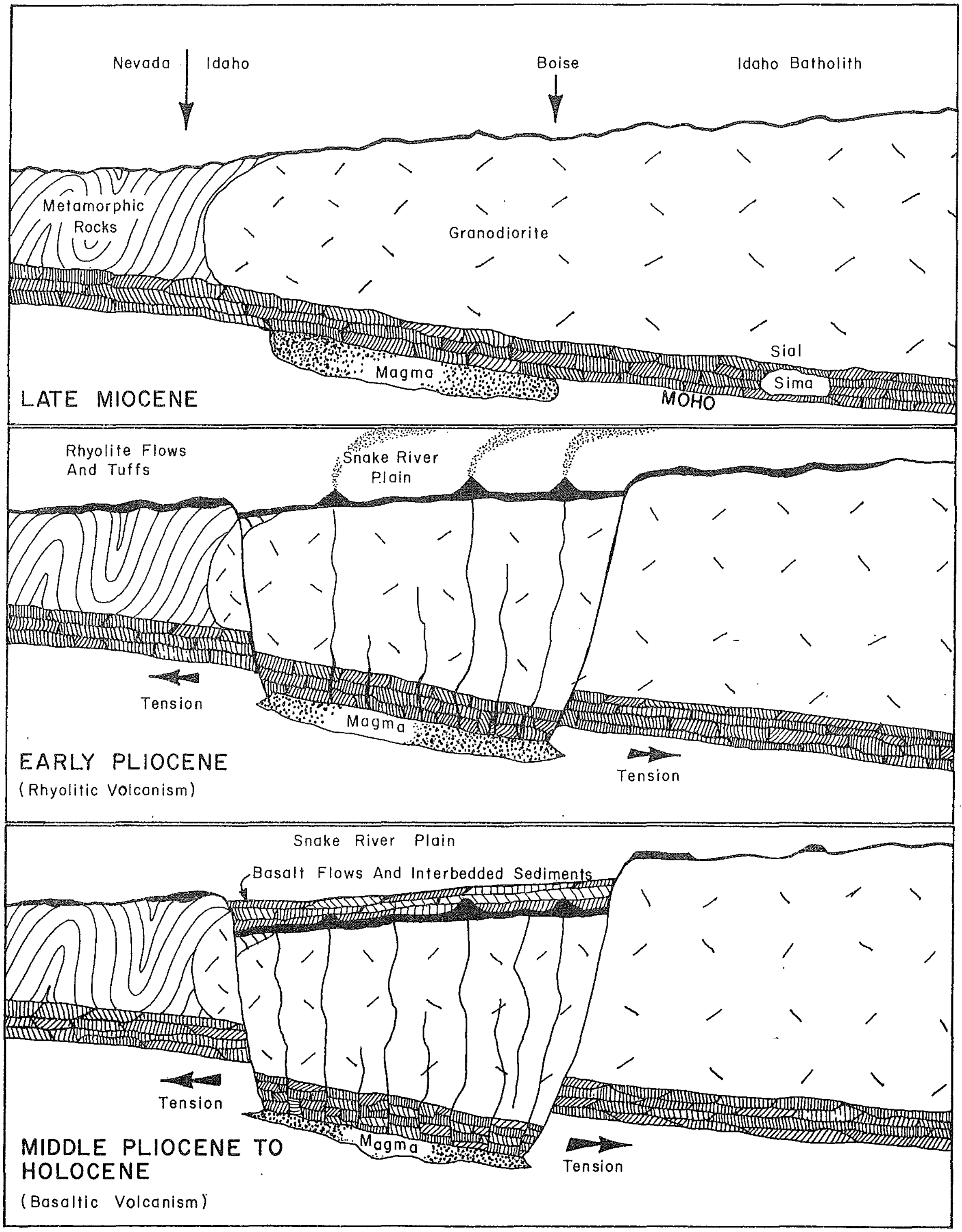


Fig. 17 Cross sections showing hypothetical stages of grabening during formation of the Snake River Plain.

TABLE II

STATISTICAL SUMMARY OF CHEMICAL ANALYSES OF 13 HOT SPRING WATERS ISSUING FROM THE IDAHO BATHOLITH (Numbers 31, 38, 40, 73, 84, 90, 91, 93, 94, 95, 116, 123, and 129 of Ross, 1970; also of Waring, 1965 and Stearns and others, 1937) COMPARED TO CHEMICAL ANALYSIS OF WATER FROM BANBURY HOT SPRING

	Mean $\bar{y}$ (mg/l)	Standard deviation s (mg/l)	Banbury Hot Spring (mg/l)	Difference in standard deviations
SiO_2	80.8	15.2	97	1.1
Ca	1.8	0.9	1.0	<1
Mg	0.2	0.2	0.01	<1
Na	68.2	11.8	106	3.2
K	2.8	2.0	1.5	<1
CO_3	29.7	11.5	16	1.1
HCO_3	53.5	31.9	127	2.3
SO_4	33.6	19.0	28	<1
Cl	6.5	4.1	25	4.5
F	10.5	3.8	15	1.2
Dissolved solids	246.2	36.1	358	3.1
pH (units)	9.38	0.27	9.14	<1
Temperature (°C)	59.8	14.8	59.4	<1

The pitfalls in attempting to relate a water composition to a specific parent rock are many. Jones (1966) amply demonstrates the many variables that may affect a saline lake water's composition before it is collected for analysis. For hot-spring waters, the proportion and composition of any initial juvenile water is the first variable. Second is the extent of reaction of the water with the host rock, and this includes such variables as residence time, temperature, mineral grain size, and crystallinity. Third, the mineral compositions and proportions affect the water composition during reaction. Fourth, precipitation of new minerals affects composition of the water as does, fifth, sorption reactions. Sixth is the real possibility of biologic alterations of the water composition, even in fairly high temperature springs (Brock, 1969). Seventh and last, but hardly least, is the possibility of mixing water of one composition with water of another composition thus yielding a hybrid for collection and analysis.

Considering all of these potential variables, one realizes that water of almost any composition can derive from reaction with almost any type of rock, provided the correct combination of variables interact properly. But precisely for this reason, the water composition in Banbury Hot Spring is more logically explained by reaction with granitic rocks than by reaction with other rocks plus extensive alterations to bring its total composition in line with hot springs on the Idaho batholith.

Thus, the composition of Banbury Hot Spring can be interpreted as the result of solution of a granitic rock. Because Banbury Hot Spring lies at about the middle of the western plain, 40 miles from the nearest outcrop of granitic rocks to the north or south, its composition strongly imples that granitic rocks lie at depth beneath it.

The relatively high temperature of Banbury Hot Spring (59.4°C) argues against deriving it by lateral transmission from the Idaho batholith to the north where hot springs range from about 25°C to as much as 80°C. However, if Banbury Hot Spring water circulates within buried granite, at a depth of 10 kilometers (6 miles), it should be much hotter. The geothermal gradient beneath the Snake River Plain is poorly known because rapid vertical and horizontal transmission of groundwater near the water table and apparent upwelling of hot water near the borders of the plain produce anomalous gradients. Perhaps the reason for Banbury Hot Spring's relative coolness is not a low geothermal gradient but rather that the batholith lies much shallower than 10 kilometers. The stratigraphic evidence (Malde and Powers, 1962) demands at least 3,000 feet of Idavada Volcanics plus Poison Creek Formation beneath Banbury Hot Spring, but a maximum depth can only be surmised from the seismic data.

Thus, the problem of the origin of the Snake River Plain remains less than satisfactorily dispatched. Recent conversations with R. L. Christiansen (1971) indicate the feeling that one explanation may not suffice for all parts of the Snake River Plain, and that when all the evidence is in, all three hypotheses may be found to be valid in restricted parts of the plain. Indeed, R. L. Christiansen and H. R. Blank (written communication, 1971) suggest a fourth hypothesis of origin, based on their extensive work on the Yellowstone Plateau. Accepting the possibility of an easterly migratory, progressively opening, tensional rift, they postulate a sequence of volcanic activity beginning with eruption of tholeitic basalt, followed by rhyolitic volcanism involving formation of calderas and the emplacement of granitic batholiths high into the crust, followed by eruption of more alkalic basalt.

The Yellowstone Plateau is presumably just one step behind the eastern Snake River Plain in evolution, and one may confidently predict the faulting, foundering, and flooding with basalt of the Yellowstone region in the near geologic future. The possibility always exists, however, that the forces responsible for producing the Snake River Plain are weakening, as indicated perhaps by the narrowing of the eastern portion of the plain, and will be unable to complete the postulated cycle of volcanism at the eastern end.

3. GEOLOGIC FACTORS PERTAINING TO NRTS OPERATIONS AND WASTE MANAGEMENT

Acceptance of the graben hypothesis for origin of the Snake River Plain results in several corollaries of potential importance to waste management, including high level radioactive wastes, and other aspects of NRTS operations:

(1) The presence of rock types other than sediment and basalt, beneath the NRTS, can be expected to affect the natural composition of the groundwater and also influence the chemical effects of wastes on the water.

(2) If tuffaceous rocks like the Idavada Volcanics exist beneath the basalts of the NRTS, they may have sufficient porosity and permeability to provide a significant groundwater reservoir; fractured Paleozic carbonate rocks may provide a still deeper and more isolated groundwater reservoir.

(3) The presence of basin and range horsts and grabens beneath the NRTS may produce separated basins with limited hydraulic connection with the upper part of the Snake River Plain aquifer and may thus provide a better storage zone for dilute or low-level wastes.

(4) Recent remobilization of silicic volcanics immediately south of the NRTS may have affected the hydraulic properties referred to in the second and third items which control the southward migration of liquid wastes.

(5) Future volcanism seems virtually assured, but the interval between major eruptions is several thousand years.

(6) Major seismic events will probably be related to movement on bounding faults with a time frame probably similar to renewed volcanism.

(7) Minor seismic events, related to adjustment of underlying basin and range structures, can be expected at irregular intervals.

IV. GEOCHEMISTRY

(Robert Schoen)

Because it is frequently possible to relate the composition of a groundwater to the minerals in rocks in contact, or previously in contact, with the water, distinctive chemical compositions of groundwaters can be used to identify separate sources of recharge. Groundwater compositions may also yield clues to the lithology of deeply buried rocks and, when adequate data are available, can be used to infer removal of chemical constituents by precipitation or sorption. Therefore, hydrochemical studies offer a relatively quick and inexpensive way to evaluate an important part of the environment. Study of the hydrochemistry at the NRTS sought, in addition to the items just described, to provide a benchmark of the hydrochemical environment prior to large-scale activities by the AEC.

Data for this study consisted of over 200 chemical analyses of water samples taken during the last 20 years from 69 wells on or near the NRTS, analyses of surface waters flowing from adjacent areas toward the plain, and analyses of hot springs bordering the plain. Most of the groundwater analyses were obtained in the early 1950's before water use by the AEC became significant. Unfortunately, many of these analyses were performed on samples of questionable representation or by techniques now known to be inadequate. In spite of this, the similarity of repeated analyses from single wells lends a degree of confidence to the values of certain constituents and to the entire group of analyses. Appendix B contains a tabulation (Table B-I) of all groundwater analyses, and includes a detailed discussion of the limitations on the analyses. From these raw data on groundwater compositions, a single "best" analysis was selected for each of the 69 wells and tabulated (Table III). Details of the process of selection are described in Appendix B.

The approach used in handling the data consisted of plotting values of individual dissolved chemical constituents on separate maps, contouring to see if areal patterns existed, and attempting to explain such patterns. Elucidation of a pattern was initially attempted by considering the distinctive chemical parameters of various sources of recharge.

1. COMPOSITION OF RECHARGE

Using the hypothesis that the mineralogy of the enclosing rocks provides the dominant control on the composition of a groundwater, particularly groundwaters with short and simple histories, the unique chemical characteristics of different sources of recharge to the eastern Snake River Plain, and the possible mineralogic controls on these unique compositions were explored and related to the unique compositions in groundwater beneath the NRTS. Because of a lack of mineralogic data on rocks in the recharge areas, only idealized mineral compositions were considered in evaluating mineral-water reactions.

TABLE III

BEST AVAILABLE CHEMICAL ANALYSES OF THE SNAKE RIVER PLAIN AQUIFER IN

TABLE III

BEST AVAILABLE CHEMICAL ANALYSES OF THE SNAKE RIVER PLAIN AQUIFER IN THE VICINITY OF NRTS, UNAFFECTED BY NRTS WASTES

Well No.	U.S.G.S. location number	Date Sampled	Method of sampling	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determined constituents	Residue on evaporation at 180°C	Milligrams per liter (upper number) and milliequivalents per liter (lower number) for indicated cations and anions										Silica (SiO_2)	Dissolved iron (Fe)	Hardness as $CaCO_3$	
											Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)			Total	Noncarbonate
USGS 1	2N-31E-35dc1	Oct. 15, 1952	Pump	582-635	54	3	7.9	284	186	181	28 1.40	11 0.90	14 0.61	2.7 0.07	148 2.43	0 0.00	14 0.29	9.0 0.25	1.2 0.02	0.6 0.03	33	0.04	115	0
USGS 2	2N-32E-29 dd1	Oct. 17, 1952	Pump	654-704	54	2	7.9	284	184	182	29 1.45	11 0.90	14 0.61	2.8 0.07	147 2.41	0 0.00	12 0.25	9.0 0.25	1.5 0.02	0.7 0.04	32	0.07	118	0
USGS 3-a	3N-33E-3 ab1	Oct. 22, 1952	Pump	672-733	55	4	8.0	275	183	179	29 1.45	9.5 0.78	15 0.65	2.7 0.07	149 2.44	0 0.00	9.1 0.19	8.0 0.23	1.5 0.02	0.9 0.05	34	0.12	110	0
USGS 4	5N-34E-9 bd1	Nov. 8, 1952	Pump	256-321	52	---	7.7	963	542	583	93 4.64	33 2.71	42 1.83	6.8 0.17	186 3.05	--- ---	57 1.19	160 4.51	29 0.47	0.3 0.02	29	0.12	368	215
USGS 5	3N-30E-12 cd1	Sept. 22, 1952	Bailer	464-500	55	2	7.8	327	203	200	41 2.05	13 1.07	7.2 0.31	1.7 0.04	172 2.82	0 0.00	20 0.42	9.5 0.27	1.3 0.02	0.2 0.01	24	0.02	156	15
USGS 6	4N-31E-16 ad1	Sept. 12, 1952	Pump	414-620	57	7	7.6	304	185	183	30 1.50	12 0.99	14 0.61	2.7 0.07	150 2.46	0 0.00	20 0.42	9.5 0.27	1.4 0.02	0.4 0.02	21	0.21	124	2
USGS 7	6N-31E-27 ba1	June 7, 1952	Pump	214-698	55	5	7.9	335	208	205	33 1.65	16 1.32	12 0.52	3.1 0.08	170 2.79	0 0.00	20 0.42	8.0 0.23	4.6 0.07	0.2 0.01	27	0.06	148	9
USGS 8	2N-27E-2 dd1	June 8, 1965	Thief	785	52	0	7.8	351	208	207	45 2.25	14 1.19	6.4 2.28	1.7 0.04	180 2.75	0 0.00	22 0.46	7.0 0.25	2.1 0.03	0.3 0.02	19	0.05	172	24
USGS 9	2N-28E-35 ad1	Dec. 18, 1951	Bailer	604-654	52	3	8.0	310	204	196	37 1.85	14 1.15	7.9 0.34	5.0 0.13	162 2.66	0 0.00	22 0.46	10 0.28	0.7 0.01	0.3 0.02	27	0.03	150	17
USGS 11	IN-29E-30 bb1	May 12, 1952	Thief	676	57	5	7.6	301	193	185	38 1.90	14 1.15	6.5 0.28	2.0 0.05	158 2.59	0 0.00	24 0.50	7.4 0.21	0.8 0.01	0.1 0.01	22	0.14	152	23
USGS 12	4N-30E-7 ad1	Sept. 30, 1952	Pump	325-634	52	2	7.7	536	313	327	67 3.34	22 1.81	11 0.48	2.0 0.05	218 3.57	0 0.00	38 0.79	40 1.13	4.1 0.07	0.2 0.01	21	0.02	258	79
USGS 13	2N-27E-33 ac2	May 7, 1952	---	983-1200	62	2	8.1	460	270	278	34 1.70	21 1.73	27 1.17	4.2 0.11	151 2.48	0 0.00	29 0.60	55 1.55	2.2 0.04	0.2 0.01	23	0.08	171	47
USGS 14	1S-30E-15 bc1	Dec. 3 1962	Thief	275	59	5	7.9	327	208	208	32 1.59	13 1.09	16 0.70	2.8 0.07	162 2.66	0 0.00	24 0.50	8.5 0.24	1.1 0.07	0.5 0.03	30	0.01	134	2
USGS 15	4N-30E-6 ab1	Sept. 29, 1952	Pump	312-1497	53	---	7.8	303	186	178	32 1.60	16 1.32	8.3 0.36	1.5 0.04	163 2.67	0 0.00	19 0.40	7.0 0.20	1.2 0.02	0.1 0.01	21	0.02	146	12
USGS 17	4N-30E-22 bd1	Nov. 30, 1951	Pump	351-497	52	—	8.3	225	144	153	28 1.40	5.9 0.49	7.0 0.30	4.2 0.11	81 1.33	9.8 0.33	21 0.44	6.6 0.19	0.5 0.01	0.2 0.01	21	0.03	94	11
USGS 18	5N-31E-14 bc1	Sept. 13, 1951	Pump	267-329	59	5	8.1	332	215	205	33 1.65	16 1.32	13 0.56	4.3 0.11	166 2.72	0 0.00	27 0.56	9.2 0.26	1.4 0.02	0.3 0.02	29	0.34	148	12
USGS 19	5N-29E-23 cd1	May 9, 1952	Thief	304	62	5	8.0	376	223	227	47 2.34	17 1.40	7.0 0.30	2.3 0.06	186 3.05	0 0.00	26 0.54	14 0.40	3.1 0.05	0.1 0.01	15	0.03	187	35
USGS 20	3N-30E 31 aa1	Oct. 3, 1952	Pump	455-678	53	2	8.0	292	180	179	35 1.75	11 0.90	7.9 0.34	2.3 0.06	144 2.36	0 0.00	17 0.35	12 0.34	0.8 0.01	0.1 0.01	23	0.07	133	15
USGS 21	5N-32E-36 ad1	June 3, 1952	Pump	330-405	55	5	7.7	315	194	195	33 1.65	11 0.90	15 0.65	3.6 0.09	140 2.29	0 0.00	25 0.52	14 0.40	2.8 0.04	0.3 0.02	20	0.03	128	13
USGS 22	3N-29E-19 cb1	June 9, 1952	Pump	604-658	62	5	8.1	350	206	228	31 1.55	10 0.82	20 0.87	3.8 0.10	88 1.44	0 0.00	22 0.46	47 1.33	4.1 0.07	0.2 0.01	25	0.05	118	46
USGS 23	4N-29E 9 dc1	June 7, 1952	Pump	395-463	60	5	7.9	349	203	203	39 1.95	18 1.48	7.5 0.33	1.4 0.04	176 2.88	0 0.00	20 0.42	11 0.31	2.3 0.04	0.3 0.02	17	0.11	171	27
USGS 24	6N-31E-13 db1	Aug. 26, 1952	Pump	214-326	50	2	7.7	365	224	222	51 2.54	13 1.07	6.6 0.29	2.3 0.06	189 3.10	0 0.00	27 0.56	7.4 0.21	2.2 0.04	0.2 0.01	21	0.04	181	26
USGS 25	7N-31E-34 bd1	Oct. 11, 1952	Pump	269-320	50	2	8.0	359	215	213	45 2.25	17 1.40	6.3 0.27	1.5 0.04	187 3.06	0 0.00	29 0.60	6.5 0.18	1.6 0.03	0.1 0.01	16	0.03	182	29
USGS 26	6N-32E-11 ab1	Oct. 31, 1952	Bailer	208-267	60	2	7.7	366	237	236	39 1.95	15 1.23	15 0.65	3.5 0.09	179 2.93	--- ---	30 0.62	11 0.31	1.7 0.03	0.5 0.03	33	0.06	159	12
USGS 28	5N-33E-17 ad1	Feb. 21, 1953	Bailer	232-334	58	2	7.8	331	217	212	33 1.65	14 1.15	15 0.65	3.6 0.09	164 2.69	0 0.00	25 0.52	9.0 0.25	1.3 0.02	0.5 0.03	35	0.01	140	6
USGS 29	5N-34E-29 da1	Apr. 25, 1953	Bailer	348-398	52	7	8.4	310	205	204	26 1.30	13 1.07	15 0.65	3.3 0.08	100 1.64	6 0.20	19 0.40	32 0.90	2.0 0.03	0.5 0.03	39	0.03	118	26
USGS 30	5N-33E-13 bd1	Apr. 27, 1953	Pump	265-359	57	5	7.9	358	233	226	36 1.80	13 1.07	18 0.78	4.1 1.10	172 2.82	0 0.00	27 0.40	14 0.40	1.0 0.02	0.6 0.03	35	0.03	143	2
USGS 31	5N-32E-10 cd1	July 11, 1953	Pump	253-429	60	2	7.9	344	223	220	36 1.80	13 1.07	14 0.61	3.3 0.08	169 2.77	0 0.00	24 0.50	10 0.28	1.3 0.02	0.5 0.03	37	0.05	143	5
USGS 32	5N-33E-23 dd1	July 8, 1953	Bailer	288-392	59	2	7.9	375	233	230	35 1.75	14 1.15	21 0.91	4.4 0.11	164 2.69	0 0.00	27 0.56	18 0.51	2.6 0.04	0.6 0.03	29	0.12	145	10
USGS 33	5N-33E-35 da1	Sept. 3, 1953	Bailer	365-516	56	2	7.8	567	335	348	51 2.54	19 1.56	33 1.43	5.1 0.13	164 2.69	0 0.00	32 0.67	69 1.95	9.9 0.16	0.6 0.03	34	0.11	205	70
USGS 83	2N-29E-13 ac1	June 7, 1965	Thief	560	53	0	7.8	269	169	172	26 1.30	12 0.96	10 0.44	2.7 0.07	124 2.03	0 0.00	19 0.40	9.5 0.27	1.5 0.02	0.4 0.02	27	0.52	114	12
ANP 1	6N-31E-13 ac1	Apr. 18, 1953	Pump	209-365	—	5	8.1	404	243	248	54 2.69	15 1.23	6.8 0.30	2.1 0.05	204 3.34	0 0.00	32 0.67	9.5 0.27	2.3 0.04	0 0.00	21	0.03	196	29
ANP 2	6N-31E-13 ac2	March 10, 1968	Pump	215-346	50	0	7.7	401	243	244	53 2.65	15 1.23	7.2 0.31	2.3 0.06	192 3.15	0 0.00	32 0.67	12 0.34	3.7 0.06	0.3 0.02	23	0.01	194	36
ANP 5	7N-31E-33 dc1	June 16, 1956	Pump	294-395	50	0	8.1	356	212	209	43 2.15	17 1.40	6.3 0.27	1.2 0.03	184 3.02	0 0.00	27 0.56	7.0 0.20	1.9 0.03	0.2 0.01	17	0.00	177	26
ANP 6	6N-31E-10 ac1	Sept. 6, 1956	Pump	213-305	55	0	8.0	392	236	239	44 2.20	17 1.40	10 0.44	2.4 0.06	176 2.88	--- ---	35 0.73	14 0.40	2.5 0.04	0.3 0.02	23	0.00	180	43

TABLE III (contd.)

Well No.	U.S.G.S. location number	Date Sampled	Method of sampling	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determined constituents	Residue on evaporation at 180°C	Milligrams per liter (upper number) and milliequivalents per liter (lower number) for indicated cations and anions												Hardness as $CaCO_3$	
											Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)	Silica (SiO_2)	Dissolved iron (Fe)	Total	Noncarbonate
ANP 7	7N-31E- 22 bdl	July 10, 1956	Pump	352-436	49.75	0	8.0	356	211	204	46 2.30	16 1.32	6.0 0.26	1.2 0.03	184 3.02	0 0.00	28 0.58	6.8 0.19	1.6 0.03	0.2 0.01	14	0.00	181	30
ANP 8	6N-32E- 26 cal	July 20, 1956	Pump	209-309	52	0	---	366	228	232	46 2.30	15 1.23	7.0 0.30	2.9 0.07	184 3.02	--- ---	29 0.60	7.2 0.20	2.6 0.04	0.2 0.01	27	0.02	176	25
ANP 9	6N-32E- 26 cdl	July 18, 1956	Pump	222-322	58	0	8.2	359	227	223	37 1.85	15 1.23	14 0.61	3.1 0.08	168 2.75	--- ---	30 0.62	11 0.31	1.7 0.03	0.4 0.02	32	0.00	154	18
ANP 10	6N-32E- 26	July 7, 1959	Pump	220-681	---	0	7.6	356	216	207	34 1.70	15 1.23	13 0.57	3.2 0.08	164 2.69	0 0.00	28 0.58	9.5 0.27	1.3 0.02	0.4 0.02	31	---	145	10
ARBOR 1	3N-32E- 13 dcl	Dec. 28, 1957	Pump	675-790	55	0	8.1	277	178	178	30 1.50	9.1 0.75	14 0.61	2.6 0.07	144 2.36	0 0.00	10 0.21	8.8 0.25	2.4 0.04	0.8 0.04	29	0.00	112	0
AREA II	3N-31E- 34 adl	Apr. 23, 1960	Pump	666-881	57	0	7.8	309	197	193	31 1.55	12 0.99	14 0.61	3.0 0.08	148 2.43	0 0.00	15 0.31	13 0.37	2.3 0.04	0.5 0.03	33	0.05	126	4
ATR-4	3N-29E- 14 cb	July 31, 1963	Pump	460-970	58	0	7.8	384	234	230	49 2.45	17 1.37	7.5 0.33	1.6 0.04	203 3.33	0 0.00	22 0.46	11 0.31	3.4 0.05	0.2 0.01	22	---	191	24
CFA-2	2N-29E- 1 dbl	Jan. 16, 1949	Pump	---	53.5	---	7.3	348	217	216	39 1.95	15 1.23	7.9 0.34	3.5 0.09	150 2.46	--- ---	21 0.44	24 0.68	1.9 0.03	0.2 0.01	30	0.04	159	36
CPP-1	3N-30E- 19 bcl	Dec. 7, 1950	Pump	450-586	54	---	7.8	334	210	208	43 2.14	13 1.07	7.9 0.34	3.5 0.09	174 2.85	0 0.00	20 0.41	10 0.28	0.9 0.01	0.2 0.01	25	0.03	161	18
CPP-2	3N-29E- 24 adl	Sept. 1, 1951	Pump	453-605	54	5	7.9	337	208	208	44 2.19	13 1.07	7.8 0.34	1.2 0.03	176 2.88	0 0.00	21 0.44	10 0.28	1.0 0.02	0.2 0.01	22	0.02	163	19
EBR-I	2N-29E- 9 cal	Aug. 12, 1949	Pump	597-1075	65.5	---	8.0	267	181	166	22 1.10	16 1.32	9.1 0.40	4.0 0.10	140 2.29	--- ---	18 0.38	6.0 0.17	1.0 0.02	0.2 0.01	36	0.10	121	6
EBR-II-11	3N-32E- 13 bb2	Oct. 3, 1958	Pump	635-745	54	0	7.7	293	192	191	32 1.60	9.7 0.80	14 0.61	3.0 0.08	149 2.44	0 0.00	13 0.27	12 0.34	0.9 0.03	0.7 0.04	33	0.25	120	0
EOCR 1	2N-30E- 5 ddl	June 28, 1960	Pump	484-1237	55	0	7.9	384	231	234	45 2.25	18 1.48	8.5 0.37	1.9 0.05	188 3.08	0 0.00	22 0.46	15 0.42	3.0 0.05	0.4 0.02	24	0.04	187	33
ETR	3N-29E- 14 ad2	June 7, 1957	Pump	458-596	54.5	0	8.2	416	245	246	52 2.60	18 1.48	9.1 0.40	1.5 0.04	214 3.51	0 0.00	25 0.52	13 0.37	4.3 0.07	0.2 0.01	17	0.00	204	29
FET 2	6N-31E- 14 ab2	May 3, 1958	Pump	200-462	52	0	8.1	371	225	227	46 2.30	15 1.23	7.9 0.34	3.8 0.10	178 2.92	0 0.00	31 0.65	9.0 0.25	2.4 0.04	0.1 0.01	22	0.12	178	32
Fire Sta. 2	3N-29E- 12 ddl	Nov. 5, 1957	Pump	420-516	51.5	5	8.1	385	222	230	51 2.54	15 1.23	7.1 0.31	2.1 0.05	188 3.08	0 0.00	22 0.46	14 0.40	2.7 0.04	0.1 0.01	15	0.06	189	15
GCRE 1	2N-30E- 1bdl	March 2, 1959	Pump	592-1340	59.5	5	7.6	358	224	223	35 1.75	15 1.23	16 0.70	3.2 0.08	158 2.59	0 0.00	24 0.50	18 0.51	2.9 0.05	0.5 0.03	31	0.08	150	21
LPTF Disp.	6N-32E- 22 ccl	June 21, 1957	Pump	210-315	50	5	8.1	354	216	217	43 2.15	15 1.23	7.1 0.31	3.1 0.08	178 2.92	0 0.00	29 0.60	6.5 0.18	2.9 0.05	0.3 0.02	21	0.00	169	23
MTR Test	3N-29E- 14 adl	Nov. 30, 1949	Pump	454-588	55	---	7.2	398	238	240	52 2.60	19 1.56	2.7 0.12	2.2 0.06	216 3.54	0 0.00	20 0.42	12 0.34	4.1 0.07	0.2 0.01	19	0.06	208	31
MTR 1	3N-29E- 14 acl	Aug. 20, 1968	Pump	457-600	---	0	7.8	418	249	254	51 2.54	18 1.48	8.4 0.37	1.6 0.04	213 3.47	0 0.00	25 0.52	14 0.39	5.2 0.06	0.2 0.01	21	0.01	201	26
NRF 2	4N-30E- 30 adl	Aug 5, 1951	Pump	366-528	54	5	7.8	529	315	342	68 3.39	21 1.73	9.4 0.41	2.4 0.06	226 3.70	0 0.00	36 0.75	38 1.07	4.8 0.08	0.2 0.01	24	0.03	256	71
OMRE	2N-30E 8 aal	March 23, 1957	Pump	480-940	55	0	8.0	364	220	221	44 2.20	15 1.23	7.9 0.34	2.1 0.05	182 2.98	--- ---	20 0.42	12 0.34	2.1 0.03	0.2 0.01	27	0.00	172	23
P&W 1	7N-31E- 28 cal	Aug. 10, 1957	Pump	317-432	49.5	0	8.0	360	207	201	45 2.25	16 1.32	6.3 0.27	1.2 0.03	182 2.98	0 0.00	28 0.58	6.5 0.18	2.0 0.03	0.3 0.02	12	0.02	178	29
P&W 2	7N-31E- 28 dal	Sept. 7, 1957	Pump	311-386	50	5	8.0	361	211	212	43 2.15	16 1.32	7.2 0.31	1.5 0.04	178 2.92	--- ---	30 0.62	7.5 0.21	2.3 0.04	0.3 0.02	15	0.00	173	17
P&W 3	7N-31E- 26 bbl	Nov. 13, 1957	Pump	304-406	49	5	8.1	357	209	206	47 2.34	16 1.32	6.1 0.26	1.3 0.03	183 3.00	0 0.00	28 0.58	7.5 0.21	1.7 0.03	0.1 0.01	11	0.02	183	33
PSTF Test	6N-31E- 21 dcl	Dec. 21, 1957	Pump	208-320	55	0	8.1	301	186	189	33 1.65	15 1.23	7.4 0.32	2.5 0.06	160 2.62	0 0.00	16 0.33	7.0 0.20	2.3 0.04	0.1 0.01	24	0.07	144	13
Site 4	3N-30E- 8 abl	Jan. 3, 1957	Pump	395-496	53	0	8.0	348	214	210	47 2.34	13 1.07	6.7 0.29	1.6 0.04	181 2.97	--- ---	21 0.44	8.5 0.24	1.6 0.03	0.2 0.01	25	0.01	171	23
Site 6-1	4N-30E- 26 ccl	Nov. 5, 1959	Pump	352-523	57	0	8.0	327	203	208	41 2.05	14 1.11	6.9 0.30	2.0 0.05	168 2.75	0 0.00	19 0.40	9.0 0.25	1.5 0.02	0.2 0.01	26	0.43	158	20
Site 14	5N-31E- 28 cbl	Feb. 20, 1962	Thief	275	62	5	7.8	322	208	211	34 1.7	12 0.99	16 0.70	3.0 0.08	159 2.61	0 0.00	23 0.48	8.5 0.24	1.5 0.02	0.5 0.03	31	0.12	134	4
Site 19	3N-29E- 14 bdl	June 9, 1960	Pump	466-575	57	0	8.1	353	217	215	40 2.00	18 1.48	7.7 0.33	2.0 0.05	176 2.88	0 0.00	22 0.46	12 0.34	3.4 0.05	0.3 0.02	24	0.27	173	29
SL-1,1	2N-30E- 12 abl	Sept. 10, 1957	Pump	606-787	57	5	8.0	328	202	202	33 1.65	13 1.07	14 0.61	3.0 0.08	151 2.48	--- ---	18 0.38	16 0.45	3.0 0.05	0.5 0.03	27	0.00	136	12
SPERT 1	3N-30E- 34 bal	Feb. 27, 1956	Pump	466-653	---	0	8.2	332	205	208	39 1.95	14 1.15	8.8 0.38	2.7 0.07	158 2.59	0 0.00	19 0.40	16 0.45	1.2 0.02	0.1 0.01	26	0.04	155	25
USBR	5S-23E- 17 cal	March 11, 1967	Bailer	308-333	55	0	7.7	281	133	188	24 1.20	14 1.15	15 0.65	4.3 0.11	143 2.34	0 0.00	20 0.42	9.0 0.25	0.5 0.01	0.60 0.03	26	0.49	118	0
USBR	4S-24E- 6 bbl	March 12, 1967	Bailer	416-445	53	5	7.7	257	164	160	26 1.30	9.6 0.79	13 0.57	2.0 0.05	127 2.08	0 0.00	16 0.33	7.5 0.21	1.0 0.02	0.5 0.03	26	0.44	104	0

The actual reactions taking place in the recharge areas may be more complicated than those presented in this section and may include some of the complicating factors enumerated in the discussion of the composition of Banbury Hot Spring in the chapter on geology. For instance, most of the hydrolysis reactions probably should be written to include carbonic acid, formed by the solution of atmospheric and soil carbon dioxide in water, rather than indicating pure water. However, lacking the data to make a complete evaluation of the geochemistry of each recharge system, only the simplest overall reaction between water and each mineral was evaluated. Details of the reactions presented in this section, together with other reactions that may be closer approaches to the truth, can be found in many publications (Garrels and Christ, 1965, pp. 352-365; Krauskopf, 1967, pp. 98-121; Stumm and Morgan, 1970; Hem, 1970).

1.1 Northwest

Precambrian rocks northwest of the eastern Snake River Plain consist of small outcrops of dominantly quartzitic sediments. Except for fractures, these rocks provide little permeability for reacting solutions and have little else than highly insoluble quartz available for reaction. Paleozoic rocks northwest of the plain primarily consist of limestones and dolomites with thinner sections of sandstone and shale. Carbonate rocks dominate the outcrop areas, perhaps because extreme intraformational deformation by faulting and plastic flow has resulted in great thicknesses of repeated section (Ross, 1961, p. 239). Solution-enlarged fractures pervade the carbonate rocks allowing large amounts of rain, snowmelt, and streamflow to disappear into the outcrops. The areal predominance of carbonate rocks, their ability to imbibe and carry all surface water, and their simple highly reactive composition consisting of relatively soluble calcite and dolomite, make them the most important geochemical controls on the northwest side of the Snake River Plain.

The reactions of calcite and dolomite with water may be represented as follows:

$$\mathrm{CaCO_3 + H_2O = Ca^{+2} + HCO_3^{-} + OH^{-}} \qquad (1)$$

$$\mathrm{CaMg(CO_3)_2 + 2H_2O = Ca^{+2} + Mg^{+2} + 2HCO_3^{-} + 2OH^{-}.} \qquad (2)$$

The first equation, reading from left to right, describes the hydrolysis of calcite to yield a calcium ion (an electrically charged particle of calcium of atomic or molecular dimensions present in aqueous solution), a bicarbonate ion, and a hydroxyl ion. The presence of a hydroxyl ion with the products of solution of calcite on the right side of the equation indicates that the dissolution reaction tends to consume acid (hydrogen ions) and make the water more alkaline. Equation (2) shows that identical products, plus the magnesium ion, form from the hydrolysis of dolomite.

Though quantitatively less important, the shale beds contain potassium and sodium feldspars, micas, and clay minerals which may react with water as follows:

$$3KAlSi_3O_8 + 2H_2O = KAl_3Si_3O_{10}(OH)_2 + 2K^+ + 2OH^- + 6SiO_2 \qquad (3)$$

$$2NaAlSi_3O_8 + 2H_2O = Al_2Si_4O_{10}(OH)_2 + 2Na^+ + 2OH^- + 2SiO_2. \qquad (4)$$

Equation (3) describes the hydrolysis of potassium feldspar to yield a mica mineral (muscovite) plus potassium ions, hydroxyl ions, and silica in solution. Equation (4) shows the hydrolysis of sodium feldspar to yield the clay mineral montmorillonite plus sodium and hydroxyl ions and silica in solution. (Only an idealized formula for montmorillonite is shown, for in nature variable amounts of magnesium, iron, and other elements are usually present.) Most natural sodium-rich feldspars contain some calcium. Hydrolysis of such a feldspar merely releases the calcium as an additional ion to the water. Mica can hydrolyze further and montmorillonite can take up water to yield the clay mineral kaolinite according to these reactions:

$$2KAl_3Si_3O_{10}(OH)_2 + 5H_2O = 3Al_2Si_2O_5(OH)_4 + 2K^+ + 2OH^- \qquad (5)$$

$$Al_2Si_4O_{10}(OH)_2 + H_2O = Al_2Si_2O_5(OH)_4 + 2SiO_2 \quad . \qquad (6)$$

And under conditions of extreme or long-continued weathering, kaolinite can take up water to yield the end-product mineral gibbsite,

$$Al_2Si_2O_5(OH)_4 + H_2O = 2Al(OH)_3 + 2SiO_2. \qquad (7)$$

Surface and groundwaters draining southeastward toward the Snake River Plain provide evidence for the relative extent of the given reactions in rocks northwest of the NRTS. Table IV shows chemical analyses for the four major streams draining this area. From south to north they are Big Lost River, Little Lost River, Birch Creek, and Medicine Lodge Creek. All contain calcium and magnesium bicarbonate water. This clearly reflects the abundance of limestone and dolomite in the mountains bordering the valleys of these streams (Figure 18). Small quantities of sodium, potassium, and silica in these waters reflect their minor occurrence in the minerals of the rocks and (or) the low solubility of the

TABLE IV

CHEMICAL ANALYSES OF SURFACE WATER AND GROUNDWATER FROM REGION NORTHWEST OF NRTS

(Analyses in milligrams per liter except as indicated. Milliequivalents per liter in parentheses.)

	Big Lost River near Moore, Idaho, Aug. 27, 1963, 1020 hr	Little Lost River near Howe, Idaho, Sept. 3, 1963, 1020 hr	Birch Crk south of Blue Dome, Idaho, Sept. 3, 1963, 1145 hr	Medicine Lodge Crk near Medicine Lodge, Idaho, Sept. 3, 1963, 1305 hr	Well 4N26E 36aa1 near Arco, Idaho, Aug. 30, 1957, Depth: 190 ft
Silica (SiO_2)	12	12	8.8	18	24
Calcium (Ca)	48 (2.40)	39 (1.95)	39 (1.95)	64 (3.19)	67 (3.34)
Magnesium (Mg)	11 (0.88)	15 (1.27)	14 (1.19)	17 (1.40)	18 (1.48)
Sodium (Na)	6.9 (0.30)	6.7 (0.29)	5.0 (0.22)	8.6 (0.37)	9.0 (0.39)
Potassium (K)	1.4 (0.04)	1.2 (0.03)	1.0 (0.03)	2.5 (0.06)	1.8 (0.05)
Bicarbonate (HCO_3)	192 (3.15)	177 (2.90)	164 (2.69)	233 (3.82)	274 (4.49)
Carbonate (CO_3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Sulfate (SO_4)	18 (0.37)	16 (0.33)	25 (0.52)	48 (1.00)	24 (0.50)
Chloride (Cl)	3.5 (0.10)	8.8 (0.25)	4.5 (0.13)	6.0 (0.17)	7.5 (0.21)
Fluoride (F)	1.9 (0.10)	0.2 (0.01)	0.2 (0.01)	0.1 (0.01)	0.3 (0.02)
Nitrate (NO_3)	0.5 (0.01)	0.6 (0.01)	0.6 (0.01)	0.1 (0.00)	1.7 (0.03)
Specific Conductance (micromhos at 25°C)	333	323	309	453	489
pH (pH units)	7.7	7.7	8.0	7.8	7.6
Residue on evaporation at 180°C	191	192	186	284	289
Temperature °C	--	12.2	14.4	12.8	13

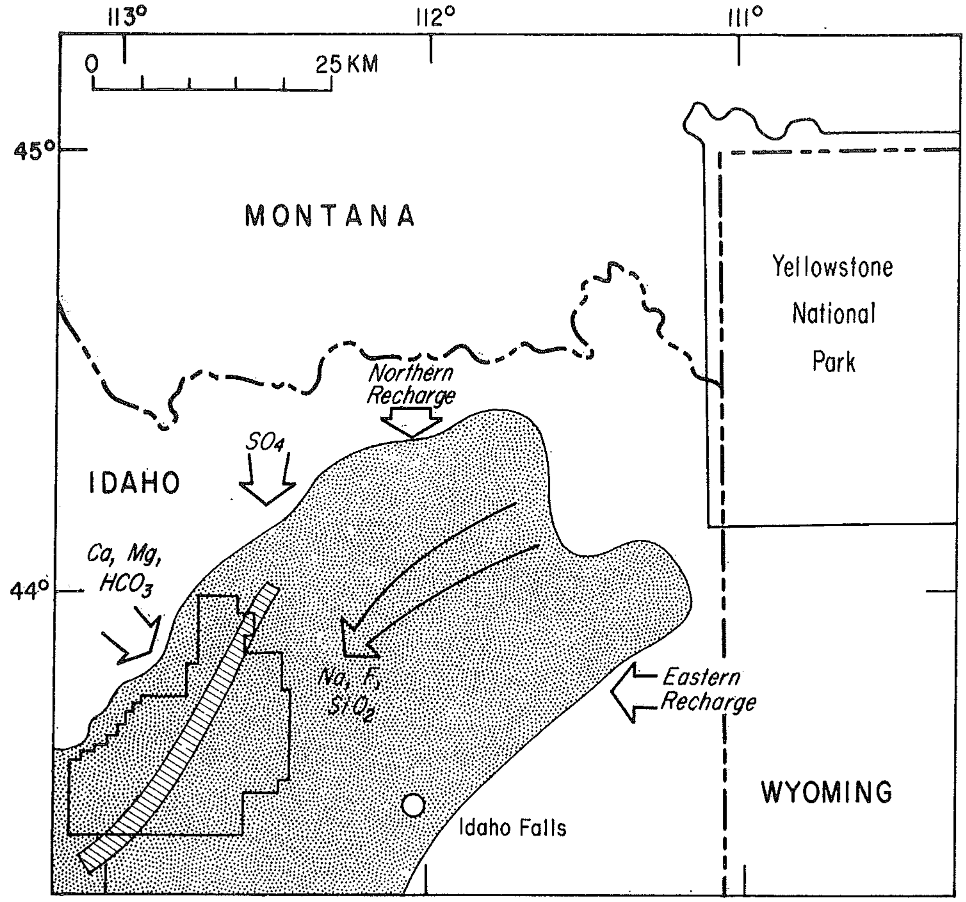


Fig. 18 Hydrochemical zones of groundwater at the NRTS and sources of chemically distinct recharge to the eastern Snake River Plain (shaded area). Zone of mixing between Ca-Mg-HCO_3 water and water enriched in Na-F-SiO_2 is indicated by diagonal ruling.

minerals. Progressive increase in anionic milliequivalents per liter of sulfate, from 10% in Big Lost River to 20% in Medicine Lodge Creek, indicates the presence of gypsum- and anhydrite-bearing rocks to the northeast where both Paleozoic and Mesozoic rocks become increasingly continental (Figure 18). The high fluoride value found in the Big Lost River at the Moore Diversion (Table IV) may indicate a local source of high fluoride water from Challis volcanic rocks immediately to the south. The lack of change in the sodium and silica values, and the low fluoride values reported upstream and downstream, however, (Crosthwaite and others, 1970, their Table 10) make this interpretation tenuous. The quality of water moving through alluvial gravels of the Big Lost River is represented by the analysis of a single well (Table IV). This well, located near the town of Arco where groundwater flow from the valley enters rocks of the Snake River Plain, matches closely the composition of river water with the exception of slightly higher dissolved solids. The much slower velocities of groundwater flow compared to surface-water flow afford additional time for reaction between water and rock.

1.2 West

Large areas of Tertiary Challis Volcanics crop out immediately west of Craters of the Moon National Monument. These thick beds of volcanic breccia and flows vary in composition from andesite to rhyolite. Because the major outcrop areas of Challis Volcanics lie southwest of the NRTS, down the groundwater flow path, their mineralogy affects groundwater of the Snake River Plain after it leaves the NRTS.

Several minerals in the Challis Volcanics may influence the composition of recharge from this area, and similar minerals occur in silicic volcanic rocks bordering other parts of the plain. In addition to potassium and sodium feldspars whose hydrolysis reactions have already been described [Equations (3) and (4)], calcium-rich feldspars typical of some Challis Volcanics may hydrolyze to yield montmorillonite according to the reaction:

$$2CaAl_2SiO_8 + 6H_2O = Al_2Si_4O_{10}(OH)_2 + 2Ca^{+2} + 10(OH)^- + 2Al^{+3} \quad (8)$$

where the aluminum may remain in solution as shown but more likely combines with hydroxyl ions to form the mineral gibbsite or an amorphous equivalent.

Minerals from the pyroxene and amphibole mineral families make up significant parts of rocks like the Challis Volcanics. The chemical composition of minerals in these two groups varies widely. They consist of combinations of a few or many elements such as calcium, magnesium, sodium, iron, aluminum, lithium, and titanium with silica. Their hydrolysis reactions may produce montmorillonite or kaolinite and release the remaining elements into solution as ions.

Tridymite, cristobalite, and quartz, all polymorphic varieties of SiO_2, can form significant portions of these rocks. Quartz is relatively insoluble but tridymite and cristobalite can dissolve to provide SiO_2 in moderate quantities to the water. If a water becomes alkaline enough in the course of hydrolysis reactions (pH 9 or greater), silicate anions may be formed and the solubility of silica will be substantially increased from all three minerals.

The mineral fluorite, present in small amounts in the Challis Volcanics, may be the source of the small but diagnostic fluoride content of the water. The mineral simply dissolves to yield its ions to the solution

$$CaF_2 = Ca^{+2} + 2F^-. \quad (9)$$

Finally, the last mineral of geochemical importance in the Challis Volcanics and similar rocks is, technically, not a mineral at all. It is the noncrystalline glass between the crystals of the rock, which cooled very rapidly as the lava poured out onto the earth's surface. This glass consists of all the elements that make up the minerals in the rock but it lacks the orderly arrangement of atoms that characterizes a crystal. This lack of order makes glass very unstable and it alters easily to very small crystallites (devitrifies). The instability of volcanic glass allows it to dissolve readily and provide such a large concentration of ions that some of the hydrolysis reactions described may be driven backward, from right to left, resulting in precipitation of the reactant minerals. This can happen readily for reactions (1), (2), and (9). The other reactions, however, involve silicates and tend to be irreversible at low temperatures. Large supersaturations with respect to silicate minerals commonly occur in groundwaters with no evident precipitation. Where precipitates do form they tend to be amorphous.

Though few water analyses exist with which to check these hypothetical reactions of the Challis Volcanics with groundwater, two U. S. Bureau of Reclamation (USBR) observation wells (Table B-I) located 25 and 35 miles south of Craters of the Moon provide some support. They are lower in calcium and bicarbonate and higher in sodium, fluoride, silica, and perhaps potassium than waters of similar total dissolved solids farther northeast on the plain. These differences may be a result of the large areas of Challis Volcanics that cover Paleozoic carbonate rocks to the west. R. L. Nace (written communication, 1959) noted an increase in sodium content from about 6 mg/l in wells on the NRTS to 15 to 20 mg/l in down-gradient wells near Rupert and Jerome, Idaho and 25 mg/l in the groundwater discharge at Thousand Springs near Hagerman, Idaho. Although this compositional change may reflect high-sodium recharge water from extensive areas of Challis Volcanics to the north and west, additions of sodium-rich leachates from irrigated tracts may also be important.

1.3 East

To the east of the eastern Snake River Plain, from Blackfoot to Idaho Falls and beyond, Paleozoic rocks similar to those on the northwest side of the plain crop out. The area differs from the northwest principally in the much smaller extent of Paleozoic carbonates and the areal dominance of Mesozoic rocks. These Mesozoic rocks, consisting of siltstones and shales of both nonmarine and marine origin, contain coal, anhydrite, and gypsum as well as thin limestones and sandstones. The Permian Phosphoria Formation provides a source for phosphate, fluoride, and many exotic metals such as vanadium and uranium that were incorporated in it during its deposition.

In addition to the ions derived from hydrolysis of feldspars, micas, clays, and carbonates already described, the eastern area provides large amounts of sulfate ions to recharge, mainly by solution of anhydrite and its hydrated analo

$$CaSO_4 = Ca^{+2} + SO_4^{-2}. \tag{10}$$

The fluorapatite that makes up much of the Phosphoria Formation can react with water by hydrolysis to yield its constituent ions:

$$Ca_5F(PO_4)_3 + 3H_2O = 5Ca^{+2} + F^- + 3HPO_4^{-2} + 3OH^-. \tag{11}$$

Small amounts of siderite associated with coaly beds react by hydrolysis like other carbonates:

$$FeCO_3 + H_2O = Fe^{+2} + HCO_3^- + OH^-. \tag{12}$$

The iron sulfides pyrite and marcasite associated with almost all coal deposits and organic shales yield different reaction products depending upon the ability of the environment to effect oxidation or reduction. Investigators still disagree about the details of these reactions and about the necessity for microorganisms, high temperatures, or trace elements to act as catalysts. Under reducing conditions, pyrite and marcasite tend to remain unchanged except at high temperatures where hydrogen sulfide gas may be generated. This is probably the origin of the sulfides in Heise Hot Spring (Table I) though isotopic evidence would be required to confirm it. Oxidation of pyrite and marcasite in oxygenated water at or near the earth's surface may take place by hydrolysis as follows:

$$FeS_2 + 3\tfrac{1}{2}O_2 + H_2O = Fe^{+2} + 2SO_4^{-2} + 2H^+ \tag{13}$$

yielding iron, sulfate, and hydrogen ions (sulfuric acid) to the water. And in the oxygenated environment postulated, the ferrous iron ion would oxidize in water by hydrolysis, and produce a yellow-brown "rusty" precipitate [$Fe(OH)_3$] as well as additional acid:

$$2Fe^{+2} + 5H_2O + \tfrac{1}{2}O_2 = 2Fe(OH)_3 + 4H^+. \tag{14}$$

Evidence for the probable extent of these reactions is contained in Table V which shows the changing composition of the Snake River as it flows from its headwaters in Yellowstone Park, around the south end of the Teton Range, through Paleozoic and Mesozoic sediments, and out onto the Snake River Plain northeast of Idaho Falls. The water initially contains only 97 mg/l of dissolved solids, 7% sulfate equivalents, and is a sodium bicarbonate chloride water with significant amounts of silica and fluoride. Much of the sodium, chloride, fluoride, and silica probably originate from thermal water in the park. During its journey south and west to Heise, the Snake River increases in dissolved solids to 270 mg/l and in sulfate to 28% of the anion equivalents. The water becomes a calcium and magnesium bicarbonate and sulfate type with low fluoride and silica (Figure 18).

1.4 North

Rocks in the Centennial Mountains on the extreme north side of the eastern Snake River Plain consist of Paleozoic and Mesozoic rocks similar to those on the east and should provide runoff and groundwater compositions of about the same kind. Table VI shows that the water from Camas Creek is a calcium and magnesium bicarbonate water with low dissolved solids and low sulfate. High precipitation in the adjoining Centennial Mountains is a major cause for the low dissolved solids content. Notably low sulfate, which is at variance with water compositions on the east, indicates minimal exposure of gypsiferous rocks in the watershed (Figure 18).

Farther south, water from Camas Creek is used for irrigation and eventually reaches Mud Lake. The analysis of water from Mud Lake (Table VI) shows an approximate doubling in the concentration of most constituents due to evaporation during irrigation. Sodium and chloride increase at a faster rate because of their continuous fallout in atmospheric dust and rapid solution from irrigated soils. High nitrate values probably reflect the use of nitrogenous fertilzers. The relative constancy of silica content is remarkable and may reflect the precipitation of some silicious phase or extraction of silica by diatoms living in the lake waters.

Groundwater in the northern part of the Snake River Plain, such as from the well of Dubois (Table VI), consists of calcium and magnesium bicarbonate water like that in the streams but of much higher dissolved-solids content. This increase reflects some evaporative concentration by irrigation as well as a much longer residence time in the rocks.

1.5 Northeast

On the extreme northeastern end of the Snake River Plain, large areas of rhyolitic volcanic rocks crop out (Figure 13). These rocks resemble those in scattered outcrops around the edge of the Snake River Plain that may form a continuous blanket beneath the basalt of the plain. The reaction products provided by these noncrystalline and

TABLE V

CHEMICAL ANALYSES OF SURFACE WATER FROM REGION EAST OF EASTERN SNAKE RIVER PLAIN

(Analyses in milligrams per liter except as indicated. Milliequivalents per liter in parentheses.)

	Lewis River (Snake River) at south entrance of Yellowstone Park, May 6, 1963, 1500 hr	Snake River at Jackson Dam, April 11, 1965, 1300 hr	Snake River, southeast of Palisades, Idaho, at Wolf Creek, Wyoming, April 12, 1965, 1000 hr	Snake River near Heise, Idaho, May 1, 1963, 1545 hr
Silica (SiO_2)	38	17	15	6.4
Calcium (Ca)	3.0 (0.15)	16 (0.80)	33 (1.65)	56 (2.79)
Magnesium (Mg)	0.7 (0.06)	2.9 (0.24)	7.6 (0.62)	16 (1.30)
Sodium (Na)	17 (0.74)	14 (0.61)	11 (0.48)	14 (0.61)
Potassium (K)	3.3 (0.08)	2.2 (0.06)	2.5 (0.06)	2.2 (0.06)
Bicarbonate (HCO_3)	36 (0.59)	70 (1.15)	117 (1.92)	179 (2.93)
Carbonate (CO_3)	0 (0)	0 (0)	0 (0)	0 (0)
Sulfate (SO_4)	3.8 (0.08)	14 (0.29)	32 (0.67)	63 (1.31)
Chloride (Cl)	9.0 (0.25)	7.8 (0.22)	5.5 (0.16)	16 (0.45)
Fluoride (F)	3.0 (0.16)	1.1 (0.06)	0.8 (0.04)	0.3 (0.02)
Nitrate (NO_3)	0.1 (0.00)	0.1 (0.00)	0.2 (0.00)	0.2 (0.00)
Specific Conductance (micromhos at 25°C)	107	172	270	444
pH (pH units)	7.2	7.7	7.9	7.8
Residue on evaporation at 180°C	97	109	163	270
Temperature (°C)	3.89	2.22	4.44	9.44

TABLE VI

CHEMICAL ANALYSES OF SURFACE WATER AND GROUNDWATER FROM REGION NORTH OF NRTS

(Analyses in milligrams per liter except as indicated.
Milliequivalents per liter in parentheses.)

	Camas Creek at bridge in Camas, Idaho, May 1, 1963, 1015 hr	Mud Lake, Idaho, April 30, 1963, 1315 hr	Well 10N36E 21ca1 Dubois, Idaho, Pumped sample Depth: 346 ft -610 ft May 24, 1957	Well 4 5N34E9bd1 NRTS, Idaho, Pumped sample Depth: 256 ft-321 ft Nov. 8, 1952
Silica (SiO_2)	20	25	35	29
Calcium (Ca)	18 (0.90)	31 (1.55)	40 (2.00)	93 (4.64)
Magnesium (Mg)	4.3 (0.36)	9.3 (0.76)	14 (1.15)	33 (2.71)
Sodium (Na)	3.8 (0.17)	10 (0.44)	11 (0.48)	42 (1.83)
Potassium (K)	2.6 (0.07)	2.5 (0.06)	2.3 (0.06)	6.8 (0.17)
Bicarbonate (HCO_3)	81 (1.33)	144 (2.36)	198 (3.25)	186 (3.05)
Carbonate (CO_3)	0 (0)	0 (0)	0 (0)	0 (0)
Sulfate (SO_4)	3.0 (0.06)	7.8 (0.16)	7.9 (0.16)	57 (1.19)
Chloride (Cl)	1.2 (0.03)	6.5 (0.18)	8.0 (0.23)	160 (4.51)
Fluoride (F)	0.2 (0.01)	0.5 (0.03)	0.2 (0.01)	0.3 (0.02)
Nitrate (NO_3)	0.4 (0.01)	1.5 (0.02)	1.7 (0.03)	2.9 (0.47)
Specific Conductance (micromhos at 25°C)	138	260	343	963
pH (pH units)	7.2	7.3	7.9	7.7
Residue on evaporation at 180°C	101	168	210	583
Temperature (°C)	8.3	--	10.6	11.1

microcrystalline flows andd tuffs, as water passes through them, are similar to those described for the Challis Volcanics to the west. In addition, some streams of this region drain the southwest corner of Yellowstone National Park as well as the Island Park caldera and may contribute small amounts of thermal water.

Henry's Fork of the Snake River is the major stream draining this area. Its composition changes little as it flows from Island Park, in the mountains, out onto the plain at Ashton (Table VII). High precipitation in these mountains accounts for the low dissolved solids content of the water. The predominantly rhyolitic rocks produce the calcium and sodium bicarbonate composition of the water and account for the relatively high silica and fluoride contents. Water from the city well at St. Anthony exhibits a similar composition with slightly more dissolved solids and considerably more nitrate, both changes presumably related to irrigation around Ashton (Figure 18).

Fall River drains the southwest corner of Yellowstone Park and enters the Henry's Fork near the city of St. Anthony. Table VII shows that its composition, as it enters the plain near Squirrel, is sodium bicarbonate and chloride with large amounts of silica and fluoride. This composition probably indicates significant contributions from the hot springs of Yellowstone Park.

1.6 Thermal Water

Hot springs bordering the plain on concealed bounding faults, as well as possible hot springs beneath the plain on buried basin and range faults, may contribute thermal water to the groundwater. Recognition of the contribution of thermal water to ordinary groundwater may be difficult. Where the proportion of thermal water is large, it will be indicated by a large temperature increase in the groundwater. Before significant dilution has occurred, a high dissolved solids content, particularly of sodium and chloride, as well as high concentrations of constituents such as fluoride, boron, lithium, and ammonia, may denote a thermal contribution.

Certainly the almost complete absence of hot springs from the surface of the eastern Snake River Plain is unusual for a recently active volcanic area. It probably is due to the effect of sealing by lava flows. The presence of inflows of thermal water at depth beneath the plain seems assured by the geologic setting.

As indicated by the linear southern edge of the Rexburg bench, the fault that controls the northwesterly course of the Snake River east of Idaho Falls extends out onto the plain. Several hot springs were accessible along this basin and range fault before inundation by Palisades Reservoir; however, only Heise Hot Spring is presently available for sampling (Table I). Attempts to explain Snake River Plain groundwater compositions along the projection of this fault (north and east of Mud Lake) should include the possibility of admixture with thermal water similar to Heise Hot Spring.

TABLE VII

CHEMICAL ANALYSES OF SURFACE WATER AND GROUNDWATER FROM REGION NORTHEAST OF NRTS

(Analyses in milligrams per liter except as indicated. Milliequivalents per liter in parentheses.)

	Henry's Fork River near Island Park, Idaho, April 3, 1965, 1230 hr	Henry's Fork River near Ashton, Idaho, April 3, 1965, 1100 hr	Fall River near Squirrel, Idaho, April 3, 1965, 0930 hr	Well 7N40E 1adl, St. Anthony, Idaho, Pumped sample Depth: 14 ft-237 ft Aug. 27, 1957
Silica (SiO_2)	32	31	43	40
Calcium (Ca)	12 (0.60)	11 (0.55)	6.8 (0.34)	18 (0.90)
Magnesium (Mg)	3.4 (0.28)	3.2 (0.27)	1.2 (0.10)	5.8 (0.48)
Sodium (Na)	12 (0.52)	11 (0.48)	33 (1.44)	15 (0.65)
Potassium (K)	2.2 (0.06)	1.9 (0.05)	3.6 (0.09)	2.4 (0.06)
Bicarbonate (HCO_3)	73 (1.20)	68 (1.11)	81 (1.33)	102 (1.67)
Carbonate (CO_3)	0 (0)	0 (0)	0 (0)	0 (0)
Sulfate (SO_4)	3.8 (0.08)	3.2 (0.07)	4.0 (0.08)	4.9 (0.10)
Chloride (Cl)	3.0 (0.08)	3.0 (0.08)	15 (0.42)	7.5 (0.21)
Fluoride (F)	1.9 (0.10)	2.0 (0.11)	3.3 (0.17)	2.0 (0.11)
Nitrate (NO_3)	0.2 (0.00)	0.3 (0.00)	0.1 (0.00)	1.4 (0.02)
Specific Conductance (micromhos at 25°C)	144	137	198	194
pH (pH units)	7.4	7.7	7.7	7.4
Residue on evaporation at 180°C	106	101	149	140
Temperature (°C)	2.22	5.56	4.44	12.0

1.7 Snake River Plain Rocks

Though less than 10 inches of annual precipitation falls on the NRTS, rocks underlying the station might affect the composition of that part of the precipitation that infiltrates. Moreover, as the chemically distinct recharges enter the Snake River Plain and move through the rocks, changes in composition effected by reaction with Snake River Plain rocks would be expected. Rocks of the plain consist of basalt, lacustrine and alluvial sediments, and probably buried silicic volcanics.

Basalt volumetrically dominates the rock section to a depth of 1,500 feet near the center of the plain. As described by Nace, Voegeli, and Deutsch (in press) the basalt contains 35 to 60% calcic plagioclase (ranging from calcic labradorite to sodic bytownite), 25 to 50% pyroxene (generally augite or titanaugite), 5 to 10% olivine, and minor magnetite and ilmenite. Olivine phenocrysts frequently exhibit a deuteric alteration rim of iddingsite (chlorite- or montmorillonite-like clay) and much of the titanaugite consists of a network of clinopyroxene intergrown with ilmenite, presumably exsolved during deuteric alteration. The basalt shows almost no alteration due to weathering. Above the water table, particularly near the land surface, layers of calcite coat joint surfaces and fill vesicles.

Hydrolysis reactions of plagioclase feldspars and pyroxene have been described earlier [Equations (4), (8), and description of recharge from the west]. Olivine consists of a solid solution of magnesium and iron in differing proportions with silica. The magnesium end member can hydrolyze in water to form the clay mineral chlorite according to the reaction:

$$4Mg_2SiO_4 + 6H_2O = Mg_6Si_4O_{10}(OH)_8 + 2Mg^{+2} + 4OH^- \quad . \qquad (15)$$

The iron end member can hydrate and oxidize to form the iron mineral goethite:

$$Fe_2SiO_4 + H_2O + \tfrac{1}{2}O_2 = 2FeO(OH) + SiO_2 \quad . \qquad (16)$$

Natural olivines contain both iron and magnesium; hence, their alteration products usually include a chlorite or montmorillonite clay containing both iron and magnesium. The minor amounts of the mineral magnetite (Fe_3O_4) and ilmenite ($FeTiO_3$) in the basalt may alter in oxygenated water to form goethite, and goethite plus rutile (TiO_2), respectively. The low solubility of these products under oxidizing conditions effectively keeps them out of the groundwater.

Scanty data on the mineralogic composition of the interflow sediments, which predominate near the borders of the plain, indicate that the finer grain sizes consist of quartz, feldspar, calcite, and various clay minerals with montmorillonite dominant. Coarser grains, pebbles, and cobbles consist of rock fragments derived from rocks of the surrounding region.

The silicic volcanic rocks consist of flows and tuffs of dominantly rhyolitic composition. Phenocrysts of sanidine (K-feldspar), plagioclase (oliogoclase), tridymite, oxyhornblende, and possibly cristobalite occur in the flows and devitrified welded tuffs (R. L. Nace, J. W. Stewart, W. C. Walton, written communication, 1959). These rocks mineralogically resemble the previously described Challis Volcanics.

1.8 Irrigation Recharge

Because large quantities of water used for irrigation of crops are recharged locally to the Snake River Plain aquifer, an understanding of the effects of crop irrigation on water composition is necessary to interpret groundwater compositions on the Snake River Plain. The effect of crop irrigation on a groundwater composition (Table VI) consists of evaporative concentration of most dissolved constituents, an additional increase in sodium and chloride, increase in fertilizer-based constituents, and a regulation of silica concentration by some external control. Evaporation rates necessary to achieve the doubling and tripling of dissolved constituents frequently observed require repeated or prolonged exposure of the water to sun and wind at the earth's surface, resulting in a rise in water temperature. Such multiple exposure commonly occurs in regions of intensive irrigation, as along the Snake River where downstream reuse of water is common. Pumping of water for irrigation from a perched body of recharged irrigation water, as occurs at Mud Lake, produces the same recycling effect. Leaching of highly soluble sodium chloride, originating from the fallout of atmospheric dust, could account for some additional increases of sodium and chloride ions.

To interpret the composition of irrigation water more fully, complete information must be obtained on its source, as well as the kinds and rates of fertilizer applications. Even climatic variations may be significant, both in altering the supply of water and in altering irrigation practices (Crosthwaite and others, 1970, p. 75).

2. COMPOSITION OF GROUNDWATER AT THE NRTS

The following detailed examination of the composition of groundwater at the NRTS attempts to delineate areal and vertical variations and relate these variations to different sources of recharge. In addition, the effects of ion exchange by the rocks beneath the NRTS on groundwater compositions are briefly considered, as is the possibility of corrosion or encrustation during use of groundwater at the NRTS.

2.1 Areal Variations

Figures 19 through 31 depict the contour patterns for concentrations of individual dissolved constituents in the upper 100 feet of groundwater beneath the NRTS. With the understanding that unique and exclusive interpretations of the data may not be possible, the following discussion seeks to explain these contour patterns in terms of the most probable geochemical controls.

2.11 Dissolved Solids. The 200 mg/l line trends across the southeast corner of the NRTS (Figure 19), parallel to the direction of groundwater flow (Figure 6), probably reflecting the presence of more dilute water to the east. In the southern part of the NRTS, the 200 mg/l line swings west, perhaps indicating a disturbance in the southwesterly flow direction caused by the postulated subsurface barrier of silicic volcanic rocks related to the chain of buttes. The wide spacing of wells produces greater uncertainty about groundwater flow directions in this area than in the rest of the NRTS (Figure 6).

High values of dissolved solids southwest of Mud Lake probably reflect the concentration of constituents by evaporation during irrigation, although the presence of some thermal water cannot be completely discounted. Rapid attenuation of these high values down gradient attests to the relatively dilute water present immediately east of the NRTS. Evidence presented in the discussion of several individual constituents shows conclusively that this dilute water comes from the northeast recharge area (Figure 18) and approximates in composition the well water at the city of St. Anthony (Table VII).

Except for the area of dilute water on the southeast, the local high values near Mud Lake, and small isolated highs and lows that may be related to disposal of waste and contamination of samples by shallow, dilute water, the dissolved-solids content of the groundwater beneath the NRTS remains within the remarkably small range of 200 to 225 mg/l over the entire area.

2.12 Temperature. The pattern of water temperatures shown in Figure 20 represents measurements made with a thermistor probe placed 50 to 100 feet below the water table in each well[a]. Temperature lines show a general parallelism to the southwesterly direction of groundwater flow with the exception of a possible disturbance near the buttes. The area of warmer groundwater near Mud Lake probably indicates recharged irrigation water heated by the sun. The stream of warm groundwater extending from TAN to Atomic City on Figure 20 may be a continuation down gradient of recharge from irrigation water northwest of Mud Lake.

---

[a] Figure 20 was prepared by F. H. Olmsted in 1962 for an unpublished report. The sample temperatures in Table III, measured with a thermometer after collection, yield a map with essentially the same gross features. Because of the much greater accuracy and reliability of in-place temperature measurements, only the figure based on them is presented.

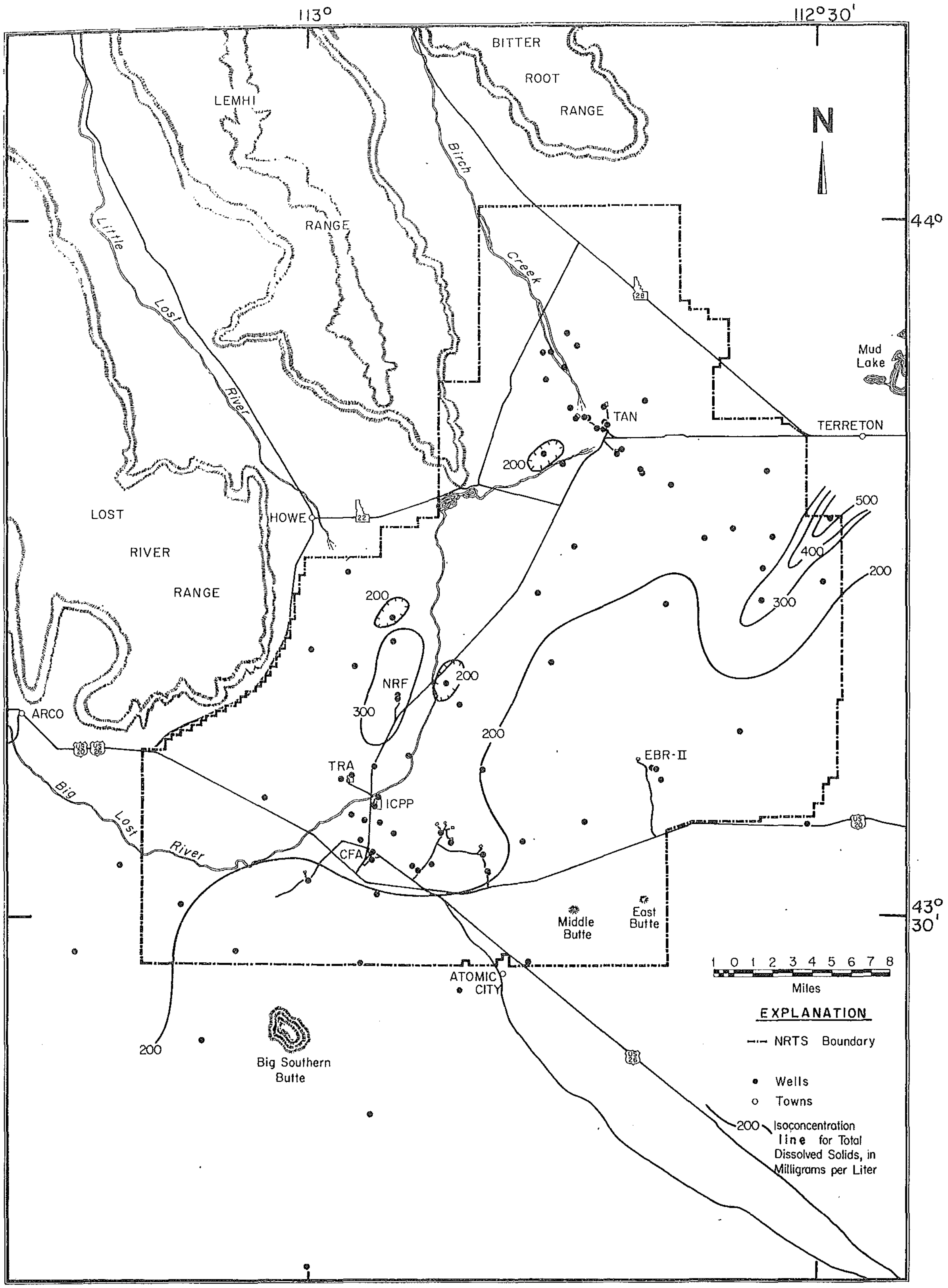


Fig. 19 Map of NRTS vicinity showing natural distribution of total dissolved solids (residue on evaporation) in the Snake River Plain aquifer water.

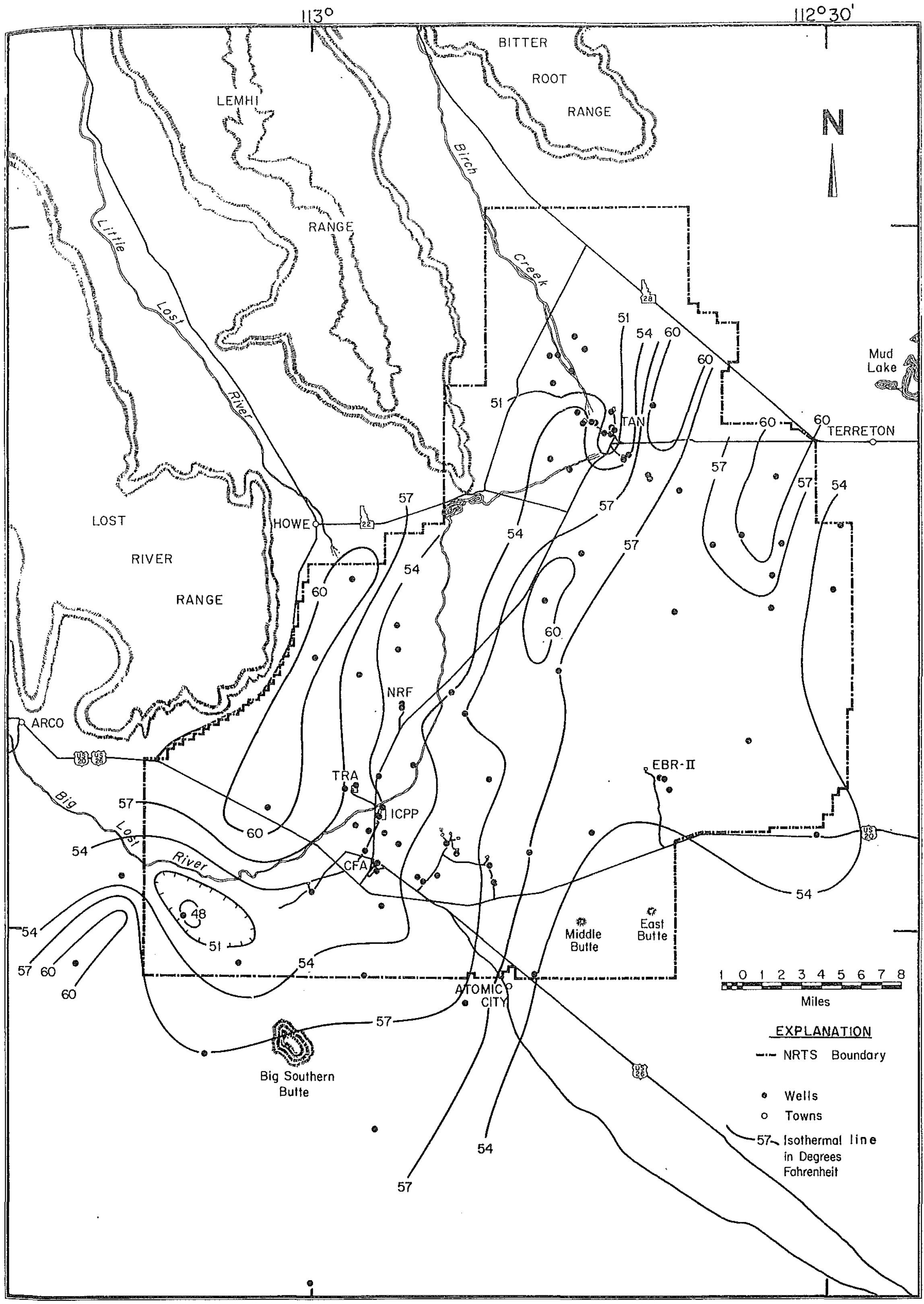


Fig. 20 Map of NRTS vicinity showing natural temperature distribution in the Snake River Plain aquifer (after Olmsted, 1962).

The western high temperature area, because of its closeness to the edge of the Snake River Plain, has been ascribed to deep contributions of thermal water. This may be so, but the small temperature differences and fairly consistent water compositions across the anomaly argue against a geothermal source. The anomaly may actually be two isolated areas separated by lower temperature groundwater in the vicinity of the Big Lost River. An alternate interpretation is that the anomaly represents recharge of irrigation water from the valley of the Little Lost River and from the valley of the Big Lost River.

2.13 Calcium. The pattern of calcium values on Figure 21 shows a high of about 50 mg/l toward the northwest next to the mountains, decreasing southeastward to about 30 mg/l. The large supply of calcium ions must come from the hydrolysis of calcite and dolomite in Paleozoic carbonate rocks that make up so much of the mountains and alluvial sediments northwest of the NRTS. High values near Mud Lake (>90 mg/l) probably represent recharge of evaporatively concentrated irrigation water.

2.14 Magnesium. The distribution of magnesium, shown in Figure 22, exhibits a pattern similar to, but not as sharply defined as, the calcium distribution. Again, the high lies in the northwest mountains with values of about 20 mg/l decreasing southeastward to about 10 mg/l. The principal source of magnesium must be the hydrolysis of dolomite in the northwestern Paleozoic rocks; however, weathering of clay minerals may contribute some. The Mud Lake irrigation high, above 30 mg/l, shows the same rapid attenuation down gradient exhibited by the calcium values.

2.15 Sodium. Distribution of sodium on Figure 23 shows a general high to the east of about 15 mg/l decreasing westward to about 6 mg/l at the mountains. The expected high appears near Mud Lake, attributable to concentration by evaporation of irrigation water. Leaching of sodium chloride from the soil and contribution of thermal water from an extension of the Heise-Rexburg Bench fault are additional possibilities for the high sodium values at Mud Lake. Attenuation of the high-sodium water down gradient takes place by dilution with possibly some loss of sodium by ion exchange onto clay minerals previously at equilibrium with groundwater containing only 15 mg/l of sodium.

The high sodium value just outside the NRTS boundaries on the southwest is based on a single well, Well 13. The high immediately inside the southwest boundaries also represents a single well, Well 22. The additional sodium in both waters is fully balanced by chloride, implying that sodium chloride is the source of these highs. The source of sodium chloride is unknown but might be from thermal water, irrigation recharge, or waste disposal.

2.16 Chloride. If sodium chloride is the major source of chloride, the chloride distribution map (Figure 24) does not show the anticipated similarity to the sodium map. Background values range from about 6 up to 10 mg/l with little indication of a regular

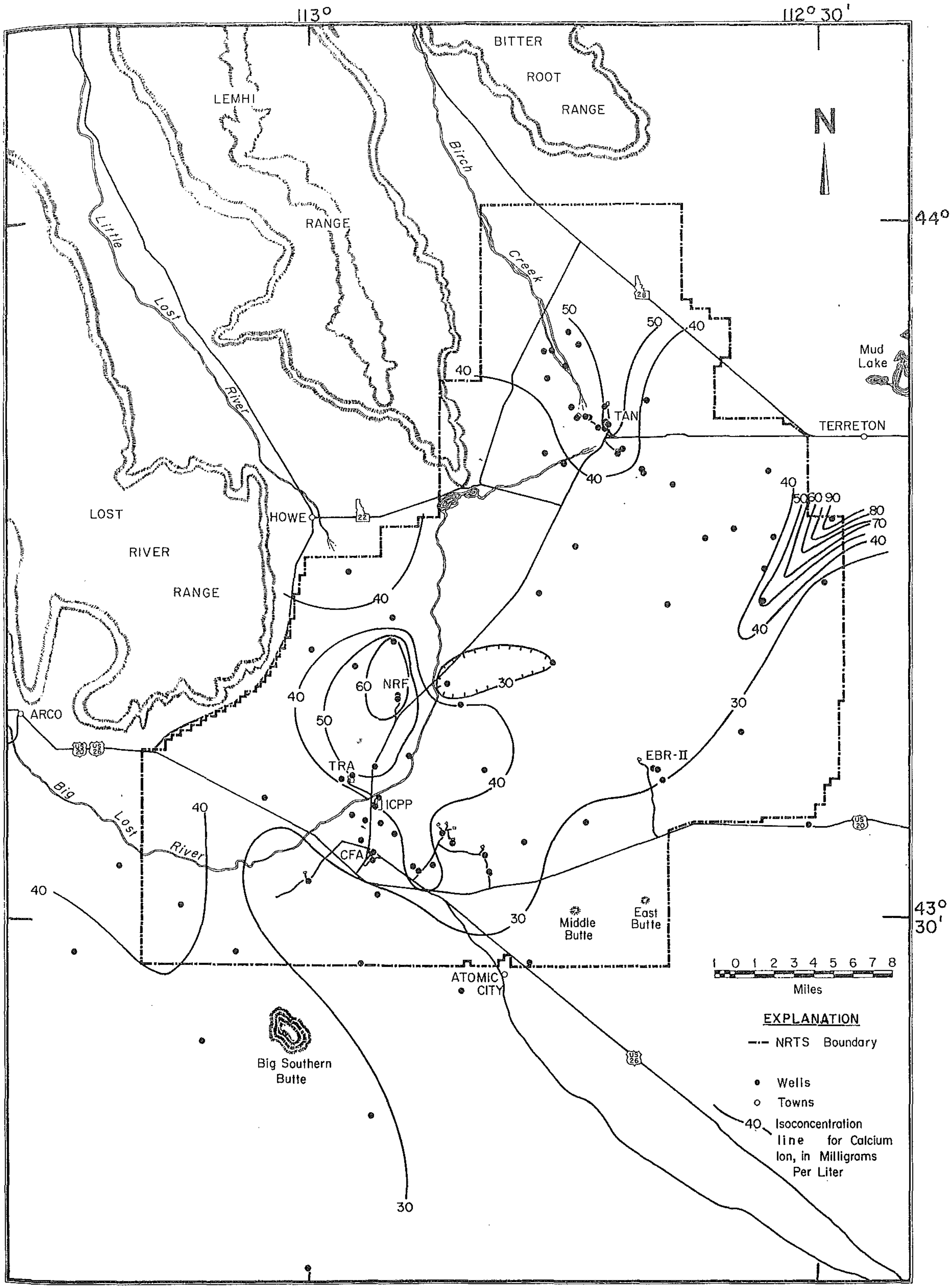


Fig. 21 Map of the NRTS vicinity showing the natural distribution of dissolved calcium in the Snake River Plain aquifer water.

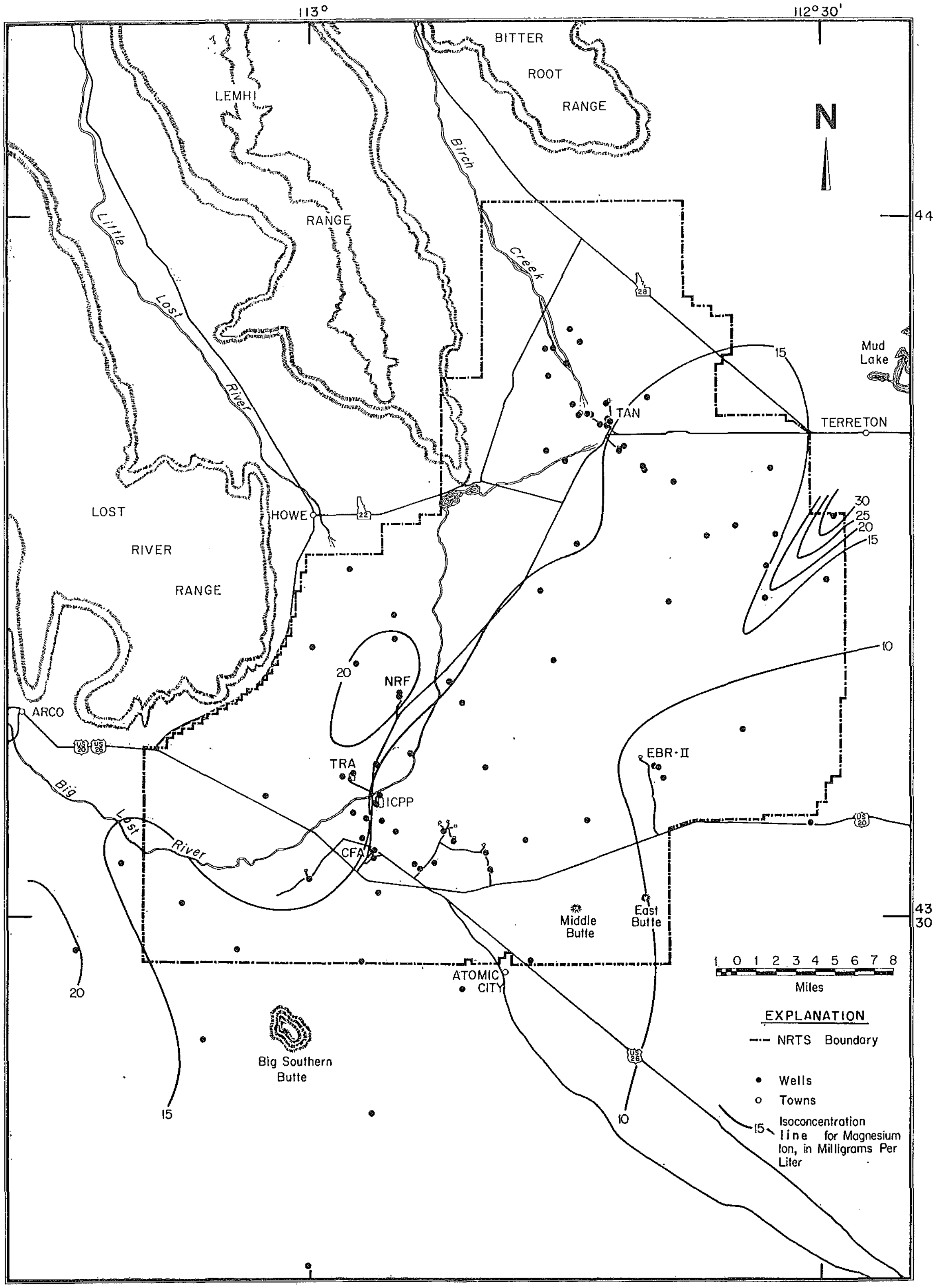


Fig. 22 Map of the NRTS vicinity showing the natural distribution of dissolved magnesium in the Snake River Plain aquifer water.

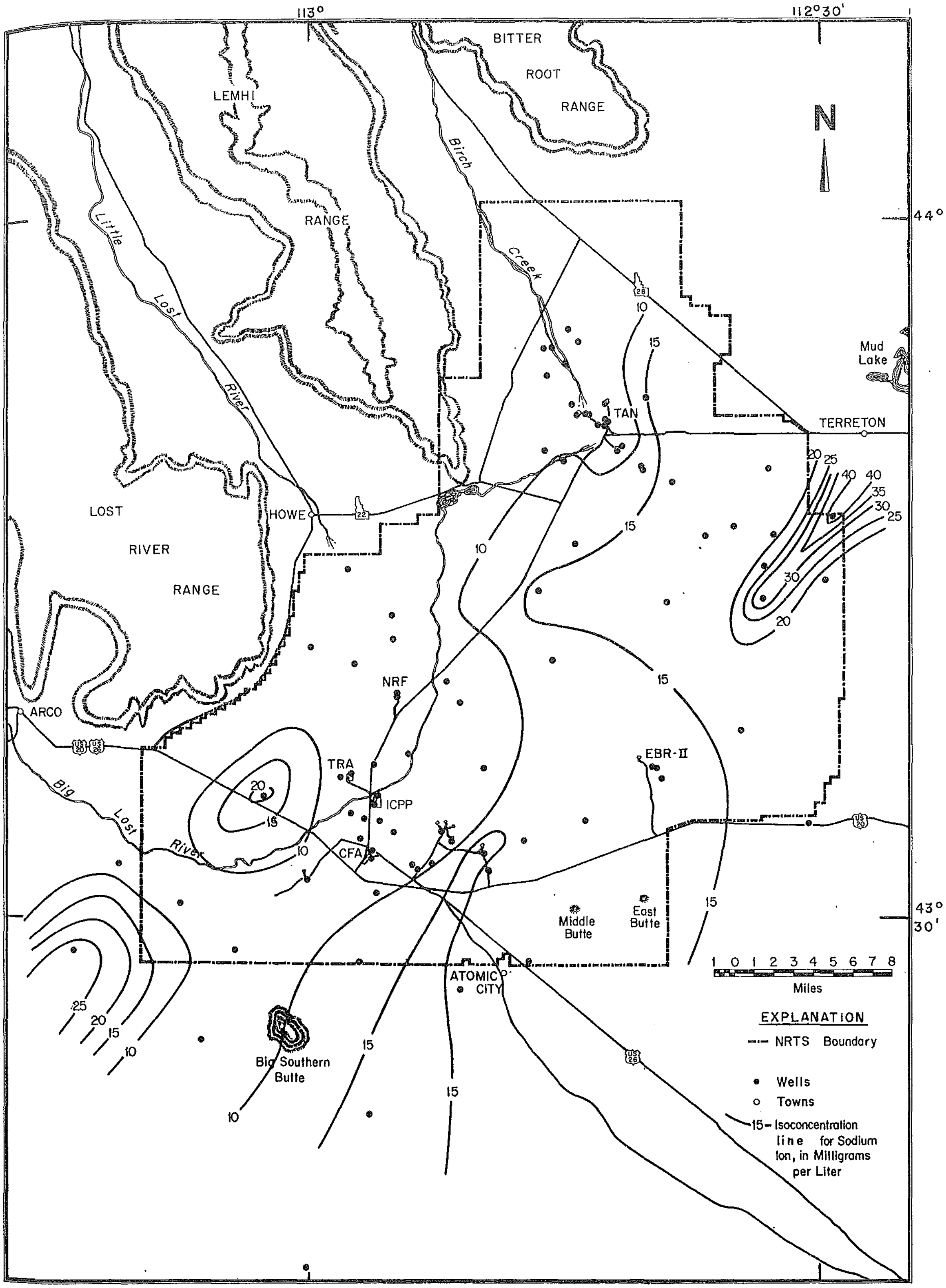


Fig. 23 Map of the NRTS vicinity showing the natural distribution of dissolved sodium in the Snake River Plain aquifer water.

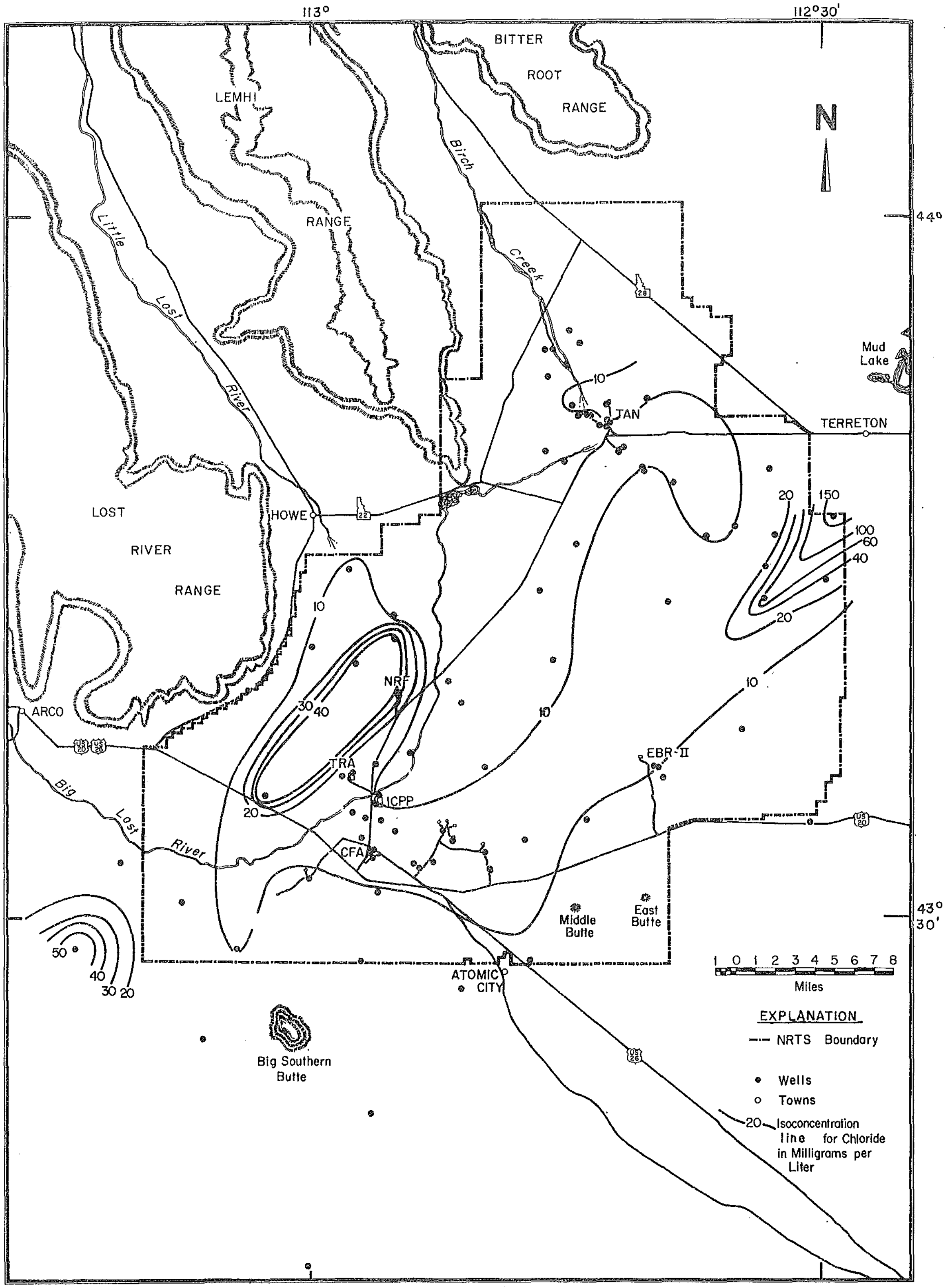


Fig. 24 Map of the NRTS vicinity showing the natural distribution of dissolved chloride in the Snake River Plain aquifer water.

pattern. Superimposed on this fairly low background are three anomalously high areas. The two on the southwest have been discussed with regard to their high sodium contents. No clear choice can be made at this time among alternative explanations involving thermal water, irrigation recharge, or waste disposal.

The third area, at Mud Lake, presents more interesting and less demonstrable possibilities for explanation than the other two. Well 4, located just inside the NRTS boundary 7 miles southwest of Mud Lake, contains 160 mg/l of chloride, and down-gradient Well 33, 5-1/2 miles farther, contains 69 mg/l chloride (Table III), evidently corroborating the existence of a local body of chloride-rich water. The analysis of water from Well 4 appears to be remarkably accurate and conforms closely to an analysis of a sample taken 2-1/2 years earlier (Table B-I). Conductivity logs, run as recently as 1967, confirm the continued presence in Well 4 of water with an unusually high dissolved-solids content. The presumed history of water from Well 4 starts with flow off the Centennial Mountains into Camas Creek with a composition like that shown in Table VI. Flowing down Camas Creek the composition changes because of concentration by evaporation (a factor of two), and solution of sodium chloride and nitrate during rather limited use for irrigation. Arriving at Mud Lake, the water has the composition shown in Table VI. Extensive and multiple irrigation takes place in the Mud Lake area yielding a recharge product at the water table perhaps like the water in Well 4. All the cations in Well 4 water, as well as the dissolved solids, increase by a factor of about three over the water in Mud Lake (Table VI). This fairly logical behavior of the cations, however, is not emulated by the anions.

Bicarbonate, the dominant anion in Mud Lake water, increases from 144 mg/l to only 186 mg/l in Well 4 water. The apparent lack of concentration of bicarbonate by a factor of three (to a value of 432 mg/l) can be explained by equilibrium of carbonate species in the water. Warming of the water when applied to fields decreases the solubility of carbon dioxide, which bubbles out of the water, upsetting the chain of equilibrium reactions governing the carbonate species. In water like that in Mud Lake, the result of warming would be a conversion of part of the bicarbonate to carbon dioxide and its loss, and a conversion of an equal part of bicarbonate to carbonate with an increase in pH which is not observed to the extent expected in Well 4 water. Evaporative concentration produces the same effects on the carbonate species as does warming. Increasing the concentration of bicarbonate beyond some value in equilibrium with the gaseous carbon dioxide in the surrounding atmosphere will cause carbon dioxide to escape from the water, accompanied by a reduction in bicarbonate as described. Photosynthetic activity of algae and other water plants could remove carbon dioxide from the water. The extent of their presence in the irrigated fields is believed to be small. Precipitation of the solids calcite and dolomite could lower the bicarbonate in the water. The relative constancy of the ratios of cations from Mud Lake water to Well 4 water, however, would seem to preclude this possibility. Bicarbonate could conceivably increase in irrigation water because of the high carbon dioxide concentrations achieved in soils where organic material decomposes. In fact, if 432 mg/l of bicarbonate were attained by evaporative concentration it could be maintained in equilibrium with a soil atmosphere containing about 10^{-2} atmospheres of carbon dioxide, a common value for cultivated soils (Mohr and Van Baren, 1954, p. 86).

In any case, the evaporative and warming processes, which seem to be well substantiated by cation ratios and temperature data, should have caused a rise in pH and formation of abundant dissolved carbonate. Neither of these conditions exists in Well 4 water. Instead, a calcium and magnesium water that was initially balanced by bicarbonate anions is now balanced by chloride (concentrated over Mud Lake water by a factor of 25) and by sulfate (concentration factor 7).

Solution of evaporite salt deposits is an explanation that must be considered for the unusual water composition. Some early analyses of waters from shallow dug wells in the vicinity of Mud Lake show high calcium and sodium, sulphate and chloride contents that might be related to, as yet undescribed, evaporite deposits (Stearns and Bryan, 1925, p. 129).

However, the possibility that salts of chloride and sulfate were added to water from Well 4 is contradicted by the constant ratios of cations which would have changed with additions of salt. Similarly, evaporative concentration of Mud Lake water by a factor of 25 to achieve the chloride composition, and precipitation of carbonate and sulfate salts of the cations would have had to take place in proportions equal to the original cation ratios. This would certainly not have occurred for soluble salts such as sodium and potassium.

The only conclusion drawn from these data is that hydrochloric acid and sulfuric acid constitute the most probably sources of the excess chloride and sulfate. Hydrogen ions from these acids would react with carbonate species removing still more carbon dioxide and lowering pH. The amount of acid required by this explanation is about 4 milliliters (ml) of 1N hydrochloric acid and 0.7 ml of 1N sulfuric acid per liter of Well 4 water. A reasonable source for this quantity of acid is not apparent at this time.

2.17 Potassium. Distribution of potassium concentration values in the groundwater, shown on Figure 25, appears random except for a crude parallelism of contours to direction of groundwater flow. There may be a tendency for a decrease from east to west which, if true, could be explained as westerly dilution of high potassium water related to the breakdown of silicic volcanics in the northeastern recharge area. The absence of definite patterns, which may be related to the magnitude of analytical error on such small amounts of potassium, as well as the possibility of irregular sorption of potassium on solid phases, precludes the accurate determination of sources and sinks for potassium. An exception is the high value related to irrigation at Mud Lake.

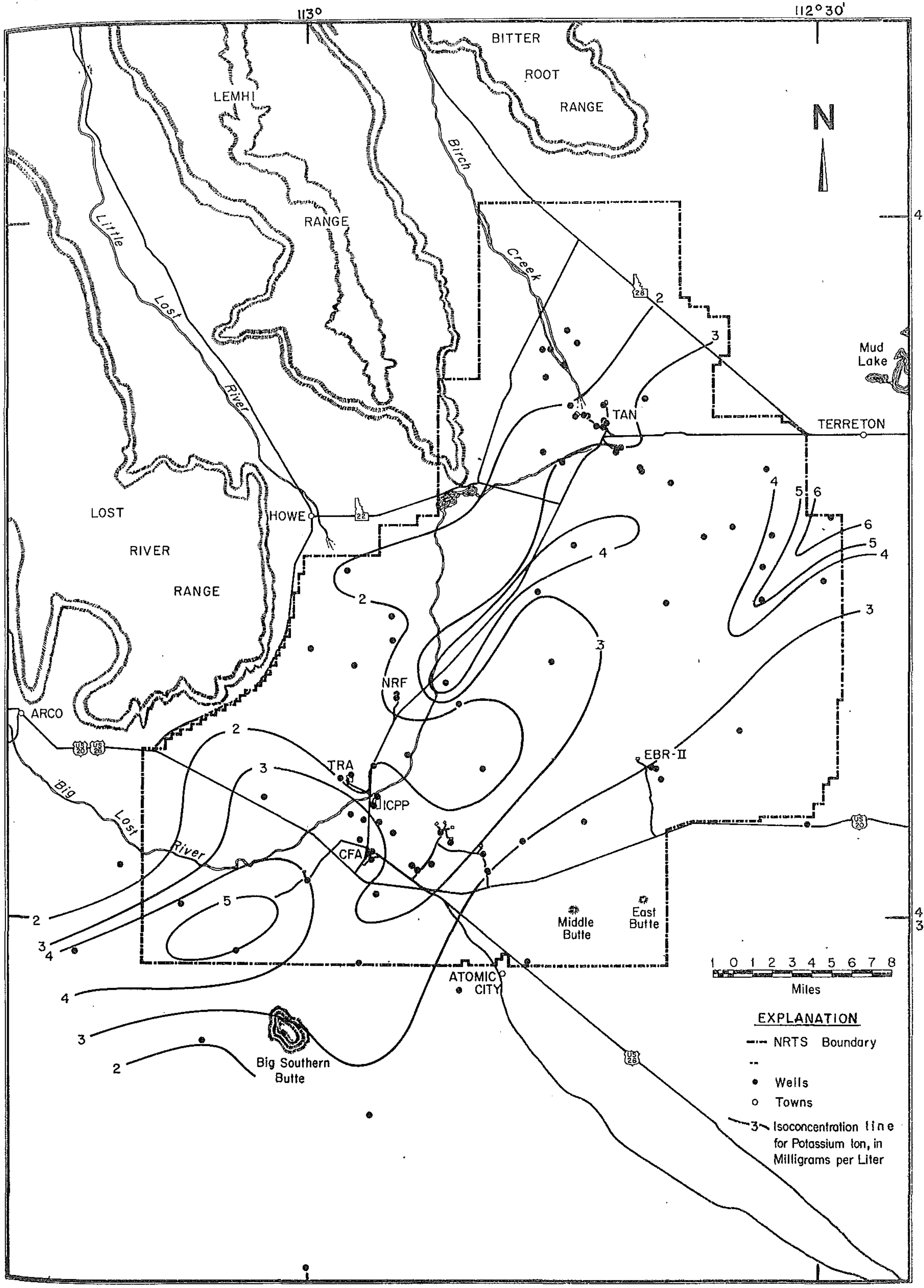


Fig. 25 Map of the NRTS vicinity showing the natural distribution of dissolved potassium in the Snake River Plain aquifer water.

2.18 Bicarbonate. Figure 26 exhibits a pattern of decreasing bicarbonate values eastward away from the mountains. This compares well with the calcium and magnesium distribution maps (Figures 21 and 22) and indicates that Paleozoic carbonates in the northwestern mountains serve as the source of bicarbonate.

The slightly high value related to irrigation near Mud Lake has been extensively discussed under Subsection 2.16, Chloride. High values of bicarbonate occur at three wells near the center of the NRTS. They may reflect the disposal of waste acid that has reacted with calcium carbonate in sediments. High values of calcium, sulfate, and chloride in these wells support this explanation. Alternatively, release and decomposition of sewage in these areas may account for some of the extra bicarbonate.

Only two of the analyses in Table III (Wells 17 and 29) have carbonate listed as a measurable constituent. The relationship between carbonate and bicarbonate and their strong dependence on pH make interpretation of the carbonate data impossible (see Appendix B). Carbonate and bicarbonate values from these two wells were ignored in preparing Figure 26. Only on-site determination of these variables from a good pumped sample will provide interpretable values.

2.19 Sulfate. The pattern of sulfate distribution in Figure 27 shows a decrease from about 25 mg/l on the northwest to about 10 mg/l on the southeast. Surface water analyses in Table IV indicate that the predominant source of sulfate is to the north (Medicine Lodge Creek).

Dilution of sulfate to values below 10 mg/l in the southeastern part of the NRTS provides good evidence for identifying the recharge to this area. Recharge with Snake River water containing 63 mg/l sulfate (Table V) is impossible. Instead, low sulfate water from the northeast (Table VII) satisfies the sulfate dilution requirement.

Enigmatically high sulfate values found in the Mud Lake sample were evaluated under Subsection 2.16, Chloride. High values near the center of the NRTS correlated with high values of bicarbonate, chloride, and calcium and seem to be related to disposal of waste.

2.110 Nitrate. Figure 28 illustrates low values of nitrate in groundwater over most of the NRTS and a crude parallelism with direction of flow. The extreme rarity of nitrogen-bearing minerals makes the presence of large amounts of nitrate an efficient detector of man's intrusion into the environment. The usual sources of excess nitrate in the environment are chemical and organic fertilizers and sewage disposal. An additional possible source is nitrogenous chemical wastes such as nitric acid.

The high nitrate value near Mud Lake is presumed to reflect nitrogenous fertilizers applied to the land or irrigation water. The source of the isolated nitrate highs near the central and northern part of the NRTS is not known.

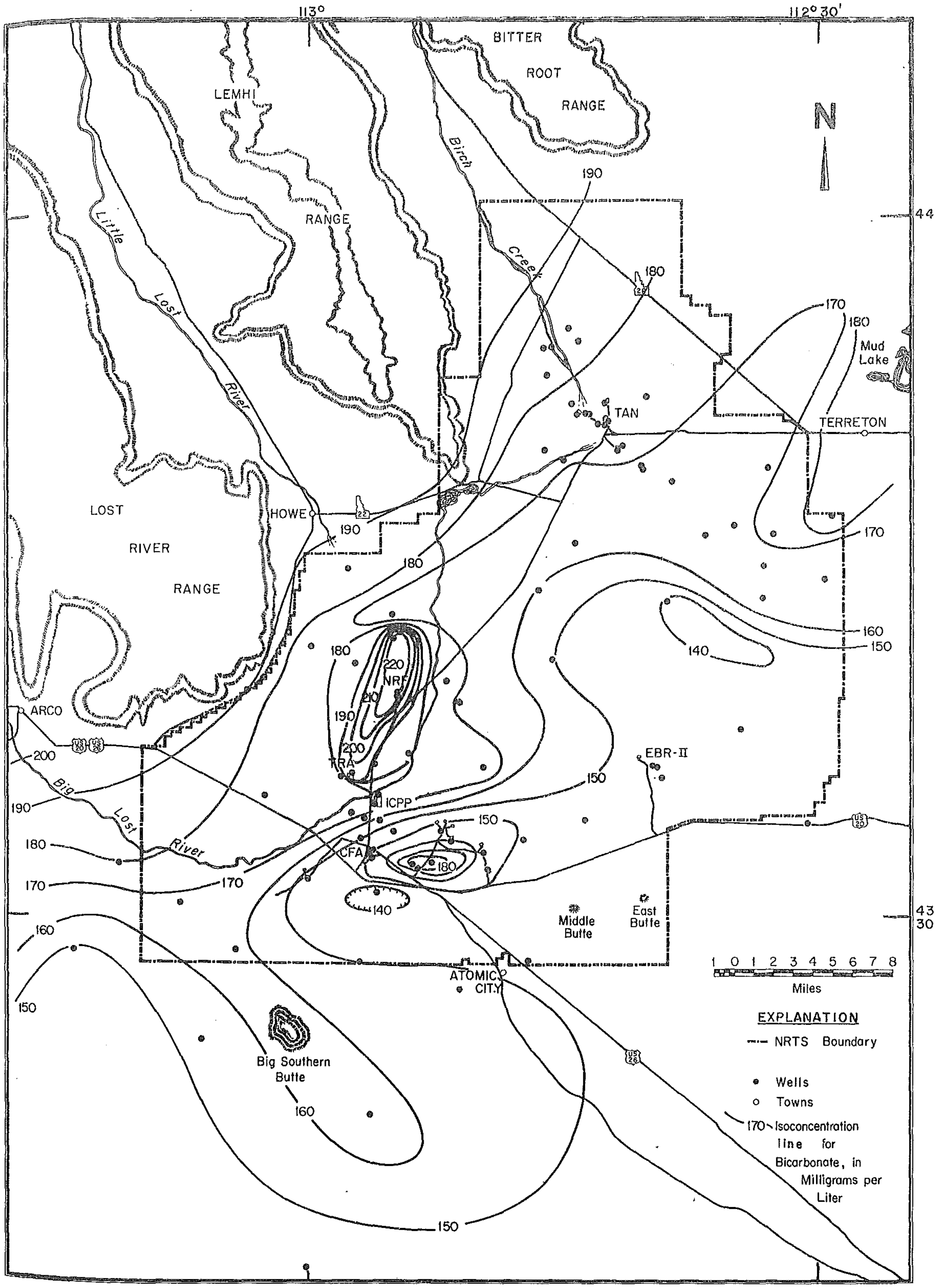


Fig. 26 Map of the NRTS vicinity showing the natural distribution of dissolved bicarbonate in the Snake River Plain aquifer water.

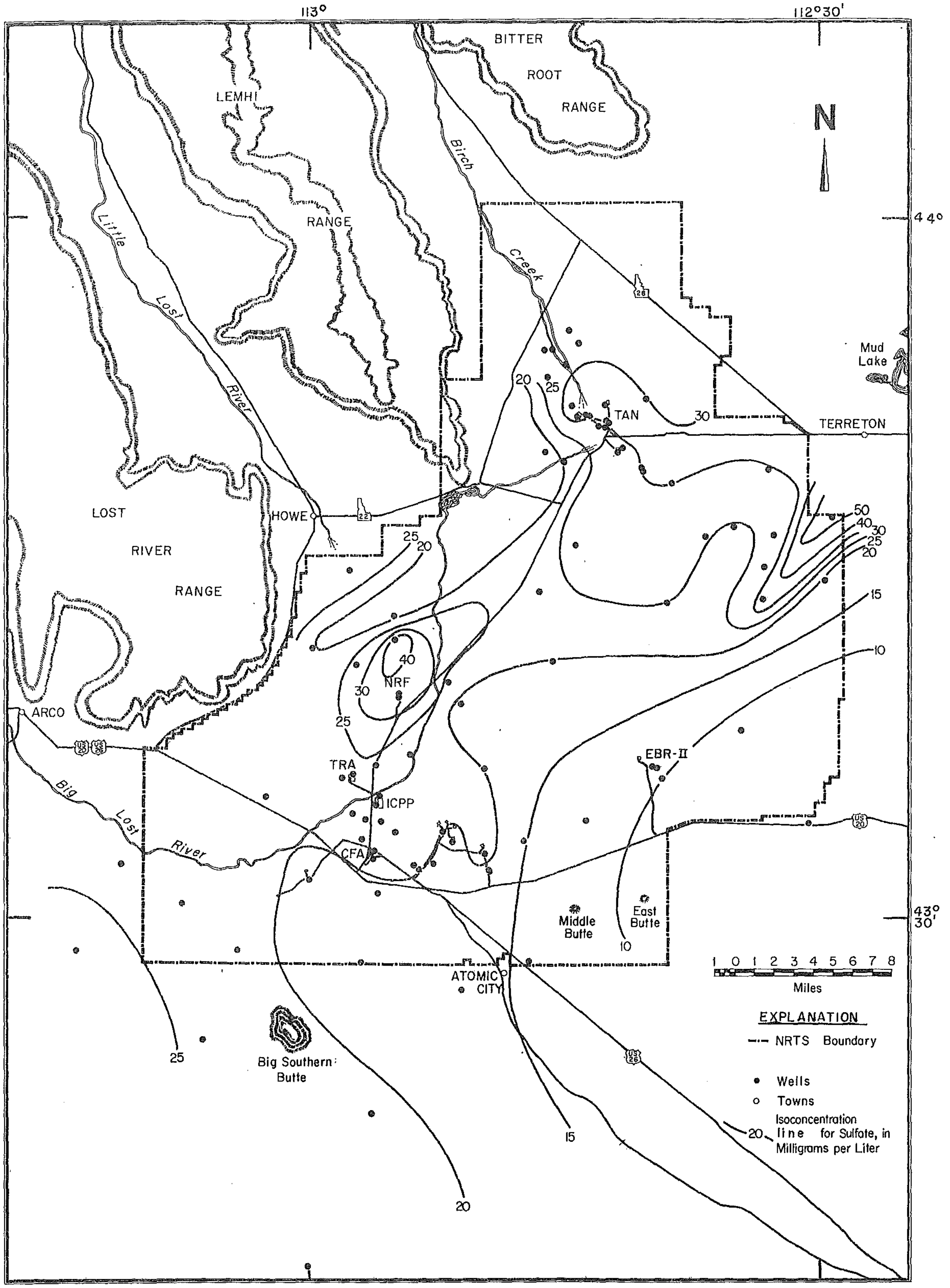


Fig. 27 Map of the NRTS vicinity showing the natural distribution of dissolved sulfate in the Snake River Plain aquifer water.

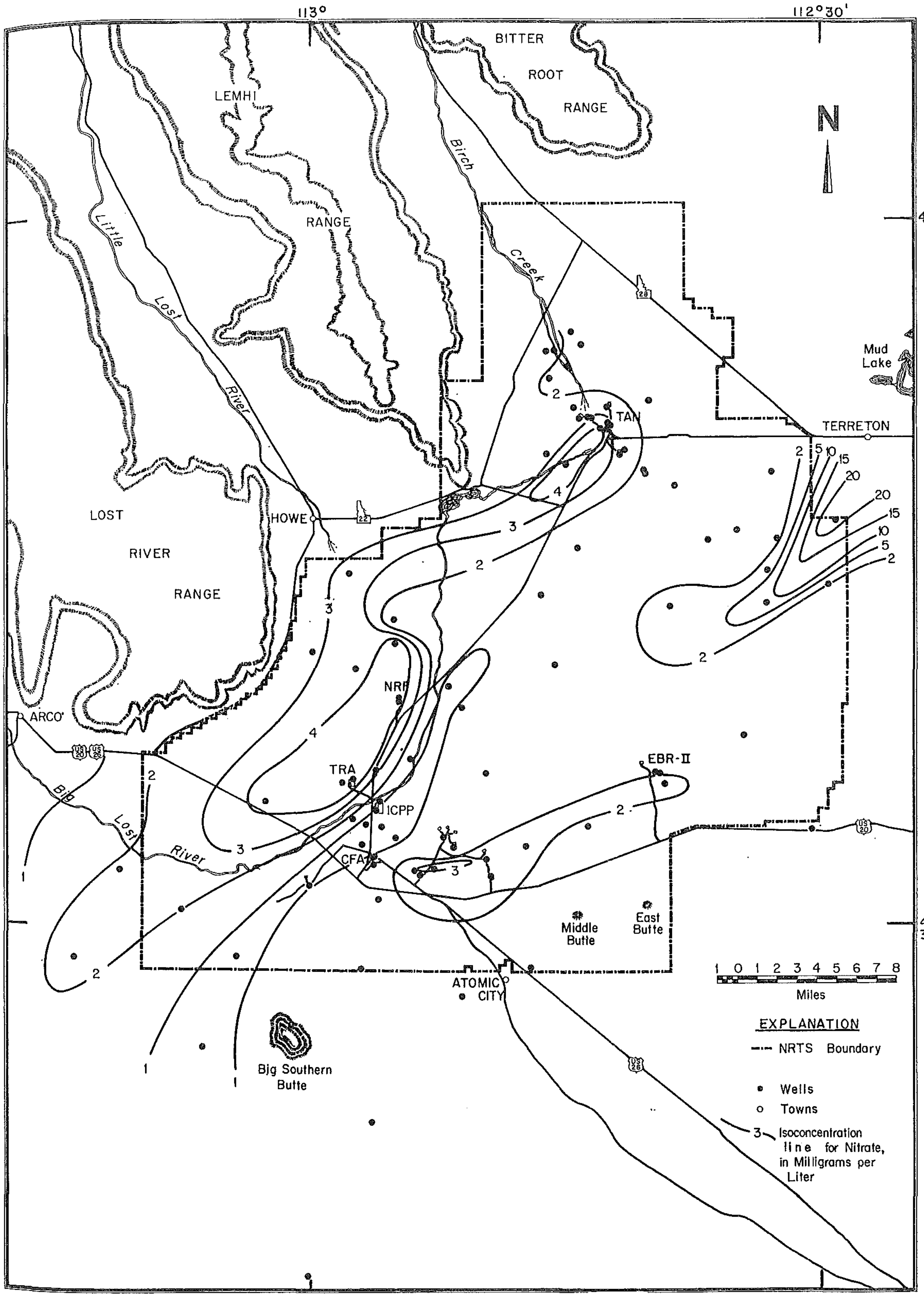


Fig. 28 Map of the NRTS vicinity showing the natural distribution of dissolved nitrate in the Snake River Plain aquifer water.

2.111 Fluoride. The general pattern of fluoride distribution shown on Figure 29 indicates a high of about 0.9 mg/l to the southeast decreasing westward to values of about 0.1 or 0.2 mg/l at the mountains. Minor highs and lows within this trend probably represent varying degrees of dilution of high fluoride water from the southeast. Lack of an evaporative-concentration high of about 1.5 mg/l in water from Well 4 (three times fluoride in Mud Lake water) may indicate control of this small amount of fluoride by precipitation of the minerals fluorite or fluorapatite. Accurate chemical analyses would be required to evaluate this possibility.

The high fluoride values in water at the southeast corner of the NRTS provide additional evidence favoring a northeastern recharge source for this water (Table VII) rather than an eastern recharge source (Table V).

2.112 Silica. Distribution of silica values on Figure 30 shows a trend decreasing from about 30 mg/l in the southeast to about 15 mg/l at the mountains. This further substantiates a northeastern recharge source for the high silica water southeast of the NRTS (Table VII) rather than a low silica source in the Snake River (Table V).

A dearth of silica values exceeding 40 mg/l, regardless of apparent evaporative concentration, indicates some organic or inorganic control operating on the silica in all the waters. Recent work (Kennedy, 1971) indicates the probability of an inorganic control, involving sorption and diffusion on mineral surfaces, for the relatively level values of silica in most natural waters.

2.2 Vertical Variations

Most of the groundwater analyses at the NRTS are on more or less mixed samples representing the upper 100 feet of the groundwater body, and these analyses provide the basis for the discussion of areal variations in composition. Two types of vertical change in composition also occur at the NRTS.

The first indication of a significant change in water composition with depth came from in-place, water-resistivity studies (inverse of conductance) made with a mobile logging unit on several wells. These studies show the presence of a body of relatively fresh water (specific conductance of 100 to 200 micromhos at 25°C) at the top of the water table, as much as 50 feet thick though usually much thinner, underlain by normal groundwater with a specific conductance of 300 to 400 micromhos. This fresh zone was first interpreted as an accumulation of rainfall and snowmelt that had percolated directly to the water table with little reaction in rocks of the plain. It was then noticed, however, that the fresh zone occurred only in cased holes and then only above the level of perforations in the casing. Further, although thief samples showed lower concentrations of dissolved solids in the fresh zone, tritium values were much higher than in deeper water.

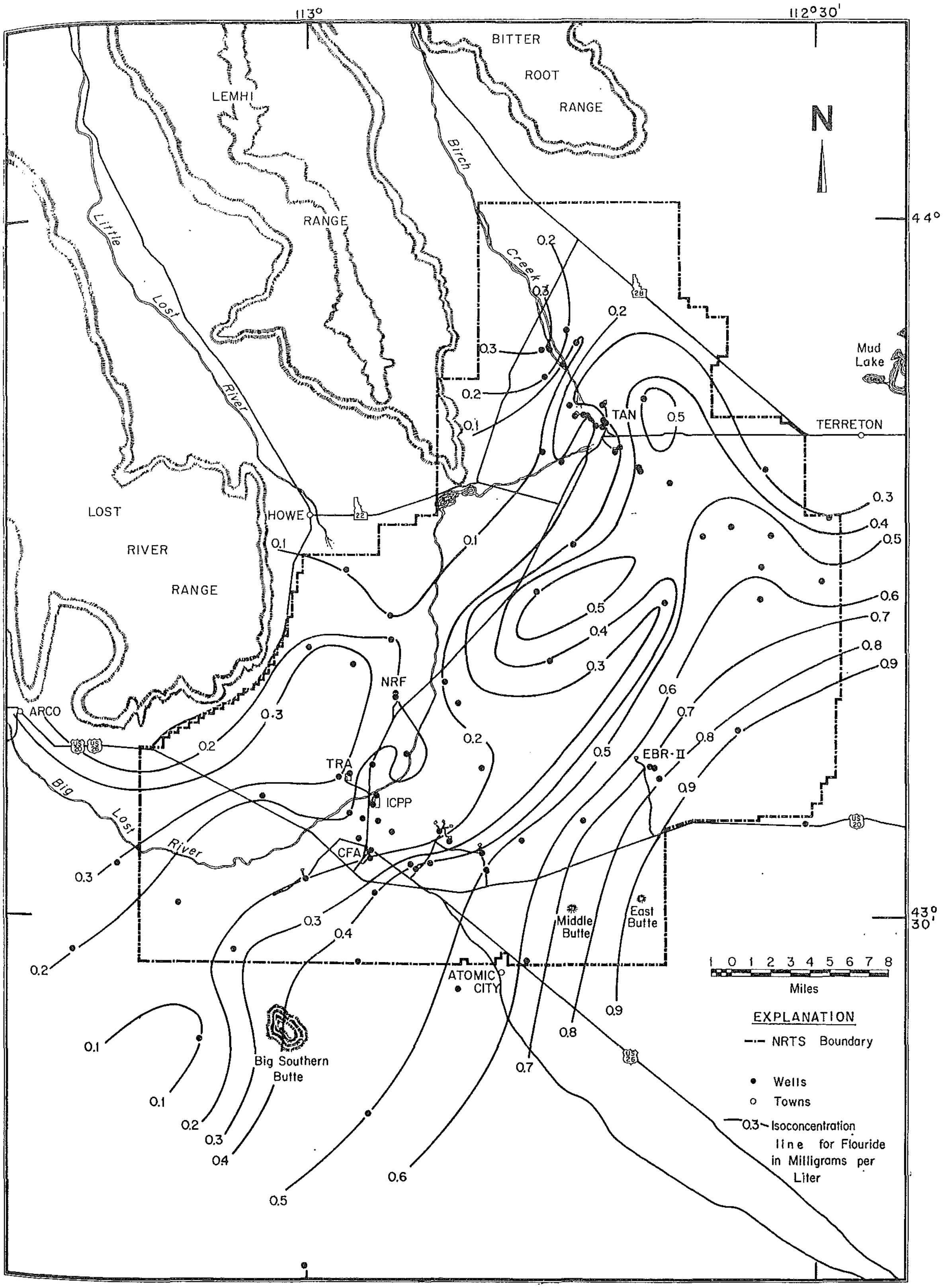


Fig. 29 Map of the NRTS vicinity showing the natural distribution of dissolved fluoride in the Snake River Plain aquifer water.

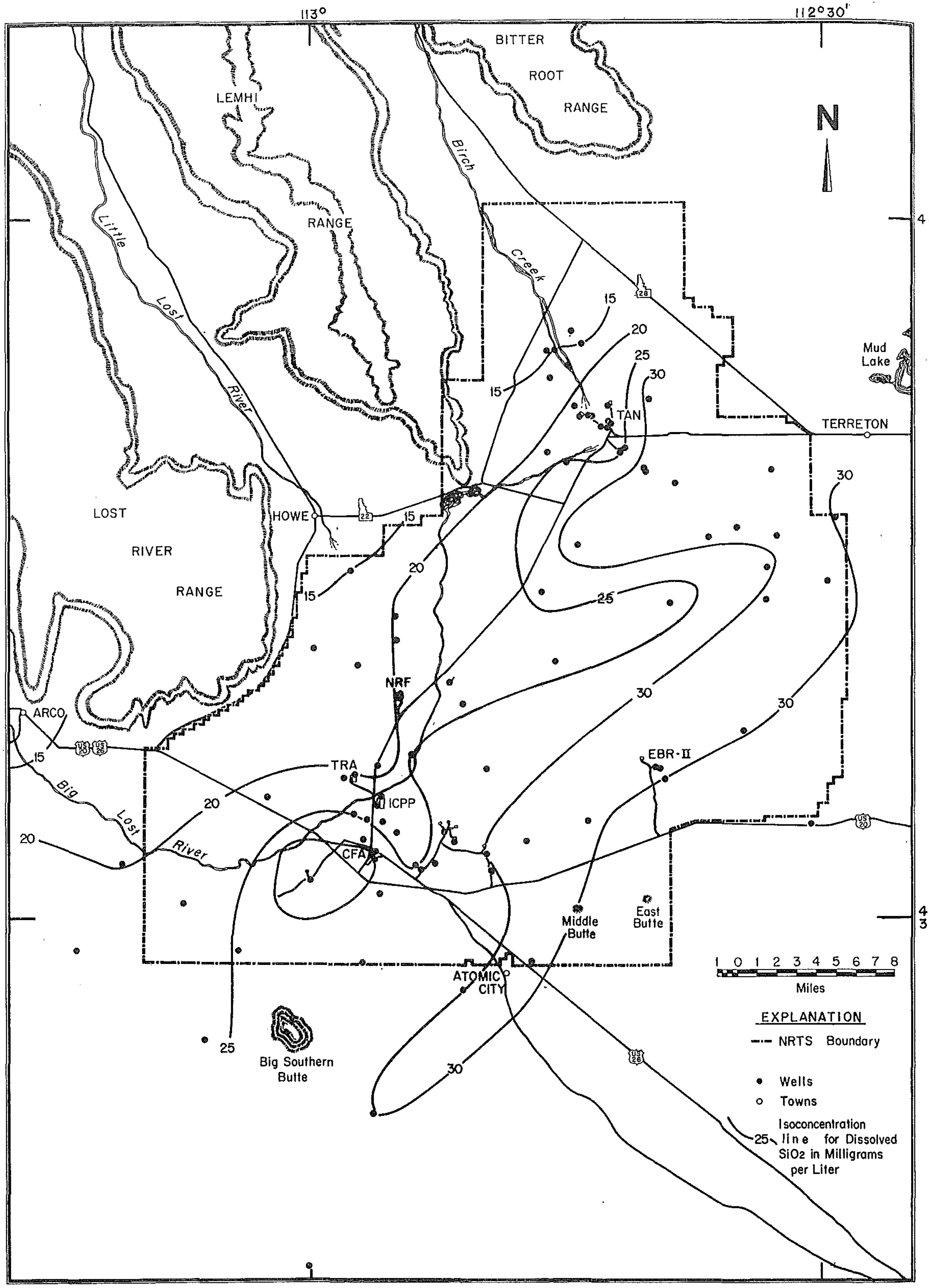


Fig. 30 Map of the NRTS vicinity showing the natural distribution of dissolved silica in the Snake River Plain aquifer water.

A satisfactory interpretation of these data has not been achieved. An alternative explanation envisions fresh water accumulating within the well casing by condensation of warm, humid, tritium-rich surface air on the cold steel casing. The fresh zone, therefore, may be only an artifact, but the data does raise serious questions about the suitability of thief samples to represent the groundwater body.

The second example of vertical compositional variation concerns a single deep well. A pumped sample taken on June 7, 1952 from Well 7 represented water from a depth of 214 feet (the water table) to 698 feet (Table III). Later the hole was deepened and on August 9, 1952 a pumped sample represented the water from 212 feet to 1,200 feet (Table B-I). In spite of the fact that the deep sample contains some unknown proportion of the same water contained in the shallow sample, the deep sample shows some significant changes. Compared to the shallower sample, deeper water exhibits a doubling of sodium, an eightfold increase in fluoride, a doubling of silica, together with small reductions in calcium, magnesium, and bicarbonate and a ninefold decrease in nitrate.

A single well hardly serves to establish a pattern of vertical compositional variations in the groundwater beneath the NRTS. This would require the support of many pumped samples from other deep wells isolated vertically by packers. The compositional changes noted in Well 7 do, however, lead to the suggestion that deep water under the NRTS may contain more sodium, silica, and fluoride than does shallow water. These constituents, especially when not accompanied by abundant chloride, point to the breakdown of silicic rocks as a source. Well 7 may be tapping water that reacts with silicic rocks at depth. The closeness of Well 7 to the margin of the plain means that silicic rocks may not be buried as deeply as they are farther out on the plain. This evidence provides additional support for the inference, based on geologic reasoning, that silicic volcanic rocks underly the basalt and sediments of the plain[a].

2.3 Mineral-Water Equilibria

The groundwater analyses in Table III were evaluated to determine their degree of saturation or supersaturation with respect to minerals in the enclosing rocks. This otherwise arduous task was performed by a computer (Barnes and Clark, 1969). Results show that groundwaters at the NRTS approach saturation with respect to calcite and dolomite, and that slight supersaturation occurs in groundwater from the northwest part of the station.

Numbers on Figure 31, indicating degree of supersaturation of the groundwater with respect to calcite and dolomite, range from 1.0 to about 1.5 for calcite and 1.0 to about 5.0

---

[a] Preliminary results of an electrical resistivity survey run recently from Blackfoot to Arco indicate rocks interpreted as silicious volcanics from a depth of 2,000 feet to 12,000 feet beneath the western part of the NRTS (A. A. R. Zohdy and W. D. Stanley, written communication, 1971).

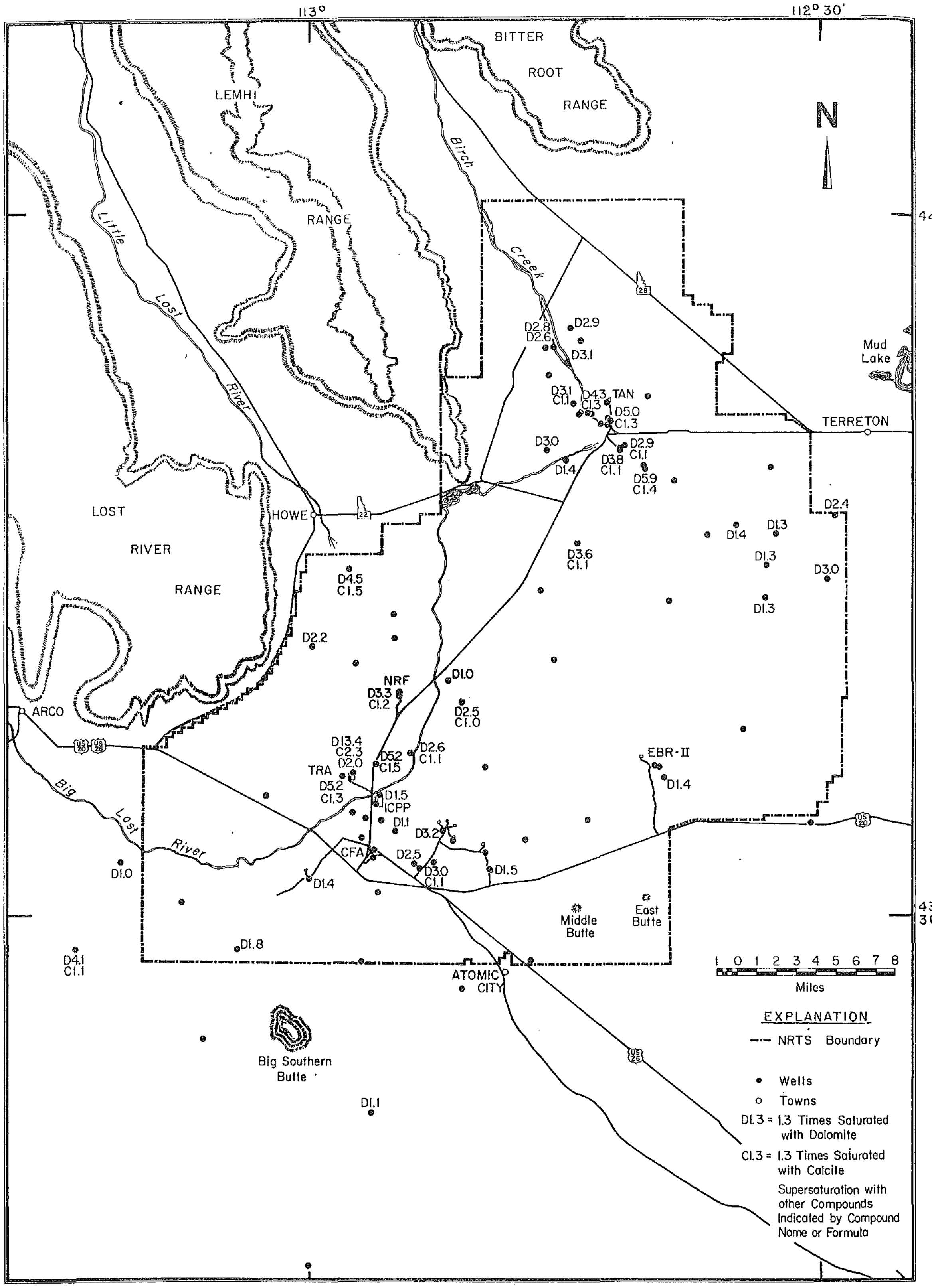


Fig. 31 Map of the NRTS vicinity showing type and degree of solute supersaturation in the Snake River Plain aquifer water.

for dolomite. An exception is a saturation of 2.3 times with calcite and 13.4 times with dolomite at one of the TRA wells. Precipitation of a solid phase depends upon kinetic factors as well as the existence of a saturated solution. Experience indicates that precipitation of calcite requires supersaturations of about 4 times or more (Barnes, 1965), and dolomite seems to require supersaturations of 10 to 30 times or more to overcome the kinetic barriers that obstruct precipitation (Ivan Barnes, oral communication, 1970). Based on this experience, no calcite or dolomite should precipitate from groundwaters beneath the NRTS under the temperature and pressure conditions prevailing in the ground. Well-crystallized calcite does form joint and vesicle coatings in the rocks above the water table where evaporation can effect a concentration of solutes.

Although supersaturation with respect to the other minerals considered does not occur, examination of the extent of dissolution of olivine in the various groundwater compositions provides an approximate measure of the degree to which the Snake River basalts react with groundwater. As noted in the section on "Composition of Recharge", olivine should be the first mineral in the basalt to react to yield weathering products such as chlorite [Equation (15)]. Unfortunately thermodynamic solubility data for chlorite were unavailable for anaysis. For the compositionally closest available substitute, the degree of saturation of several groundwaters with respect to magnesian serpentine was evaluated according to the following reaction (Barnes and O'Neil, 1969).

$$6H^{+} + Mg_3Si_2O_5(OH)_4 = 3Mg^{+2} + 2H_4SiO_4 + H_2O$$

No water listed in Table III is saturated with respect to magnesian serpentine; however, the difference between the composition of the water and the theoretical composition of a saturated water indicates the extent of approach toward saturation. If the groundwater reacts with appreciable amounts of olivine to form serpentine (or a serpentine-like mineral), smaller differences should exist in samples that have been in contact longer with basalt (downgradient along flowlines), between the water sample compositions and the theoretical equilibrium compositions. Table VIII shows the departures from saturation, in terms of free energy of reaction, for several wells along a northeast-southwest transection as well as along a northwest-southeast transection.

The northeast-southwest transection in Table VIII (parallel to groundwater flow) shows an erratic pattern of undersaturation with respect to magnesian serpentine. The lack of a pattern showing an increasing approach toward saturation to the southwest argues against there being any significant reaction between the basalt and the groundwater.

TABLE VIII

FREE-ENERGY OF REACTION FOR THE DISSOLUTION OF MAGNESIAN SERPENTINE IN THE GROUNDWATER AT SELECTED WELLS

(ΔF_R for saturation with respect to magnesian serpentine = 0.)

Northeast to Southwest

Well Number	ΔF_R (kilocalories)
31	-3.7
21	-6.7
6	-7.1
5	-5.5
83	-5.6
9	-3.9
11	-6.8

Northwest to Southeast

Well Number	ΔF_R (kilocalories)
19	-3.3
15	-5.4
6	-7.1
3	-4.0

The northwest-southeast transection in Table VIII shows increasing undersaturation of groundwater out and away from the mountains to about the middle of the NRTS. Then at the extreme eastern edge of the NRTS there is an increase toward saturation with respect to magnesian serpentine. Magnesium and silica in solution, as well as pH, control the solubility of magnesian serpentine. Reduction of magnesium in groundwater away from the mountains (Figure 22) explains the increasing undersaturation eastward. Increasing saturation at the extreme eastern edge of the NRTS depends upon the high silica content of the water (Figure 30). This pattern indicates little or no control over the water composition by bedrock.

Perhaps the major reason for this lack of reaction between the groundwater and rock is the relatively brief period of time that the two have been together. Groundwater within 200 feet of the water table seems to be moving quite rapidly with short-term rates as high as 54 feet per day and long-term rates averaging 6 to 8 feet per day (Morris, 1967). Therefore, groundwater beneath the NRTS probably has not had sufficient time to equilibrate with minerals in the basalt. Very deep groundwater beneath the NRTS may, however, move much more slowly through the rocks and thus approach a composition in equilibrium with the minerals.

2.4 Sorption

The composition of groundwater at the NRTS can be affected in a limited way by the phenomenon of cation sorption. A good description of details of the process is found in the book "Ion Exchange" (Helfferich, 1962), and only a simplified summary of the pertinent effects will be presented here.

Minerals capable of sorbing cations within their structure such as some clay minerals, fine-grained minerals, and amorphous solids capable of sorbing cations at broken bonds on their surfaces, edges, and corners, tend to exchange and equilibrate with cations in the surrounding solution. The frequently amorphous, hydrous oxides of iron and manganese exert the dominant control over sorption of heavy metals (Jenne, 1968). Carbonate minerals exercise a strong control over the sorption of strontium (Jenne and Wahlberg, 1968). In natural groundwater systems, changes in water composition tend to be slight and extend over such long periods that exchangeable cations on solids always approach equilibrium with the surrounding solution. Only relatively large changes in water composition of extended duration will produce major changes in the ratio of cations held by exchange.

Recharge of recycled irrigation water containing sodium in a greater ratio to the other cations than exists in the groundwater tends to remove exchangeable calcium, magnesium, and potassium from the rock or soil and replace them with equivalent amounts of sodium. When sufficient sodium has been removed from the percolating water to restore the original cation ratios, the process of removing sodium will stop. Of course, while sodium is being removed from solution, the other cations are displaced into solution, thus tending to create a new solution with cation ratios closer to the original groundwater. If the groundwater moves rapidly, dispersal of recharged irrigation water into the groundwater will tend to make compositional differences less apparent. Both these processes tend to buffer any extensive changes in the ratios of cations sorbed by the solid phases.

Discharge of waste through a well may effect a more drastic change in the naturally sorbed cations. This is because waste discharge passes through very limited areas as it leaves the well. Waste that is grossly different in composition from the groundwater may produce large changes in sorbed cations; however, unless waste discharge continues, rapid groundwater flow, like that under the NRTS, will reestablish the original pattern of exchangeable cations on the solids.

If concentrated sodium solutions (a few thousand milligrams per liter or more) were to be discharged into groundwater at the NRTS, they could produce deleterious local effects. However, no such discharges presently occur or are anticipated. Montmorillonitic clay minerals that are presently dominantly saturated with calcium and magnesium may obtain sufficient sodium by exchange to become dispersed, mobile, and plug rock pores. Additionally, the calcium and magnesium removed from exchange sites and put into solution may provide the additional supersaturation required to precipitate calcite and dolomite in rock pores near the well. Either phenomenon might reduce the specific capacity of a well. Although the amount of calcite or dolomite precipitated from a given volume of groundwater might not be sufficient to measurably plug rock pores, episodic disposal of waste in which the boundary between waste and groundwater fluctuates may cause recurrent precipitation in the same rock interval and, consequently, cause serious plugging of the formation.

2.5 Corrosion and Incrustation

The danger of corrosion of metal objects placed in groundwater, like well casing, is usually determined empirically. Waters saturated with calcite seldom produce corrosion, probably because they act as cathodic inhibitors. Because groundwater at the NRTS is nearly saturated or slightly supersaturated with respect to calcite, corrosion should not be a serious problem in well casing exposed only to groundwater. Utilization of deionized groundwater in heat exchangers presents a more complicated problem in corrosion control.

Incrustation, the plugging of well-casing slots by the precipitation of minerals, depends upon the degree of supersaturation with respect to possible precipitates as well as on kinetic factors (Barnes and Clarke, 1969). In the same way that formation plugging might occur by the periodic precipitation of calcite or dolomite, discharge of calcium- and magnesium-rich waste or very alkaline waste directly into the high calcium and magnesium groundwater in a well may precipitate calcite or dolomite. If groundwater returns to the well during intervals when waste is not being injected, repeated precipitation of calcite, dolomite, or other solids may occur on the well casing.

Incrustation of the soil immediately beneath disposal ponds by fine-grained carbonate precipitates has occurred at the NRTS. Some of the precipitates probably formed by evaporative concentration of waste in the ponds, as well as in aereated soils near the edges of the ponds, in the same way that caliche forms in soils subject to periodic drying. In addition, the mixing of chemically incompatible wastes in the ponds has produced some of the precipitates which contributed to slower percolation of wastes.

2.6 Geochemical Conclusions

Groundwater in the Snake River Plain is very dilute and is satisfactory for most purposes without treatment. The low dissolved solids content reflects the abundant rain and snowfall in the surrounding mountains. The composition of the groundwater indicates reaction with minerals in rocks of the surrounding mountains and alluvial valleys where residence time of the groundwater is relatively long. Groundwater compositions do not show detectable effects of reaction with Snake River Plain rocks in which water movement is rapid. High evaporation rates on the arid plain increase the dissolved solids in water used for irrigation, but recharged irrigation water loses its identity quickly in groundwater due to rapid dilution and dispersion.

V. NRTS LIQUID WASTE DISPOSAL

(J. B. Robertson, J. T. Barraclough)

Since 1952, a variety of liquid wastes have been discharged to seepage ponds and disposal wells at several NRTS facilities. These wastes include low-level radioactive, chemical, and sanitary effluents. The types and quantities have varied greatly with time and location. Each facility produces different kinds of liquid wastes and disposes of them independently.

Three principal facilities, the Test Reactor Area (TRA), the Idaho Chemical Processing Plant (ICPP), and the Naval Reactor Facility (NRF), discharge over 90% of the total NRTS liquid wastes and thus receive the most attention in this report. Special emphasis is placed on the waste discharges of TRA and ICPP, which comprise 75% of the NRTS total volume, because the quantities, compositions, and effects of their wastes are the best documented of all the NRTS facilities.

1. TEST REACTOR AREA

The Test Reactor Area is in the south-central part of the NRTS (Figure 2) on the flood plain of the Big Lost River. Liquid wastes at the TRA have been discharged to several ponds and one well, and the effects of the waste disposal have been under study for several years. The TRA discharges the greatest waste of all NRTS facilities in terms of total volume and total radioactive and chemical content.

1.1 Disposal Ponds

The TRA uses six disposal ponds: three to dispose of liquid radioactive waste, two to dispose of nonradioactive sanitary wastes, and one to dispose of nonradioactive chemical wastes (Figure 32). All ponds were dug in the permeable gravel, sand, and silt of the Big Lost River alluvium to allow downward infiltration.

1.11 Radioactive Waste Ponds. The first of three low-level liquid radioactive waste ponds at TRA was dug in 1952 with bottom dimensions of 150 by 250 feet with 2:1 side slopes and a depth of 15 feet. Because of decreased permeability and additional discharge, a second pond was dug in 1957. The two ponds form one pond when the water level is greater than 11 feet deep. The 1957 pond bottom is 125 by 230 feet with 2:1 side slopes and a depth of 15 feet. The 1952-57 pond has a capacity of 9.7 million gallons when the water is 15 feet deep (Figure 33).

All the liquid wastes (except sanitary) were discharged to the 1952-57 pond from 1952 until 1962. The infiltration rate from these ponds decreased over the years because of

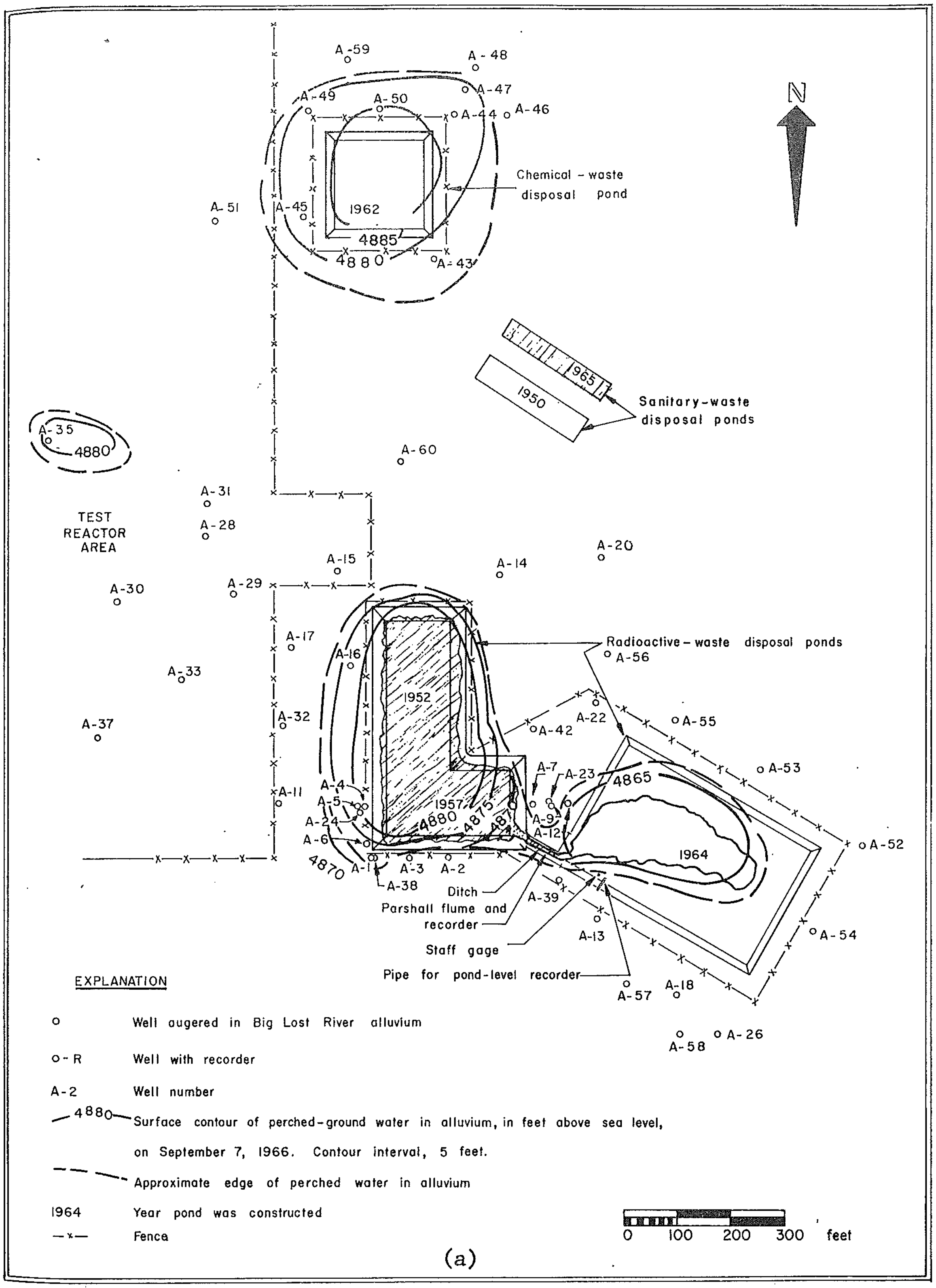


Fig. 32 Maps of the Test Reactor Area (TRA) showing the location of disposal ponds, auger holes, and the extent and water-level contours of the perched groundwater in alluvium on September 7, 1966 (a) and March 27, 1967 (b).

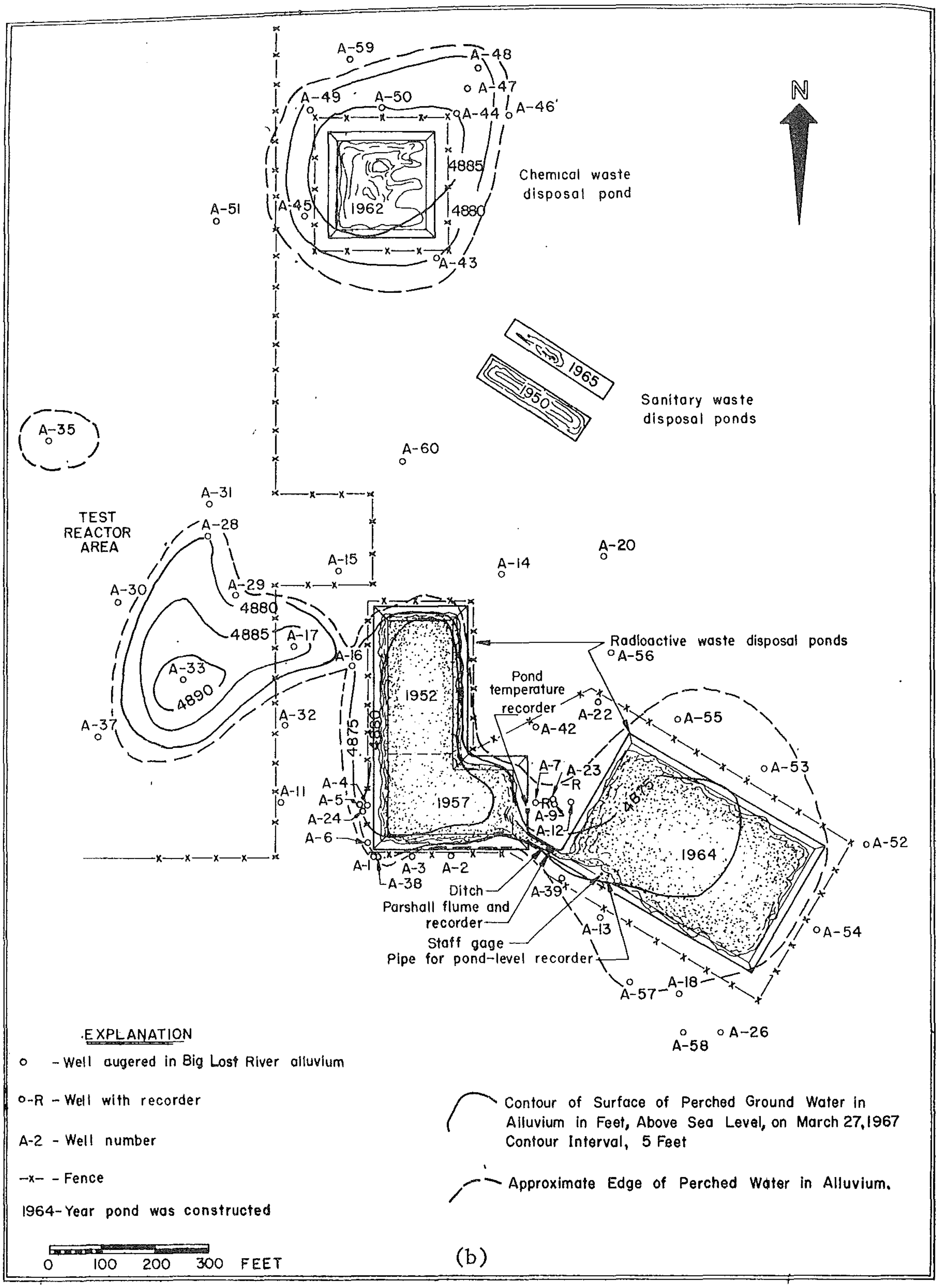

N
A-59
A-48
A-47
A-49
A-50
A-44
A-46
4885
Chemical waste disposal pond
A-51
A-45
1962
4880
A-43
1965
1950
Sanitary waste disposal ponds
A-35
A-60
A-31
TEST REACTOR AREA
A-28
A-15
A-14
A-20
A-30
A-29
4880
4885
A-17
A-16
A-33
4890
Radioactive waste disposal ponds
A-56
Pond temperature recorder
1952
A-42
A-22
A-55
A-37
A-32
4875
4880
A-7
A-23
R
A-53
A-11
A-4
A-5
A-24
A-6
1957
R
A-9
A-12
4870
1964
A-52
A-1
A-3
A-2
A-38
Ditch
Parshall flume and recorder
A-39
Staff gage
A-13
Pipe for pond-level recorder
A-54
A-57
A-18
A-58
A-26
EXPLANATION
o - Well augered in Big Lost River alluvium
o-R - Well with recorder
A-2 - Well number
-x- - Fence
1964 - Year pond was constructed
Contour of Surface of Perched Ground Water in Alluvium in Feet, Above Sea Level, on March 27,1967 Contour Interval, 5 Feet
Approximate Edge of Perched Water in Alluvium.
0 100 200 300 FEET
(b)

Fig. 32(b).

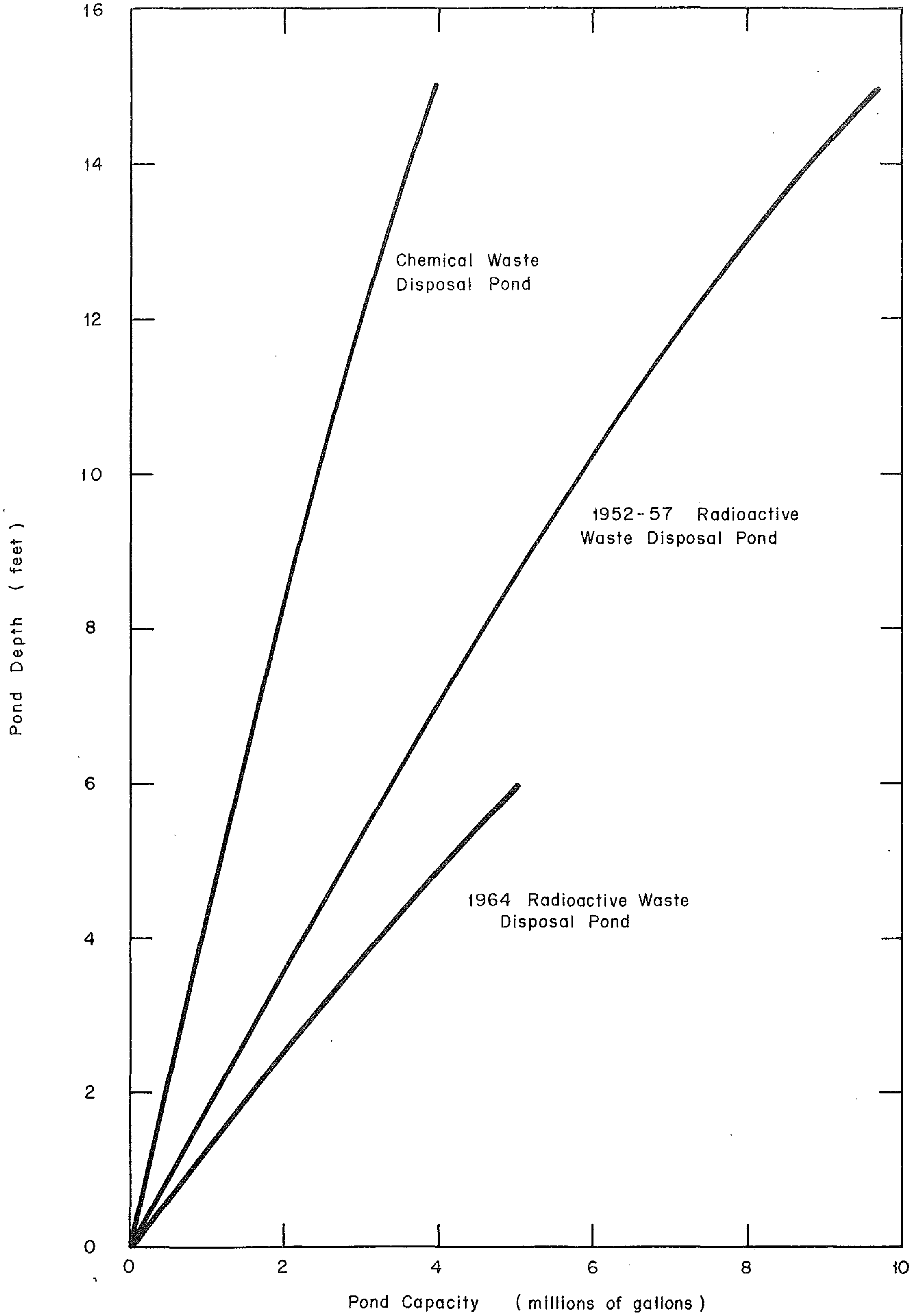


Fig. 33 Graph showing the relationship of storage capacity to depth for three disposal ponds at the Test Reactor Area.

a precipitation of silica gel which partly sealed the bottom and lower sides of the pond (Horan and others, 1962). The gel was as thick as six inches in 1961. Fine-grained sediments, algae, and other chemical precipitates doubtless also contributed to the decreased permeability of the pond. To avoid the formation of the silica gel, liquid waste separation was initiated in 1962. The radioactive wastes continued to be discharged to the 1952-57 pond, but a separate pond was excavated for chemical wastes, and a deep well was drilled to dispose of cooling tower blowdown waste water. Nevertheless, the permeability of the bottom and sides of the 1952-57 pond continued to decrease and the pond water level began to rise in 1963. By the middle of 1964, the pond was nearly overflowing. The third and largest pond was excavated in 1964. The pond bottom is 250 by 400 feet with 2:1 side slopes and has a maximum depth of nearly six feet. The pond contains 4 million gallons when the water is five feet deep (Figure 33). The total capacity of three radioactive waste ponds at the TRA is 15 million gallons when the ponds are full. The radioactive waste is pumped into the 1952-57 pond where it then flows by gravity through a small canal to the 1964 pond. A Parshall flume was installed in the canal between the ponds to enable the discharge to be measured and recorded. These records can be compared with the pond discharge records compiled by the operating contractor (presently Aerojet Nuclear Company).

Volume discharged to the ponds (Figure 37) has ranged from 7 million to 30 million gallons per month and has averaged about 190 million gallons per year.

The permeability of the 1964 pond decreased substantially in 1969. The pond water level started rising in the fall of 1969 and the rate of rise increased in the late spring. In order to investigate the causes of the permeability decline, the canal from the 1952-57 ponds to the 1964 pond was dammed and the 1964 pond was allowed to drain dry in 1970. The 1952-57 ponds disposed of all the liquid radioactive wastes for two months. Colonies of algae, a white precipitate on the alluvium surfaces, and plant growth had formed in the 1964 pond bottom. The white precipitate was calcium carbonate, primarily aragonite with some calcite. Analyses of pond water samples indicated that it was supersaturated with respect to calcium carbonate at times. During the drying period, desiccation cracks formed and the algae were killed. Infiltration tests indicate that most of the permeability was restored by drying and that scarifying the pond bottom did not increase the permeability.

These observations indicated that periodic drying of the pond during the summer months would kill the algae without using chemicals. Drying cracks would also increase the permeability. Reduction of the pH of the water from 9 or 10 down to 7 or 8 would reduce the formation of the calcium carbonate.

Tritium (as tritiated water) is one of the most significant radionuclides discharged to the TRA ponds. Its relatively large discharge quantities, long half-life (12.3 years) and low-level detectability enables tritium to be readily traced in groundwater containing pond wastes. Studies of the extent and concentrations of tritium in water near the TRA have therefore been useful for evaluating the overall effects of the waste disposal. The tritiated water is not readily exchanged with the soil or rock minerals and thereby becomes a very good groundwater tracer. Measurements of the tritium content of the radioactive waste discharge to the TRA ponds are available only from October 1961 to the present (Figure 34). Since 1961, tritium has averaged 9.2% of the gross beta-gamma activity. The pre-1961 tritium releases were estimated using the same percentage. The total estimated plus measured amount of tritum discharged to the TRA ponds from 1952 through 1970 is about 6,000 curies (Ci), an average of about 330 Ci/yr or 0.9 Ci/day. Allowing for decay, the remaining tritium at the end of 1970 would be about 4,400 Ci.

The yearly amount of tritium discharged to the TRA ponds varies by a factor of three (Figure 34). However, the monthly average concentrations of tritium in the TRA ponds varied from 154 to 1,600 picocuries per milliliter (pCi/ml) (Figure 35). The average yearly concentrations of tritium in the TRA ponds were 260 pCi/ml in 1962, 472 in 1963, 663 in 1964, 609 in 1965, 816 in 1966, 640 in 1967, 749 in 1968, and 710 pCi/ml in 1969. The average concentration of tritium in the TRA ponds from 1962-69 was 615 pCi/ml.

It is interesting to note the circumstances which led to the discovery of tritium as a major NRTS waste product. Because of its low energy beta activity, it was not detected in NRTS waste effluents prior to 1960. Neither was the nuclear chemistry of its formation understood, so that it was not suspected as a waste product. The Geological Survey, in 1960, was conducting various hydrologic studies related to the NRTS and the Snake River Plain and became interested in the hydrologic effects of radioactive fallout from atmospheric weapons testing. The study included mapping the distribution of tritium, a prominent fallout component, in the Snake River Plain aquifer. In analyzing the tritium content on many wells throughout the plain, an anomalously high cencentration was found in the MTR Test well near the TRA on NRTS. The concentration was far too high for fallout tritium, so the source subsequently was traced to liquid waste discharged to TRA disposal ponds. It was then determined that tritium was the most abundant waste isotope at both the TRA and ICPP.

In addition to tritium, several other significant isotopes are discharged to the TRA ponds. Approximately 44 Ci of strontium-90 (Sr-90) have been discharged to the ponds from 1952 through 1970. The concentration has varied considerably because the annual disposal of Sr-90 has ranged from 0.1 to 8.1 Ci and the quantity of water disposed has varied. The estimated average concentration of Sr-90 in the TRA pond water is 3 to 5 pCi/ml. The disposal of Sr-90 was the highest in 1967, 1969, and 1970 when 8.1, 8.1, and 7.2 Ci, respectively, were discharged. These three years account for about 53% of the total Sr-90 discharged to the TRA ponds.

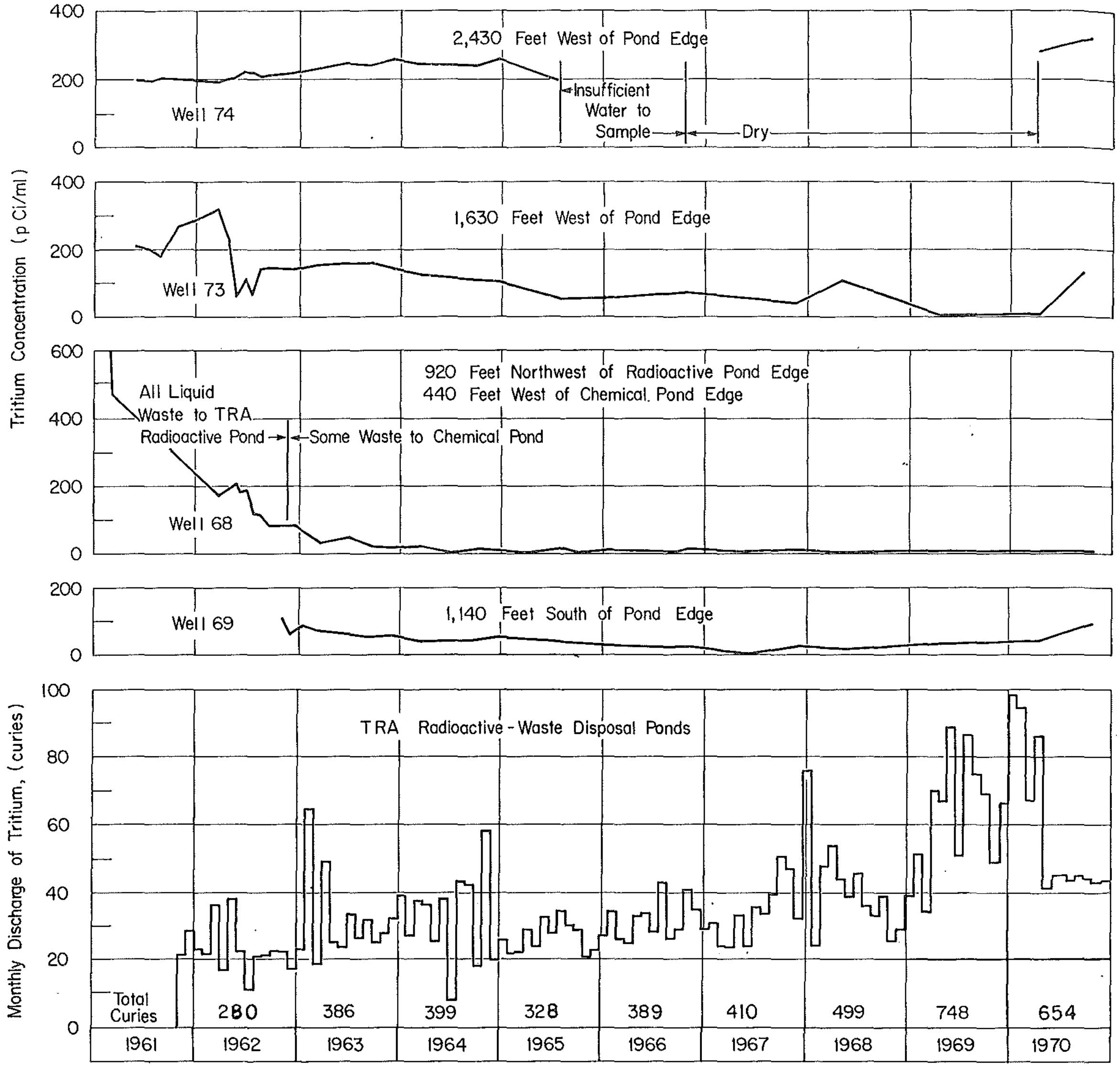


Fig. 34 Graphs showing the quantity of tritium discharged to the Test Reactor Area ponds and the tritium concentrations of water from Wells 74, 73, 68, and 69.

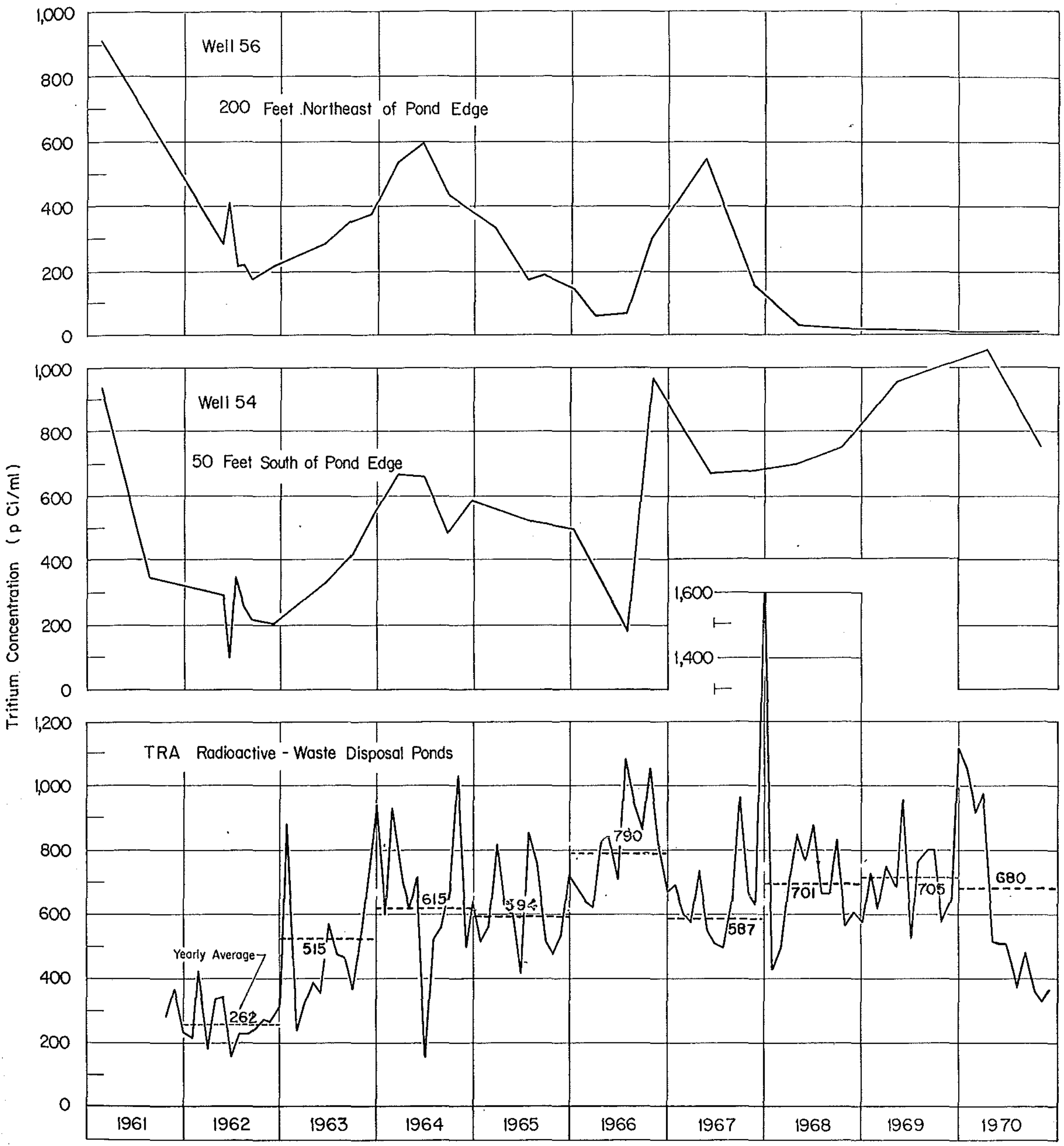


Fig. 35 Graphs showing the tritium concentrations of water from the Test Reactor Area ponds and Wells 56 and 54, tapping perched water.

About 104 Ci of cesium-137 have been disposed to the TRA radioactive-waste disposal ponds from 1953 through 1970 and the annual discharge has ranged from 1 to 13 Ci. The average rate has been almost 6 Ci/yr. The three highest years were 1959, 1960, and 1969 when 11, 13, and 11 Ci were discharged, respectively.

About 194 Ci of cobalt-60 (Co-60) have been discharged to the TRA radioactive-waste disposal ponds from 1962 through 1970. The least amount, 7 Ci, was discharged in 1966 and the largest quantity was 39 Ci in 1964. The average amount was 21.6 Ci/yr. The rate of Co-60 discharge prior to 1962 is unknown, although it was probably higher than the current average (B. L. Schmalz, 1972). Assuming the discharge rate of Co-60 was the same as present rates from 1952 through 1961, then about 190 Ci of Co-60 would have been disposed in the first ten years of operation (1952-61). The total estimated discharge from 1952 through 1970 would then be at least 380 Ci which would have decayed to 140 Ci by the end of 1970. B. L. Schmalz (1972) estimates that more than 700 Ci of Co-60 are contained within the first 21 inches of soil beneath the ponds. This suggests that estimated discharge could be much too low.

1.12 Chemical Waste Pond. The liquid chemical waste pond at TRA is 170 by 170 feet at the bottom, has 1:1 side slopes, and contains 1.15 million gallons when it is five feet deep (Figure 33). The average discharge to the pond has been about 120,000 gallons per day (gpd) since its first use in November 1962. The yearly discharge is about 44 million gallons and the total discharge to the pond from November 1962 until December 1970 was about 350 million gallons.

The chemical wastes include process treatment wastes from regenerations of four cationic exchangers (sulfuric acid), two anionic exchangers (caustic), and four softeners (salt). The TRA uses about 1,000 tons per year of sulfuric acid, about 500 tons per year of sodium hydroxide, and about 50 tons per year of sodium chloride for regeneration of the demineralizers. Other wastes include calcium and magnesium sulfates and bicarbonates.

1.13 Sewage. Sewage wastes at the TRA are channeled to an Imhoff tank, trickling filter, chlorination basin, drying beds, and two seepage ponds. The first sanitary pond was excavated in 1950. The pond is 75 by 250 feet and contains 55,000 gallons when it is one foot deep and 330,000 gallons when it is five feet deep. The pond bottom has been scraped, dried, or excavated as needed to help restore the permeability. A second sanitary waste pond was excavated in 1965. This pond is 30 by 250 feet and contains 10,000 gallons when it is one foot deep and 79,000 gallons when it is five feet deep.

The design capacity of the sewage system at the TRA is 59,000 gpd (Schmalz, 1968). The estimated flow in 1968 was 27,000 gpd and the average discharges in 1965 and 1966 were 33,420 and 35,000 gpd, respectively. The sewage waste discharged at the TRA is not monitored by nearby wells. Water in some of the deeper wells is doubtless derived in part from sewage waste. The Geological Survey has not monitored the subsurface effects of sewage waste at the TRA.

1.2 Deep-Disposal Well

The TRA nonradioactive waste-disposal well (Figure 36) was drilled in 1962-63 for disposing of nonradioactive liquid wastes. The well is 1,271 feet deep and is cased to the bottom with casing ranging in diameter from 18 to 6 inches. The well is perforated at several intervals from 512 to 1,267 feet below the land surface. Because of inadequate completion, the well initially accepted water at the rate of 330 gpm for only two or three days, then the water rose to the land surface. Successful redevelopment measures were completed in 1963-64 (Morris and others, 1965, pp. 67-91). The well is presently capable of accepting more than 1,000 gpm with no detectable head buildup.

Disposal to the well started in November 1964 and yearly discharges have ranged from 4.6 million gallons in 1964 to 276 million gallons in 1970. The total quantity disposed from November 1964 through December 1970 was about 912 million gallons. Monthly discharge volumes range from nil to 33 million gallons (Figure 37). The average disposal rate for this period was 150 million gallons per year and 410,000 gpd. The average rate for 1970 was 760,000 gpd, or 530 gpm, the highest annual disposal rate over the period of record. The average disposal rate for 1968 was 142,000 gpd, or 100 gpm, the lowest annual rate over the period of record.

Waste waters from the TRA cooling towers compose a major part of the waste that is disposed of in the TRA disposal well. Other waste streams are derived from air coolers, floor drains, secondary system drains, and other similar types of drains. The wastes discharged to the well contain no radioactivity above natural groundwater levels. The wastes usually contain about 500 mg/l of dissolved solids which consists mainly of the salts of calcium and magnesium. Normal dissolved solids content in water pumped from the Snake River Plain aquifer at the TRA is about 200 to 250 mg/l.

The waste component in the effluent discharged to the well generating the most interest is hexavalent chromium, Cr(VI). According to U.S. Public Health Service (1962) Cr(VI) is a possible health hazard and has therefore been given a maximum permissible concentration limit of 0.05 mg/l in public drinking water.

Chromium is used as a corrosion inhibitor in the TRA secondary cooling system. The cooling tower water is maintained with a Cr(VI) concentration between 11 and 14 mg/l. The concentration of Cr(VI) in the cooling tower blowdown streams is about 4 to 5 mg/l. Further dilution from other waste streams occurs before the chromium enters the well so that the average Cr(VI) concentration in the water discharged to the well is from 0.7 to 2 mg/l. Seventy-five samples of the water discharged to the well, 1970 and 1971, averaged 1.4 mg/l in total chromium concentration (B. L. Schmalz, oral communication, 1972).

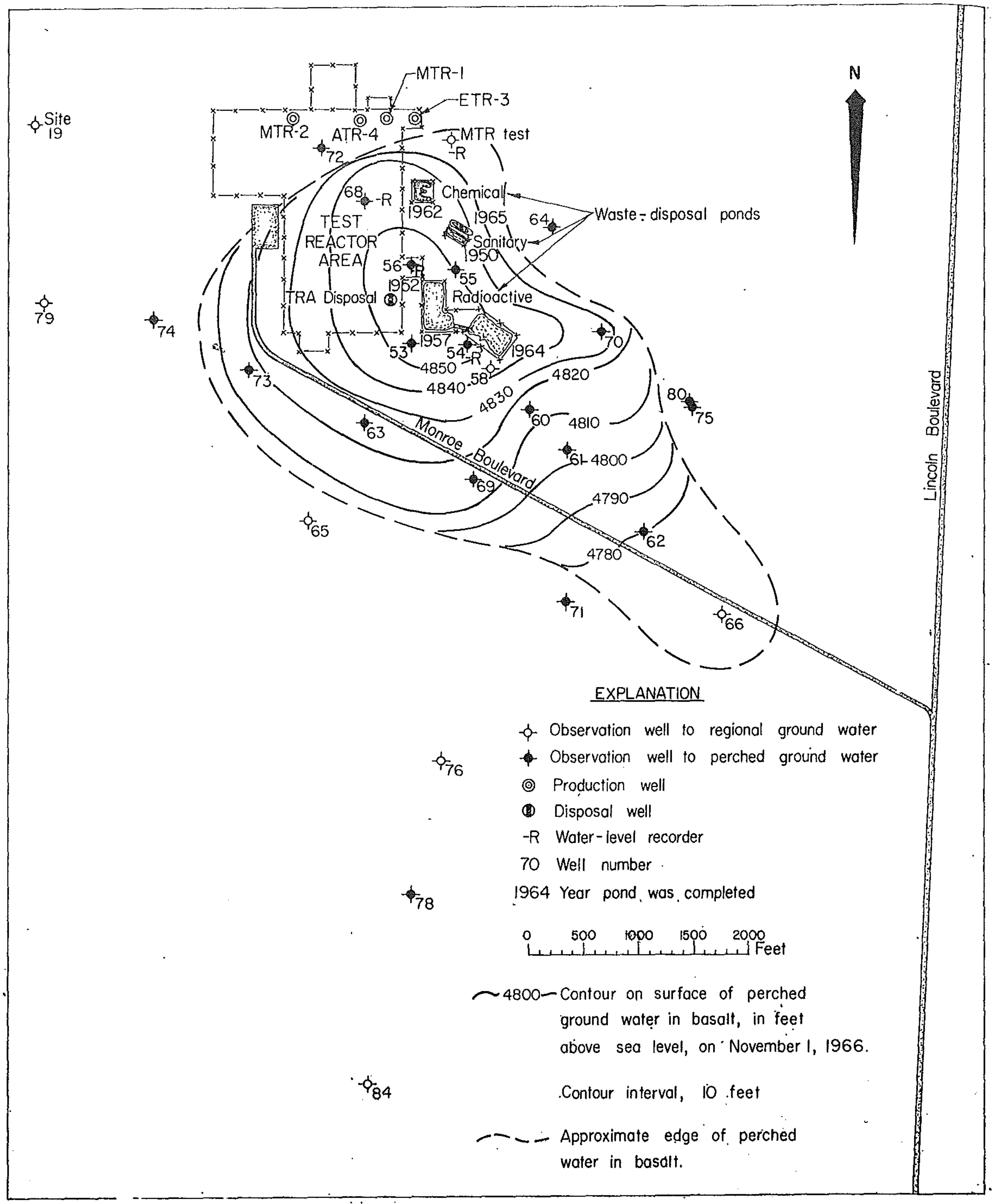


Fig. 36 Map of the Test Reactor Area showing water-level contours on the surface of the perched groundwater in the basalt on November 1, 1966.

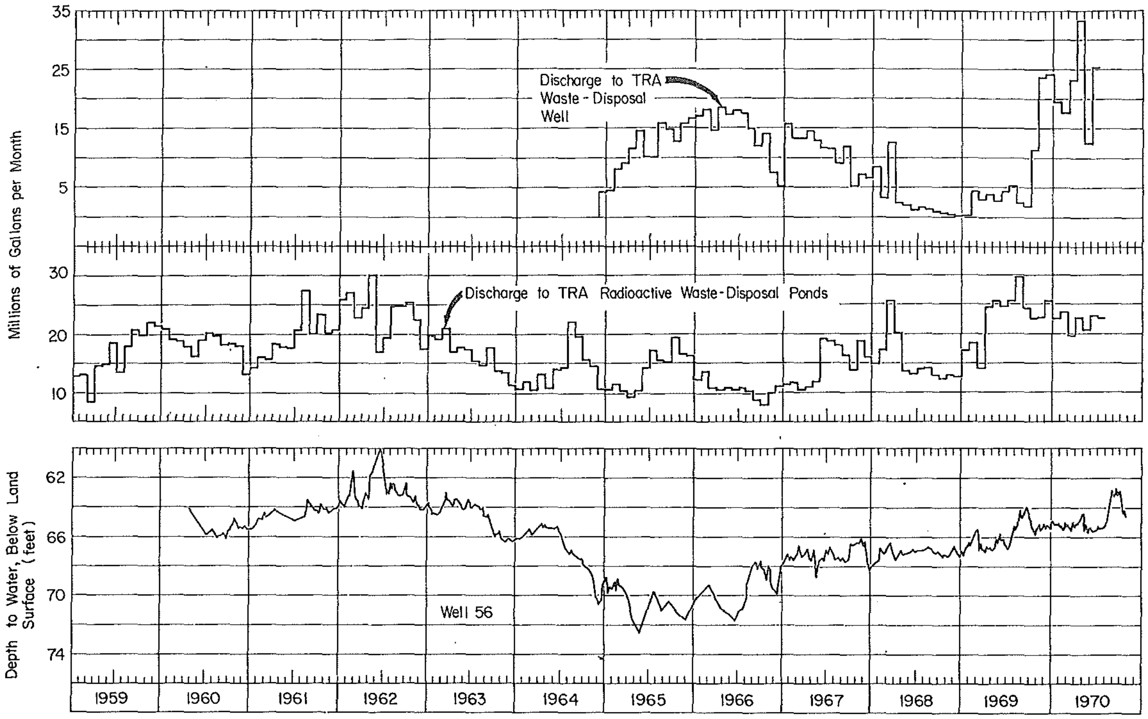


Fig. 37 Graphs of the waste discharged to ponds and to a well in the Test Reactor Area, and also the hydrograph of Well 56.

Chromium from the TRA ponds was present in the aquifer in 1963 prior to the time chromium disposal began in the TRA disposal well in November 1964. The chromium content of wells south of the disposal well has increased since 1964. Plans have been made to eliminate the discharge of chromium by substituting a phosphate-based water treatment process.

1.3 Perched Water at TRA

Infiltration from the TRA ponds has formed at least two major perched-water bodies beneath the TRA (Figures 36 and 38). One is perched on the basalt layer located about 50 feet below the surface. A second, and much larger, perched-water body occurs on a layer of clay and silt within the basalt about 150 feet below the surface and about 300 feet above the regional water table. Lower sediment layers within the basalt retard the water as it moves downward to the Snake River Plain aquifer and probably cause additional perched-water bodies.

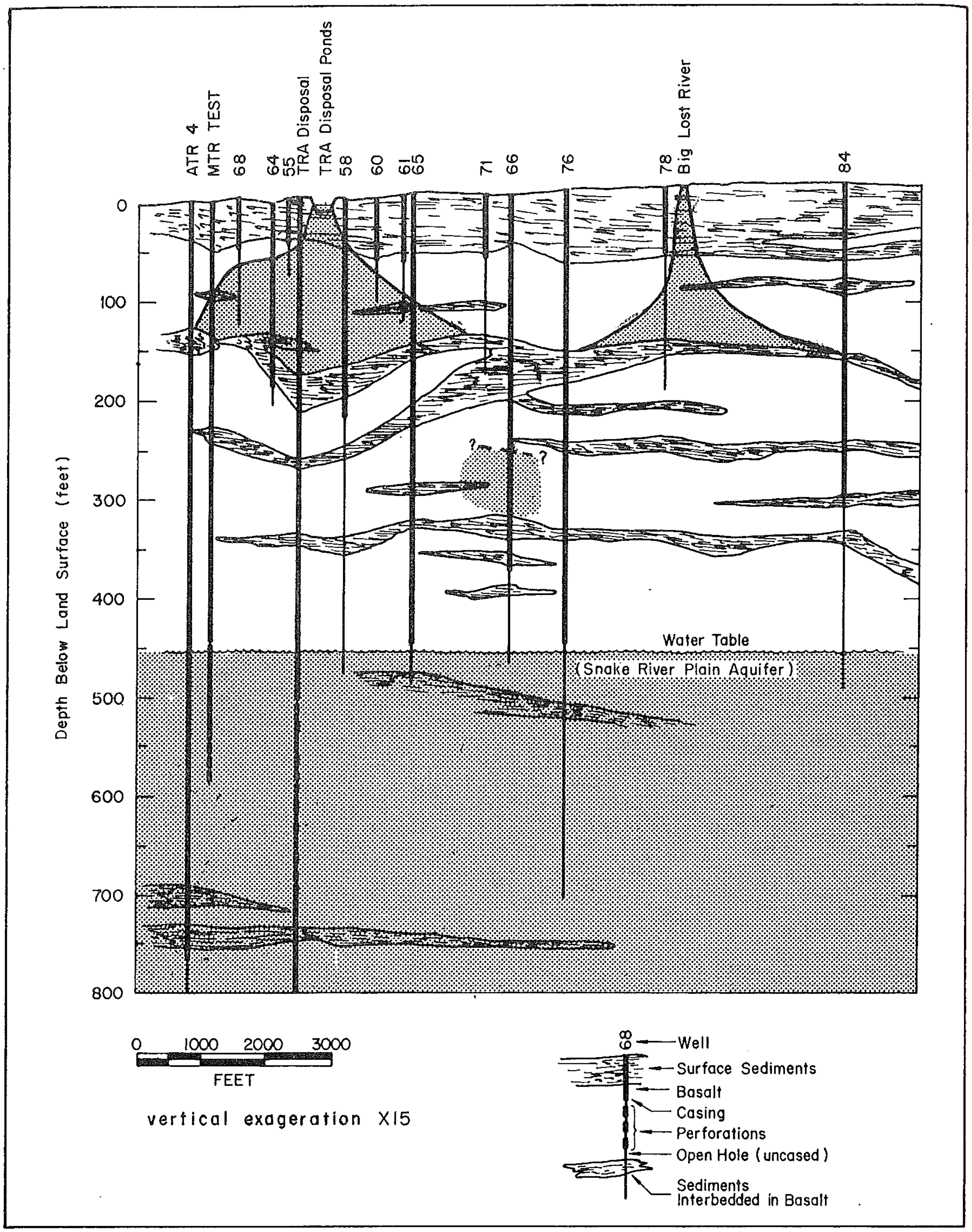


Fig. 38 Geologic cross section at the Test Reactor Area showing the bodies of perched water and the Snake River Plain aquifer.

1.31 Perched Water in Alluvium. The perched water in the alluvium near the radioactive waste-disposal ponds covered an area of about six acres in 1966 (Figure 32). The average discharge rate to the ponds during 1966 was 357,000 gpd which was the lowest rate for the preceding nine years. This explains the relatively small size of the perched water body shown in Figure 32(a).

The contours of the perched groundwater in the alluvium shown in Figure 32(b) illustrate a significant change when compared with Figure 32(a). The subsurface area west of the 1952-57 pond was dry in September 1966 and contained a body of perched water on March 27, 1967. This perched water is derived from leakage from a buried waste-retention basin or from water lines that convey waste water from the retention basin to the pond and not from pond seepage.

The shallow saturated area near the 1952-57 pond bottom has not changed appreciably while the saturated area beneath the 1964 pond has expanded and contracted considerably during the study. The permeability of the 1952-57 pond bottom and lower sides has decreased considerably over the years. The shallow perched water is usually near the bottom of the ponds and the saturated zone is not very thick. Because of the permeability decline in the 1952-57 pond bottom, most of the waste water infiltrated downward from the 1964 pond.

The perched body of water in the alluvium around the chemical waste-disposal pond covers an area of about four acres [Figure 32(b)]. This water seeps generally downward into the basalt to form another perched body which tends to prevent perched radioactive waste water from moving northward toward the TRA supply wells. The body of perched chemical waste water has generally remained about the same size during the study.

A small body of perched water has formed by leakage from an unknown source within the TRA compound [Figures 32(a) and 32(b), Well A-35]. The lateral movement of this small amount of water is probably to the southeast toward the main perched body. The perched water contains few dissolved minerals and may be derived from some demineralized water in a nearby building.

Other small perched water bodies in the alluvium may occur at the TRA. The primary source would be from small leaks. The detection of such perched water, if present, would require additional shallow wells.

1.32 Perched Water in Basalt. The large perched-water body within the basalt at TRA covers an area of about 325 acres (6,000 by 3,000 feet) and saturates a maximum thickness of 100 feet between the depths of 60 and 160 feet below the surface (Figure 36). The water table slopes laterally outward below the ponds in every direction and at a gradient of from 150 to 200 feet per mile. The perched-water body in the basalt is composed of seepage water from all the ponds in the TRA. The chemical content of the water indicates from which ponds the water is derived.

The general shape of the perched water body has not changed much in the past 10 years since it was first mapped in 1961 (Jones, 1961); However, the perched water level in individual wells have fluctuated over a wide range. The fluctuations respond to variations in the pond discharge. Approximately the same quantity of liquid waste as is being disposed of daily is percolating through the perching beds and then downward through the unsaturated zone to the Snake River Plain aquifer. Little is known of the waste water movement in the zone between the major perching zone and the aquifer.

Infiltration from the Big Lost River has created a perched water body in the basalt near TRA which has an influence on the TRA perched waste water. Flow in the river induces groundwater recharge which in turn causes water-level rises in the TRA perched water table. The data on these water-level responses from a known source of water are useful to compare with nearby movement of waste water through the perching beds. Well 78 (203 feet deep) is 235 feet from the river, and its water level shows a rapid response to initial flow in the river (Figure 5). In April 1966, the water level in Well 78 started an abrupt rise within 4.5 days after water first flowed in the Big Lost channel. The water moved 170 feet downward and 325 feet laterally in 4.5 days or about 80 to 90 feet per day. This value is reasonable because of the permeability of the rocks and the steep hydraulic gradient. Recharge from the river has caused the water level in Well 78 to rise as much as 125 feet (Figure 5).

1.33 Fluctuations of the Perched Water Levels. The perched water table in the basalt fluctuates according to the fluctuation in discharge to the ponds, as demonstrated by the Well 56 (northwest of ponds; Figure 36) hydrograph (Figure 37). In general, from 1960 to the summer of 1964 the water level in Well 56 rose as the discharge increased and declined as the discharge decreased. Since then, some of the waste water uncontaminated with radionuclides has been diverted to a separate pond and the disposal well, altering the relationship somewhat. The water level began a general decline in June 1962, which has been more rapid since the summer of 1964 when most of the waste was diverted to the new disposal ponds. The water level started a general rise in 1966 which has continued through 1970. The water level has fluctuated 12 feet in 11 years.

The regional water table (Snake River Plain aquifer) at the TRA, as shown by the water level in the MTR test well, rises during years of high runoff and declines during years of low runoff in the Big and Little Lost Rivers and had little apparent relationship to the perched water fluctuations (Figure 39). The regional water table has fluctuated about 11 feet during the 21 years of record. The water level is now the highest it has been since 1959.

Fluctuations in the deep perched water nearer the ponds relate to the quantities of waste discharged and the ponds to which the wastes were discharged (Figure 39). The water

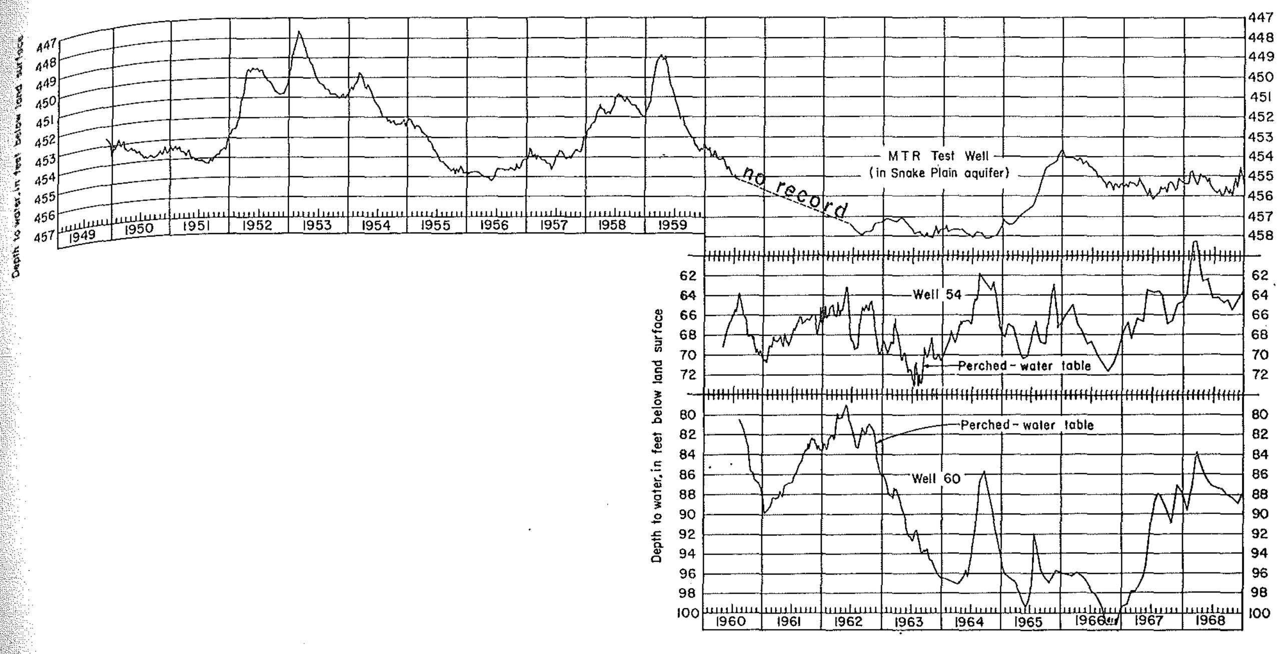


Fig. 39 Hydrographs of Wells MTR Test, 54, and 60.

level in Well 54 (south of ponds) fluctuated 17 feet during the 11 years of record and was highest in 1969 and the lowest in 1963. The hydrograph of Well 60 (southeast of ponds) shows 25 feet of fluctuations in the perched-water table during 10.5 years of record (Figure 39). The water level was highest in 1969 and lowest (well was dry) in 1966 when the largest and smallest amounts of waste, respectively, were discharged. The 11-foot rise in the summer of 1965 was a result of waste disposal to the new pond. The water level rose an additional 12 feet in 1967 and again in 1969.

Perched water levels in two wells southeast of the ponds (Wells 62 and 71, Figure 36) respond not only to pond discharges but also to the flow in the Big Lost River (Figure 40). The abrupt water-level rise in Wells 62 and 71 during 1965 are attributed to recharge from the unusually high flows of the nearby Big Lost River rather than to discharges to the disposal ponds. The recharge from the river created a mound in the groundwater which may have a "damming" effect on the perched water from the ponds. Well 71 is 2,200 feet and Well 62 is 2,500 feet northwest of the river. The effects of river recharge reached the wells in about 70 days, traveling at a horizontal rate of 30 to 35 feet per day. The 1969 water-level rises were again in response to sustained high flows in the Big Lost River.

Well 66 (southeast of the ponds) taps a lower perched aquifer in the basalt whose water level is generally about 125 to 150 feet below the upper perched-water level in the nearby wells (Figures 36 and 40). Its water level also responds to Big Lost River recharge.

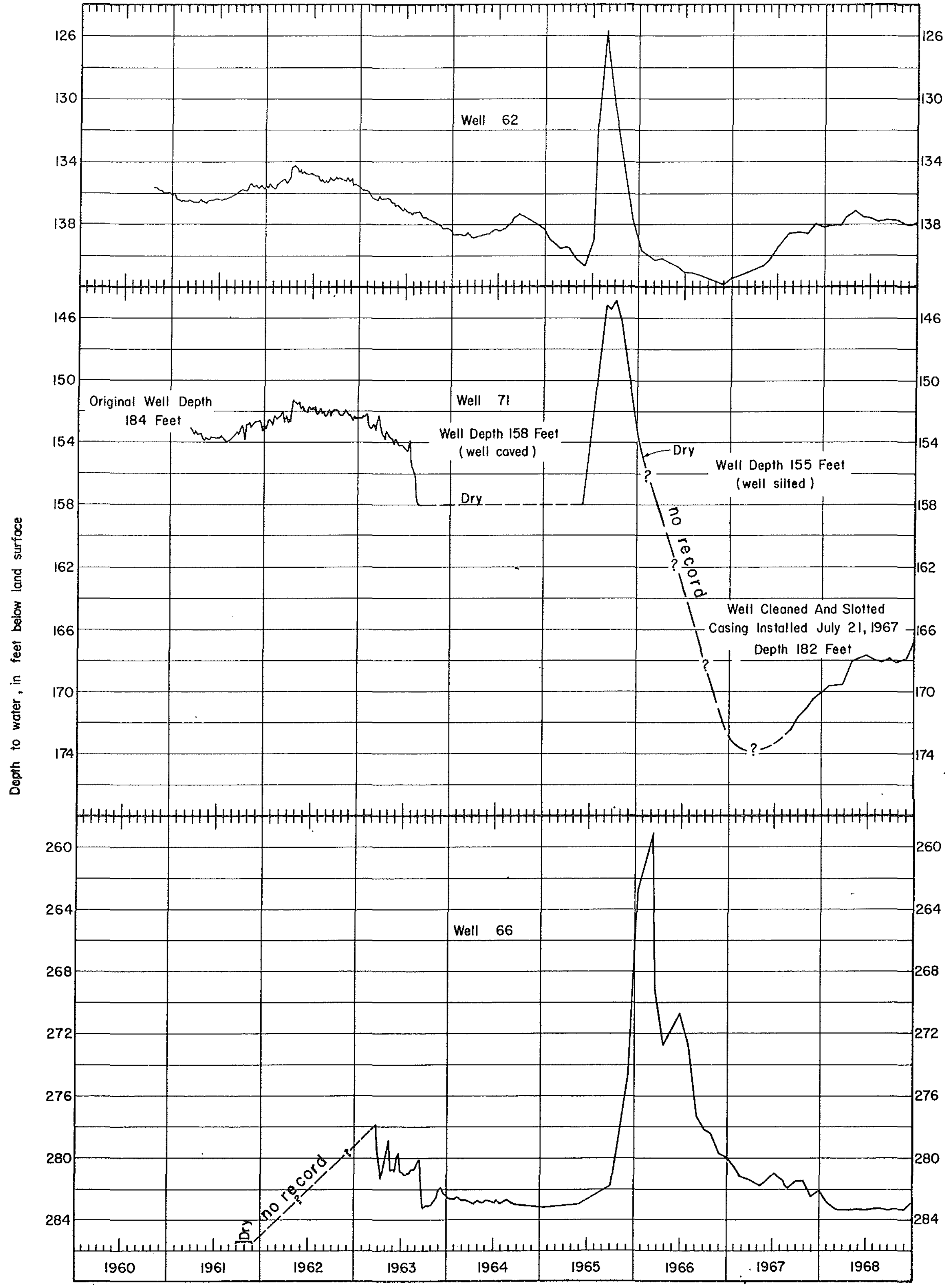


Fig. 40 Hydrographs of Wells 62, 71, and 66, tapping perched water.

About 4.5 to 5 months was required for the 1965 recharge water to move through the upper perching layers to the lower perched-water table of Well 66. A similar water-level rise occurred in Well 66 during October 1969, another year of high river discharge. The time lag for the 1969 river water to move through the perching beds was also about 4 to 5 months.

Water levels in Wells 73 and 74, tapping the perched-water body in the basalt (west of the disposal ponds), reflect the fluctuations of waste-discharge rates (Figure 41). Well 74 obtains its water from a permeable zone between two clay beds which form part of the perching layers within the basalt. Its hydrograph reflects only long-term waste-discharge trends, which suggest that the upper clay layer attenuates the pond effects. The peak water level occurred in the spring of 1963, probably as a result of the high waste discharge in 1962. Thus, the time required for the water to percolate through the upper clay is about nine months. Well 74 went dry in 1966 and remained dry until the summer of 1969. The 1969-70 water-level rise probably correlates with the water-level rise in Well 73 which started eight months earlier.

1.34 <u>Tritium.</u> Approximately 4,400 Ci of tritium appear to have been discharged to the ponds (as of 1970, after decay), of which about 25 Ci is estimated to be in the perched water in the alluvium, 1,000 Ci in the perched water in the basalt, and about 800 Ci in the Snake River Plain aquifer, and an unknown quantity, less than 2,000 Ci, in the zone between the perched water in the basalt and the Snake River Plain aquifer. Some of this is undoubtedly in additional deeper perched water zones.

In general, the tritium concentration in the perched water varies with the input concentrations and with the changes in disposal methods and locations. The tritium concentration of the perched water near the pond can be greatly reduced or increased in a matter of weeks. Significant changes can be effected in the tritium concentration of the perched water farther away from the ponds in a year or so. The tritium concentrations of water from wells near the extreme edges of the perched water body appear to change only slightly over the years.

Tritium concentrations in the perched water in the basalt from Well 54 to Well 56 do not indicate direct correlation with the pond water concentrations (Figure 35). Apparently, this is because the concentrations shown for the pond water are average values whereas the concentrations shown for the perched groundwater represent the concentration in individual well samples. The water in Well 56 is derived primarily from leakage from nonradioactive ponds, especially after 1964. The Well 56 concentration would probably follow the pond tritium concentrations more closely if more samples had been collected and analyzed.

Tritium concentrations of perched water in the basalt from four wells more than 1,000 feet west or south of the radioactive-waste pond have changed relatively little since 1963 (Figure 34). Concentrations from Wells 69 and 73 have decreased over most of the

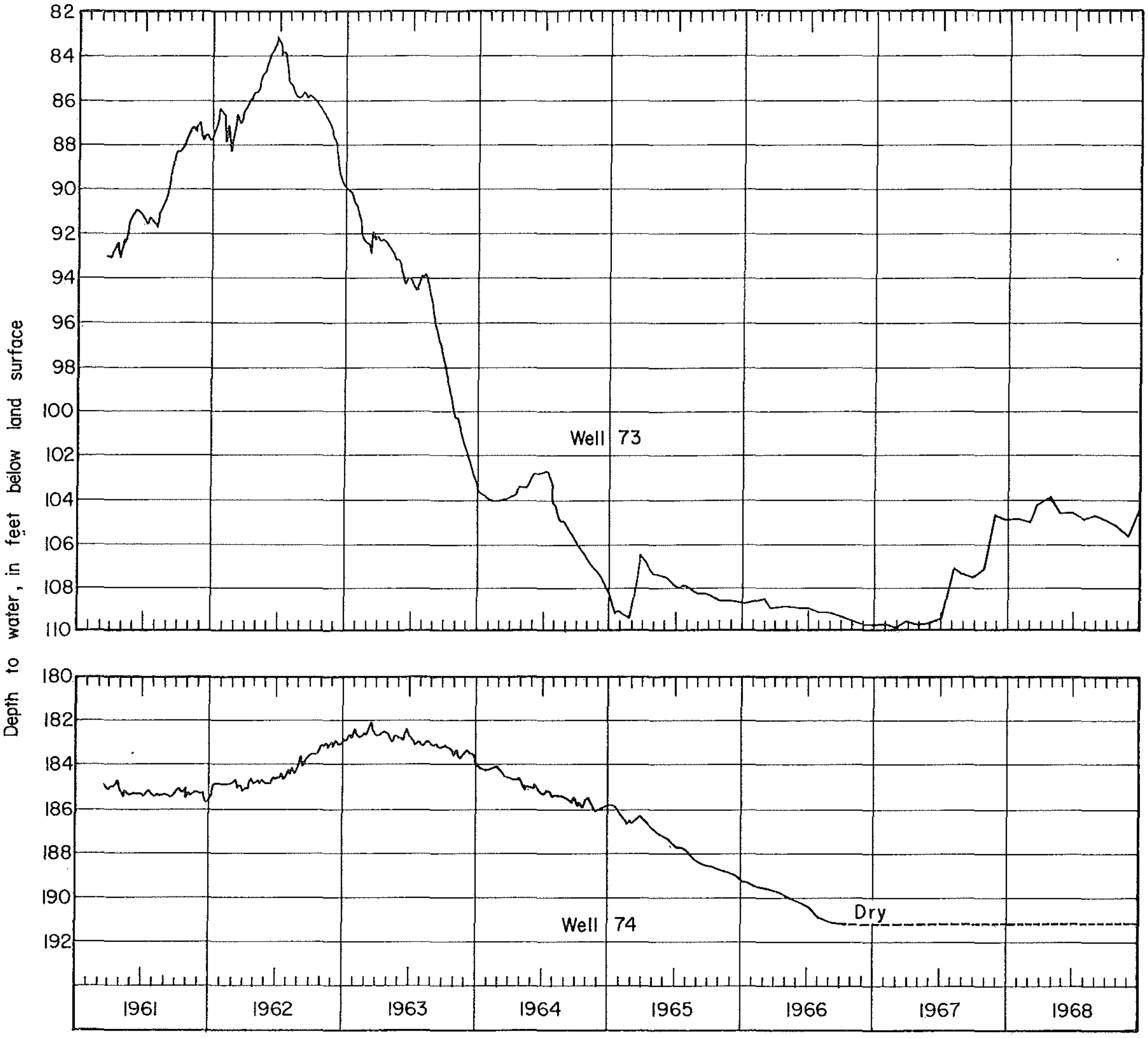


Fig. 41 Hydrographs of Wells 73 and 74, tapping perched water.

record but currently appear to be increasing because of higher tritium discharge concentrations. The low concentrations in Well 68 since 1962 are apparently due to water from the nearby nonradioactive waste pond (440 feet away).

The tritium concentrations in the water from five wells east and southeast of the radioactive ponds fluctuate considerably (Figure 42), showing more correlation to pond discharge than do concentrations at wells located at a similar distance in other directions from the pond. Data from the tritium graphs for Wells 60, 62, and 70 were used to compute approximate travel times of water from the radioactive-waste ponds to the wells. The graphs suggest that it took about four months for water to travel the 560 feet from the ponds to Well 60. The approximate rate of travel was 4.7 feet per day. The time required to

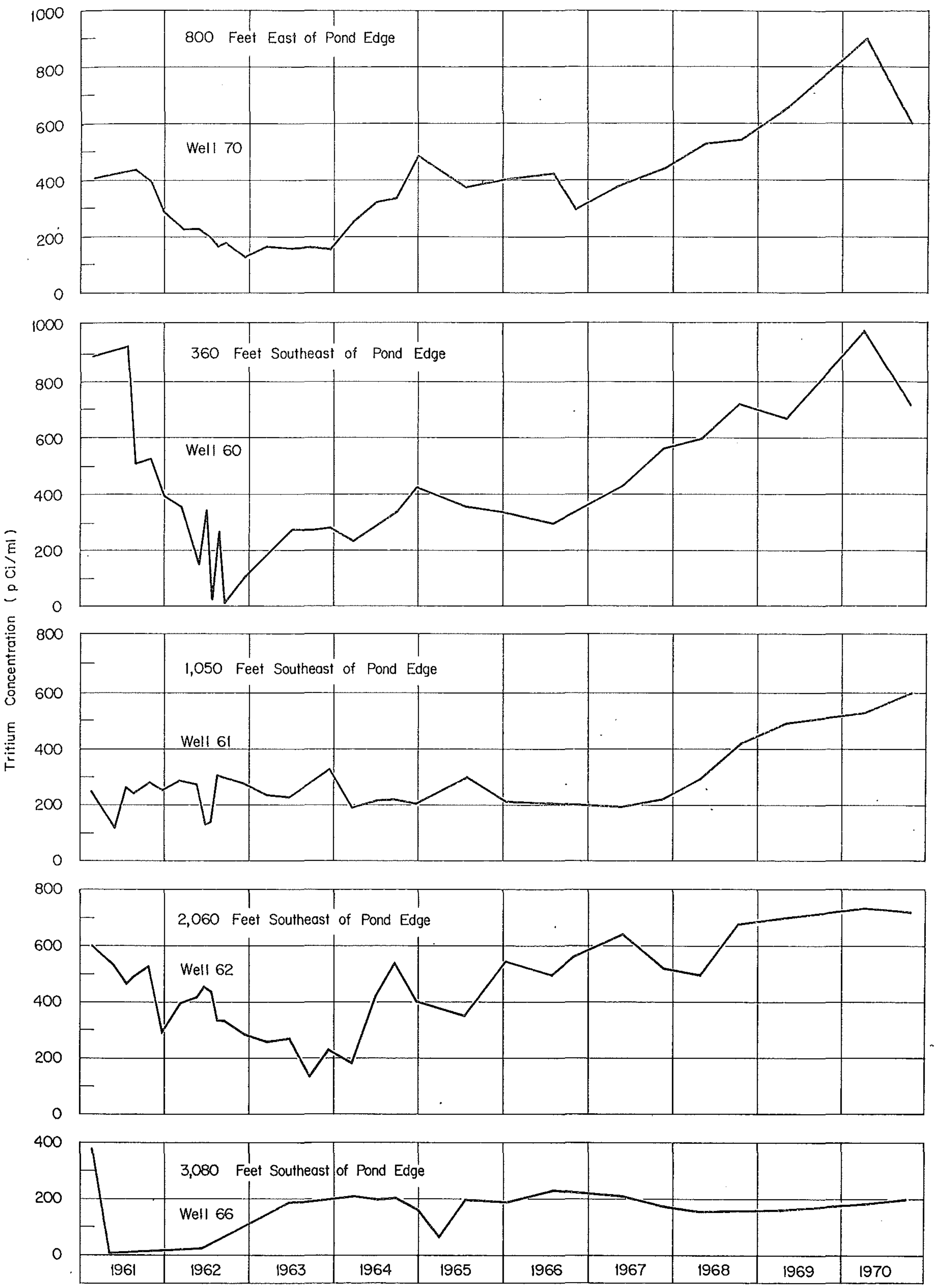


Fig. 42 Graphs showing tritium concentrations of water from Wells 70, 60, 61, 62, and 66, tapping perched water.

travel the 800 feet to Well 70 was 10 months which gives an apparent rate of 2.7 feet per day. The time required for water to travel the 2,060 feet from the pond to Well 62 was 15.5 months. The apparent velocity was 4.4 feet per day. Since the slightly preferred direction of movement in the perched-water body appears to be the southeast (Figure 43), these travel times are probably near maximum. These rates compare with rates of flow of about 2 to 10 feet per day that Morris (1967, p. 139) determined in the TRA. The tritium concentrations for Wells 70, 60, 61, and 62 have increased during the past three years (Figure 42). It is inferred that this is a result of increased tritium discharged to the TRA ponds since 1966. In 1970, the water in Well 60 had a tritium concentration of 970 pCi/ml and the water in Well 70 had a tritium concentration of 900 pCi/ml. These are the highest values measured since 1961. The tritium concentration in water from Wells 61 and 62 was in the 600 to 700 pCi/ml range in 1970. These values are also the highest of record. The tritium content of water from Well 66 has not changed much in the last five years.

The earliest data available on the tritium content of the perched water in the basalt is February 1961 [Figure 43(a)]. The concentration of tritium was highest near the 1952-57 pond and diminished radially outward. The map indicates outward radial movement of the water except for a preferred southeast direction of groundwater movement around Well 62. All the tritium waste was being discharged to the 1952-57 pond in 1961. The tritium decreases by a factor of 10 from the highest concentration outward to the line representing 100 pCi/ml. The explanation for this anomalous decrease in tritium concentration outward from the pond is not clear. Some of the decrease could be caused by dilution and radioactive decay. Dilution from other pond wastes, from older water from the radioactive-waste ponds which had a lower tritium concentration, from infiltrating precipitation, and recharge from the Big Lost River is believed to have the biggest influence on the tritium concentration in the perched water. If the average input tritium concentration were 1,000 pCi/ml, radioactive decay would reduce this concentration to about 890 pCi/ml in two years and to about 800 pCi/ml in four years. Therefore, radioactive decay accounts for a small part of the reduced concentrations of tritium in the perched water. Part of the outward decrease might be explained by the hydrodynamics of the system. The water around the outer edge of the perched zone may simply be older water which is not being replaced by fresher discharges. The fresh waste water may be percolating downward in the central part of the perched zone before it can move laterally outward. This phenomenon would allow the old water around the edge to decay to its present concentration.

A considerable change in the tritium content in the perched water in the basalt took place from February 1961 to May 1962 [Figure 43(a), (b)]. The 1962 tritium content of perched water near the pond declined to about one-third of the 1961 value. The highest tritium value was over 400 pCi/ml for water from Well 62 and the lowest was 15 pCi/ml for water from Well 60. In 1961, water from Well 60 had a tritium concentration greater than 900 pCi/ml. The comparison of contours on Figures 43(a) and 43(b) shows that significant

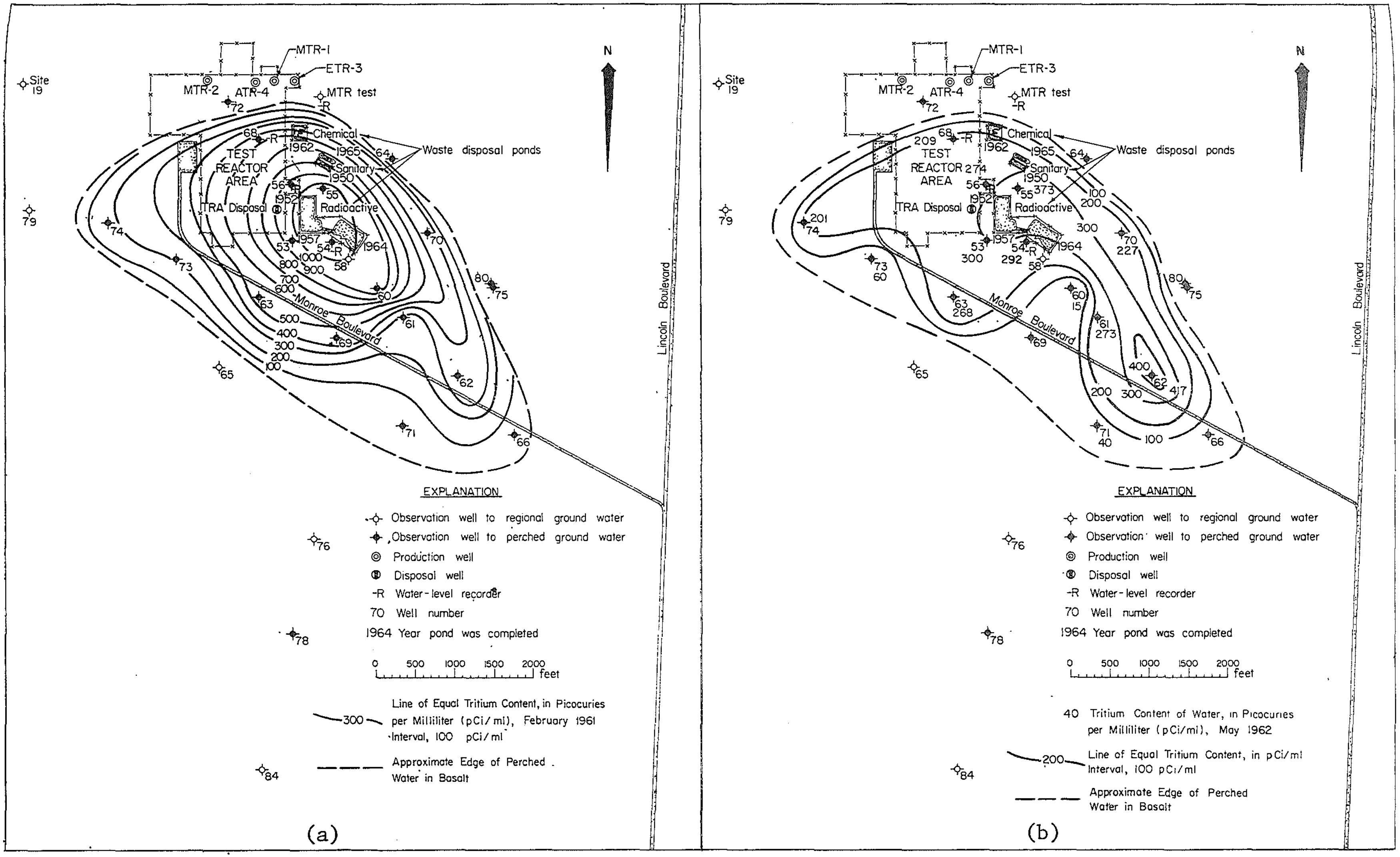


Fig. 43 Maps of the Test Reactor Area (TRA) showing the tritium content in the perched groundwater in the basalt, February 1961 (a), May 1962 (b), November 1966 (c), and April 1970 (d).

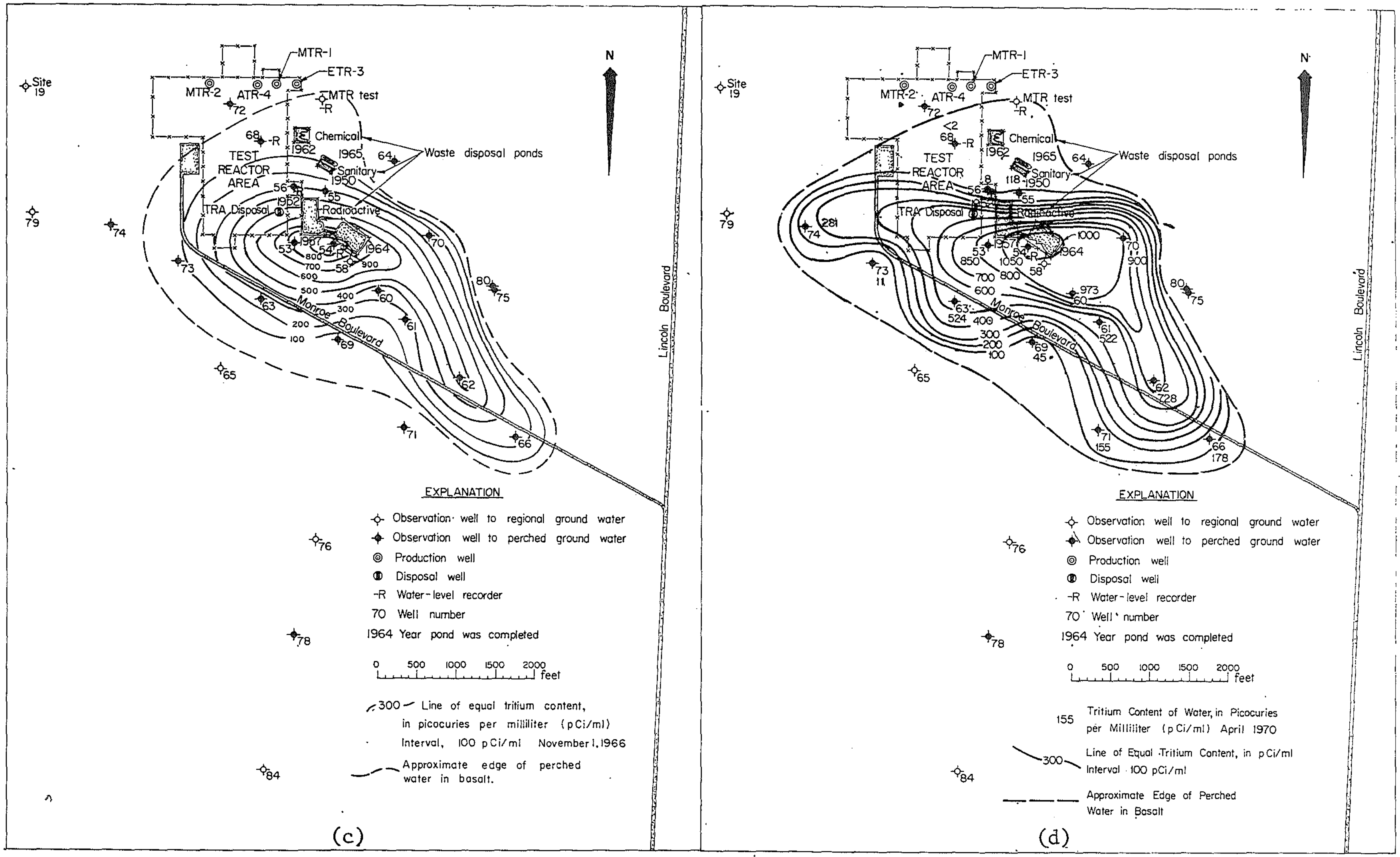


Fig. 43 Maps of the Test Reactor Area (TRA) showing the tritium content in the perched groundwater in the basalt, February 1961 (a), May 1962 (b), November 1966 (c), and April 1970 (d).

changes in the tritium concentration of perched water can take place within 15 months. The tritiated water can move a distance of one-half mile in this interval or an average rate of about 5.5 feet per day outward from the pond.

Data for November 1966 [Figure 43(c)] indicate that the concentration of tritium is highest just south of the radioactive-waste disposal ponds and diminishes outward. The map suggests a preferred southeast direction of movement for some of the water. The permeability may be greatest in that direction. The tritium concentrations in the perched water range from about 10 to almost 1,000 pCi/ml. Water from Well 54 contained 969 pCi/ml, the highest concentration, and water from Well 68 contained 11 pCi/ml, the lowest concentration. Well 54 is only 50 feet south of the edge of the radioactive-waste pond. Water in Well 68 is derived from both radioactive- and nonradioactive-waste ponds. The concentration lines on Figure 43(c) are similar to those on Figure 43(b). The biggest change occurs near the chemical waste disposal pond which was used after November 1962. The water discharged to the chemical waste pond contains relatively little tritium so the lowered tritium content of water near the pond is a result of flushing of tritiated water. The reduced tritium content extends southward to the 1952-57 pond. Another change is a result of the use of the 1964 pond for waste discharge. This change appears to shift the tritium contours of the perched water toward the east.

The tritium content of the perched water in the basalt for April 1970 [Figure 43(d)] generally is similar to the earlier years. The effects of disposal to the chemical waste disposal pond can be seen in the zone of low tritium content in the upper part of the map. The highest tritium content was in water from Well 54, with 1,050 pCi/ml, and the lowest was in water from Well 68, with less than 2 pCi/ml.

The rather rapid changes that may occur in the tritium concentration illustrated the dynamic nature of the perched water in the basalt. The waste water is continuously moving downward and outward from the pond. The input rate is approximately balanced by the percolation rate through the bottom of the perching layers of fine-grained sediments. In other words, the perched water body has spread outward until the quantity of water being discharged to the ponds (minus evaporation) is equaled by the quantity water leaking downward through the perching beds. This water then moves downward toward the Snake River Plain aquifer through 250 feet of unsaturated basalts and sediments. Little quantitative information is known on the behavior of the waste water in this zone. After entering the Snake River Plain aquifer, the waste water flows southwestward with the aquifer water.

In addition to the detailed studies of tritium concentration and movement in the perched water, the occurrence of strontium-90 (Sr-90), cobalt-60 (Co-60), cesium-137 (Cs-137), and gamma activity in the perched water was also investigated. Tritium is the only waste radionuclide that can be detected in the Snake River Plain aquifer beneath the TRA ponds (see Figure 71). Knowledge of the movement and concentrations of waste radionuclides in the perched water is important to evaluate the effects of pond disposal.

1.35 Strontium-90. Generally, the Sr-90 content in the perched water is above the detection limit only near the pond. The concentration of Sr-90 was determined for 10 perched-water samples and eight regional water samples at the TRA on November 1, 1966. The concentration of Sr-90 at TRA was less than 0.003 pCi/ml in water from eight deep wells (tapping the Snake River Plain aquifer) and from six of the shallow wells (tapping the perched water in the basalt). On November 1, 1966, concentration of Sr-90 was above the detection limit in water from only four wells that tap perched water. Water from Well 53 contained 0.088 pCi/ml; Well 56 contained 0.056 pCi/ml; Well 54 contained 0.021; and Well 70 contained 0.006 pCi/ml. Three of these wells are within 200 feet of the TRA radioactive-waste disposal pond, and Well 70 is 800 feet from the pond edge.

Sr-90 was detected in 5 out of 15 wells in the perched water near the radioactive-waste disposal pond in October 1970, as shown in Figure 44. Samples from nine wells in the Snake River Plain aquifer beneath the perched water failed to show any Sr-90. Water from Well 53 contained 0.12 pCi/ml; Well 54 contained 0.024 pCi/ml; Well 56 contained 0.012 pCi/ml; and Well 70 contained 0.012 pCi/ml. The detection limit was 0.004 pCi/ml.

The areal extent of the perched water in the basalt where Sr-90 is above the detection limit has not increased much from 1966 to 1970. However, the concentration of Sr-90 has increased considerably. The increased concentrations are attributed to the increased Sr-90 discharged since 1966, and to saturation by Sr-90 of ion-exchange (or adsorption) sites (B. L. Schmalz, 1972). The outward movement of Sr-90 in the perched water is expected to progress in the future as the cation-exchange capacity (2 to 4 meq/100g) of the central part of the sediments is exhausted. The detectable presence of Sr-90 in the Snake River Plain aquifer below the TRA ponds is not expected in the near future because of the ion-exchange capacity (perhaps 10 to 15 meq/100g) of the sediments within the basalt below the perched water and because of the large area of the perched water and small quantities of water percolating downward which would greatly dilute the Sr-90 even if it could penetrate the sediments.

1.36 Cesium-137. Cs-137 has not been detected in any sample from the perched water in the basalt. A complete set of perched water samples collected in September 1969 shows the Cs-137 concentration to be less than 0.1 pCi/ml. The approximate average discharge concentration of Cs-137 in TRA pond water is about 10 pCi/ml. Apparently the Cs-137 is exchanged on the alluvial sediments directly beneath the TRA ponds and sediments within the basalt which contain considerable quantities of silts and clays (illite, montmorillonite, and kaolinite) (B. L. Schmalz, 1972).

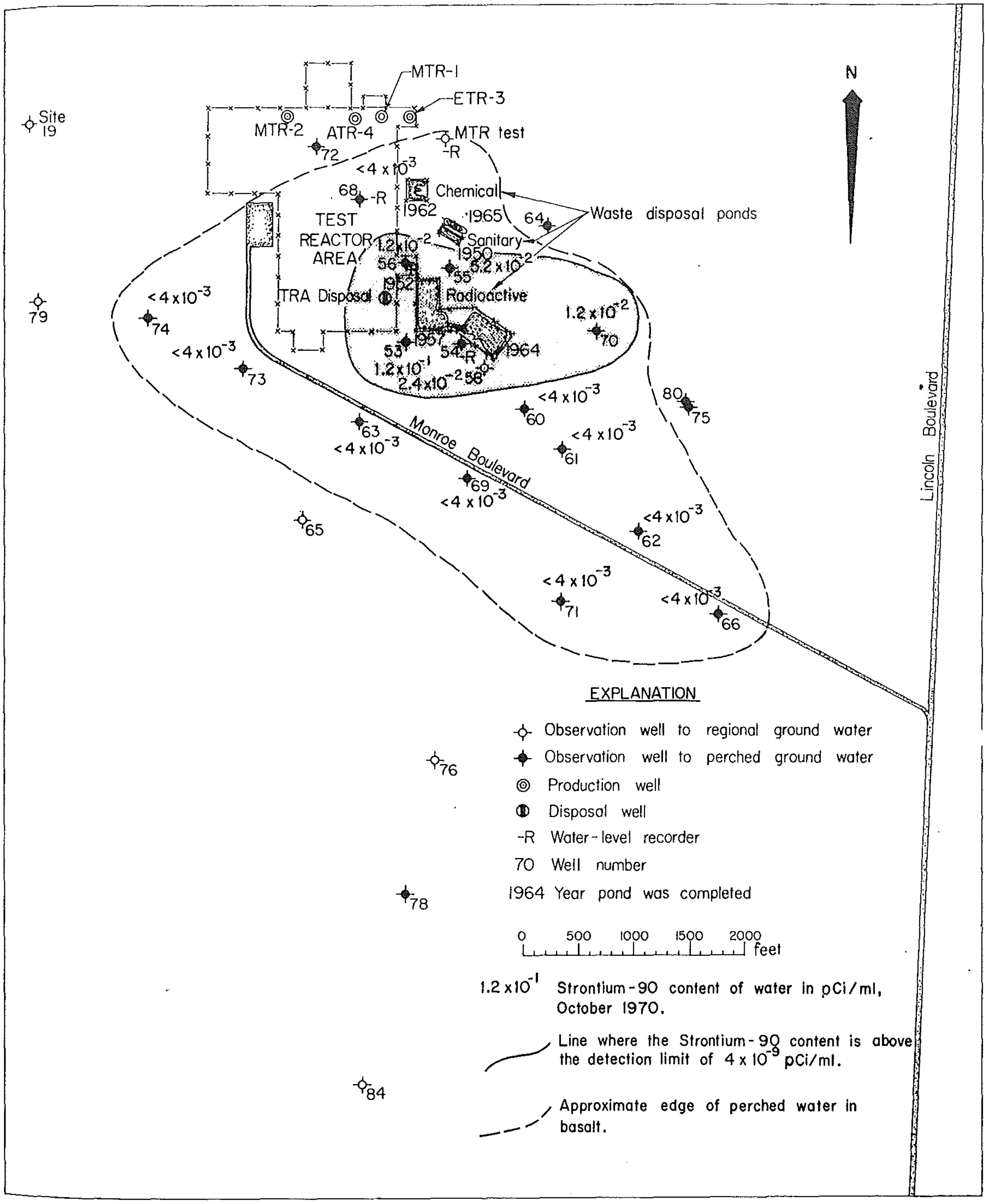


Fig. 44 Map of the Test Reactor Area showing the strontium-90 content in the perched groundwater in the basalt, October 1970.

1.37 Cobalt-60. The average concentration of Co-60 in the pond water was about 30 pCi/ml from 1962-70. Of 15 perched-water wells sampled in October 1970 seven samples contained Co-60 in quantities greater than the detection limit of 1.4 pCi/ml (Figure 45). The Co-60 content of the seven samples ranged from 4 to 16 pCi/ml and averaged 7.7 pCi/ml. The area where the perched water contains detectable Co-60 is located near the radioactive waste ponds. All the perched wells within this area contain detectable Co-60 and all the outlying wells do not contain detectable amounts of Co-60. No detectable amounts of Co-60 were observed in water from wells that penetrate into the Snake River Plain aquifer. Waste Co-60 moved more than 2,000 feet from the ponds in the southeast direction by October 1970. The relatively high concentration of Co-60 in Well 54 (16 pCi/ml) is about one-half the average pond-water concentration of 30 pCi/ml. The chemical form of the cobalt in the waste streams has not been determined but it is either cationic or complexed. The complex form would not be highly subject to ion exchange if it were uncharged. Field and laboratory studies (B. L. Schmalz, 1972) have indicated that a considerable amount of waste Co-60 is adsorbed on the sediments beneath the TRA ponds. The possibility of significant concentrations of Co-60 in the Snake River Plain aquifer seems remote because of the fine-grained sediments available for sorption (or ion exchange), the relatively short half-life of Co-60 which would reduce the quantity considerably as the waste product migrated slowly downward toward the aquifer, and because of the large amount of dilution when small waste streams seep into the large quantities of water in the Snake River Plain aquifer.

1.38 Nonradioactive Wastes. The nonradioactive wastes of TRA consist mainly of mineralized water. In November 1966, the specific conductance of the perched water in the basalt at the TRA ranged from 158 to 3,310 μmhos per cm (micromhos per centimeter at 25°C) and averaged 895 μmhos. Well 68, near the chemical pond, has the highest value and Well 69 had the lowest value. Relatively little change in mineralization of the perched water at the TRA occurred in 1966. In October 1970, the specific conductance of the perched water in the basalt at the TRA ranged from 140 to 3,900 μmhos and averaged 910 μmhos (Figure 46). Well 68 had the highest value and Well 54 had the lowest value. The water is more mineralized to the north and west and less mineralized to the south and east. The mineralized water from the chemical-waste disposal pond is indicated on the figure.

The chloride content of water from wells that tap the perched water in the basalt near the TRA ranged from 6 to 179 mg/l in October 1970 (Figure 47). The water from Well 54 contained the least chloride and the water from Well 68 contained the most. Perched water with higher chloride concentration, which is derived from wastes from the chemical-waste disposal pond, occurred to the north and west. The perched water nearer the radioactive-waste disposal ponds generally contained less than 25 mg/l.

During July 1966, hexavalent chromium, Cr(VI), concentrations ranged from less than 0.005 to 1.71 mg/l in samples from nine wells that tap the perched water at the TRA. The highest chromium content was in water from Well 62 and the lowest was in water from Well

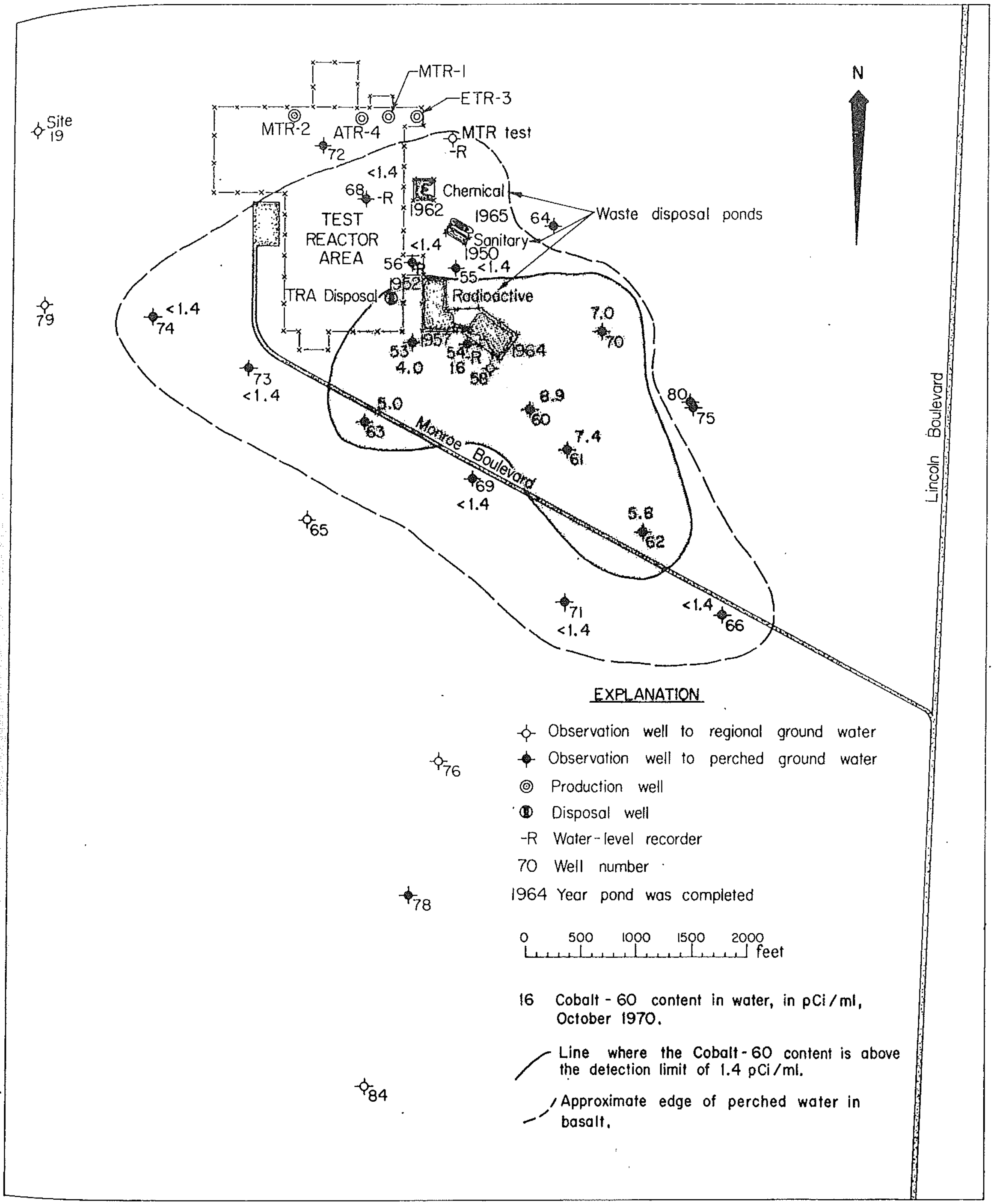


Fig. 45 Map of the Test Reactor Area showing the cobalt-60 content in the perched groundwater in the basalt, October 1970.

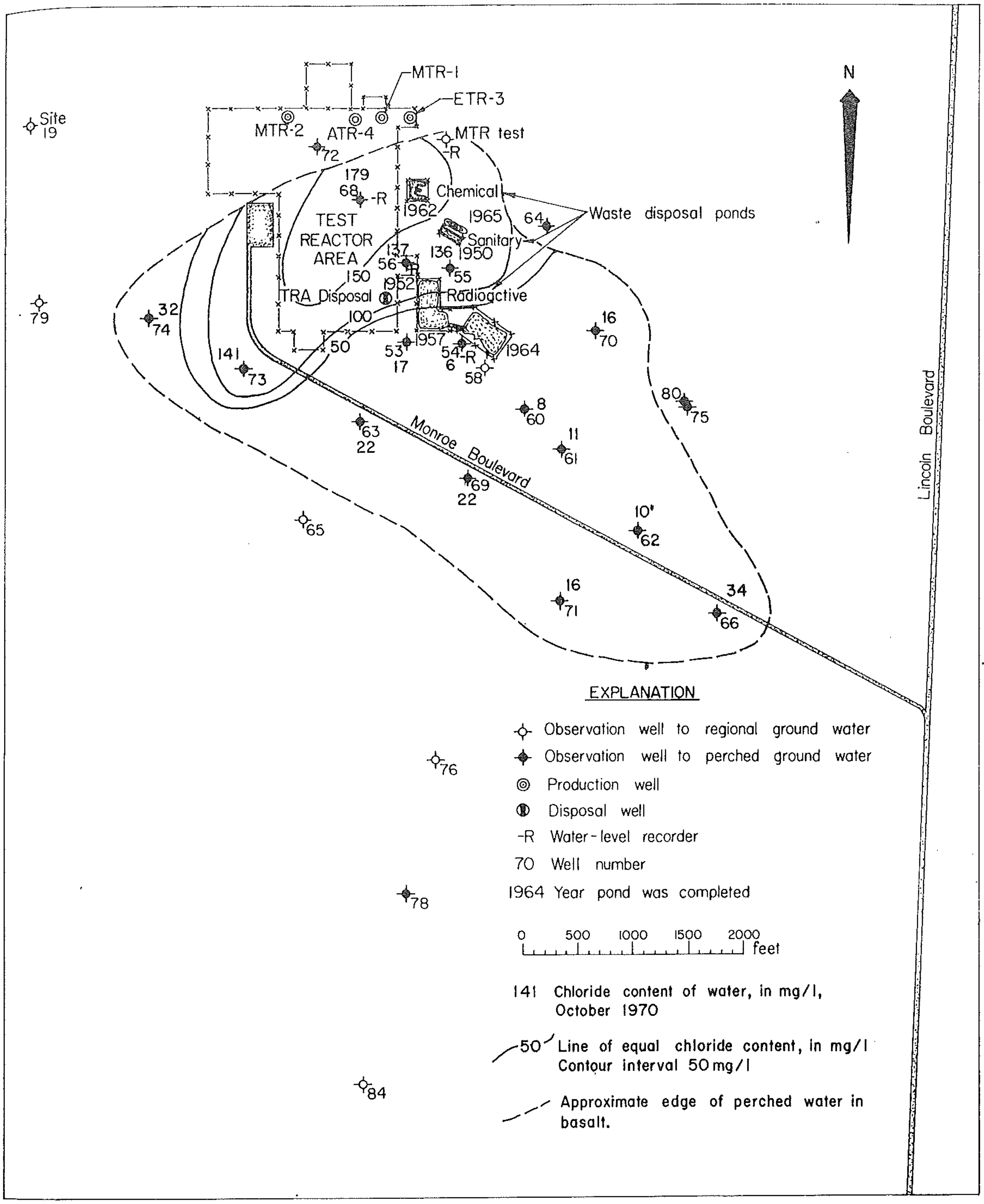


Fig. 47 Map of the Test Reactor Area showing the chloride content in the perched groundwater in the basalt, October 1970.

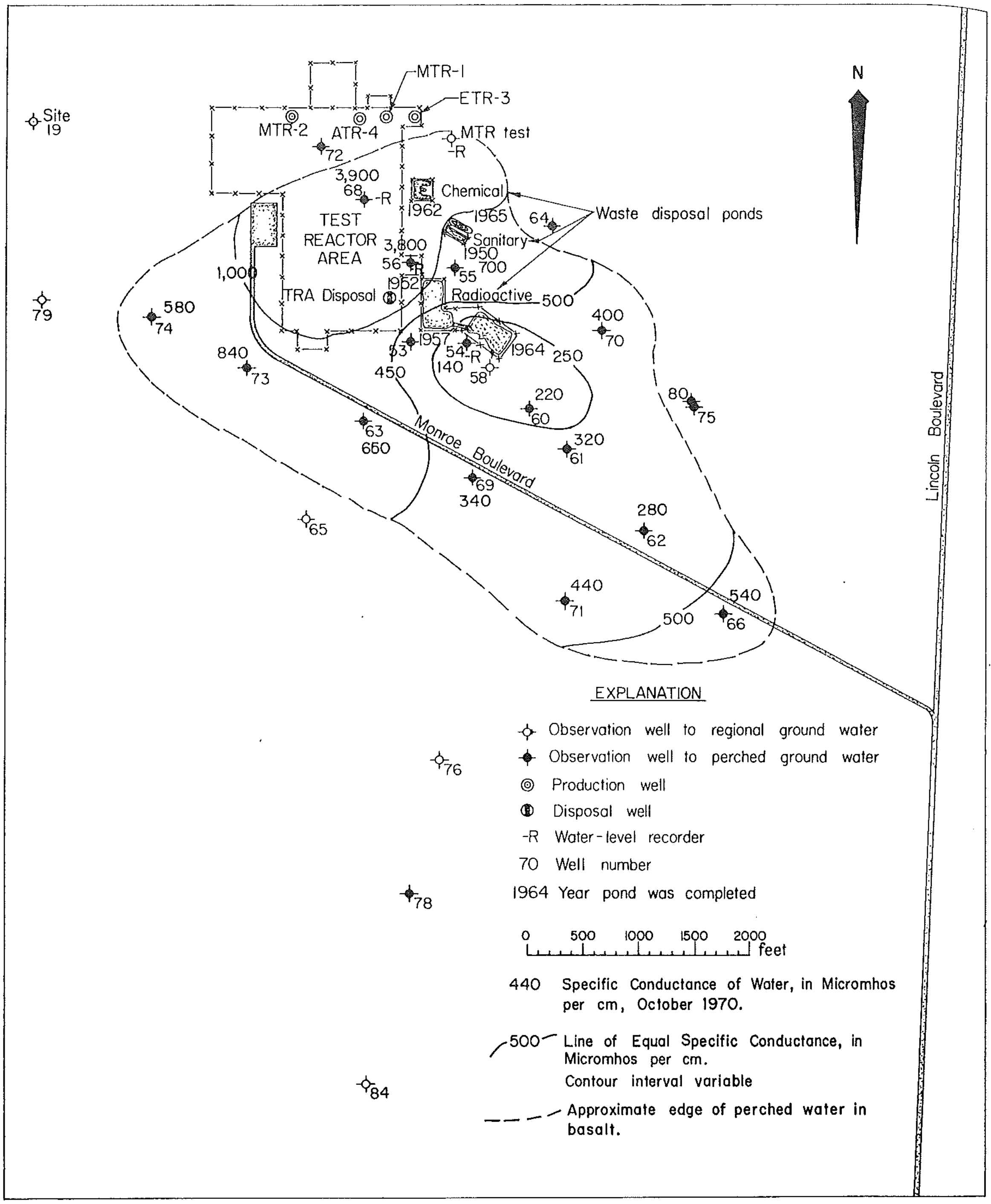


Fig. 46 Map of the Test Reactor Area showing the specific conductance of samples from the perched groundwater in the basalt, October 1970.

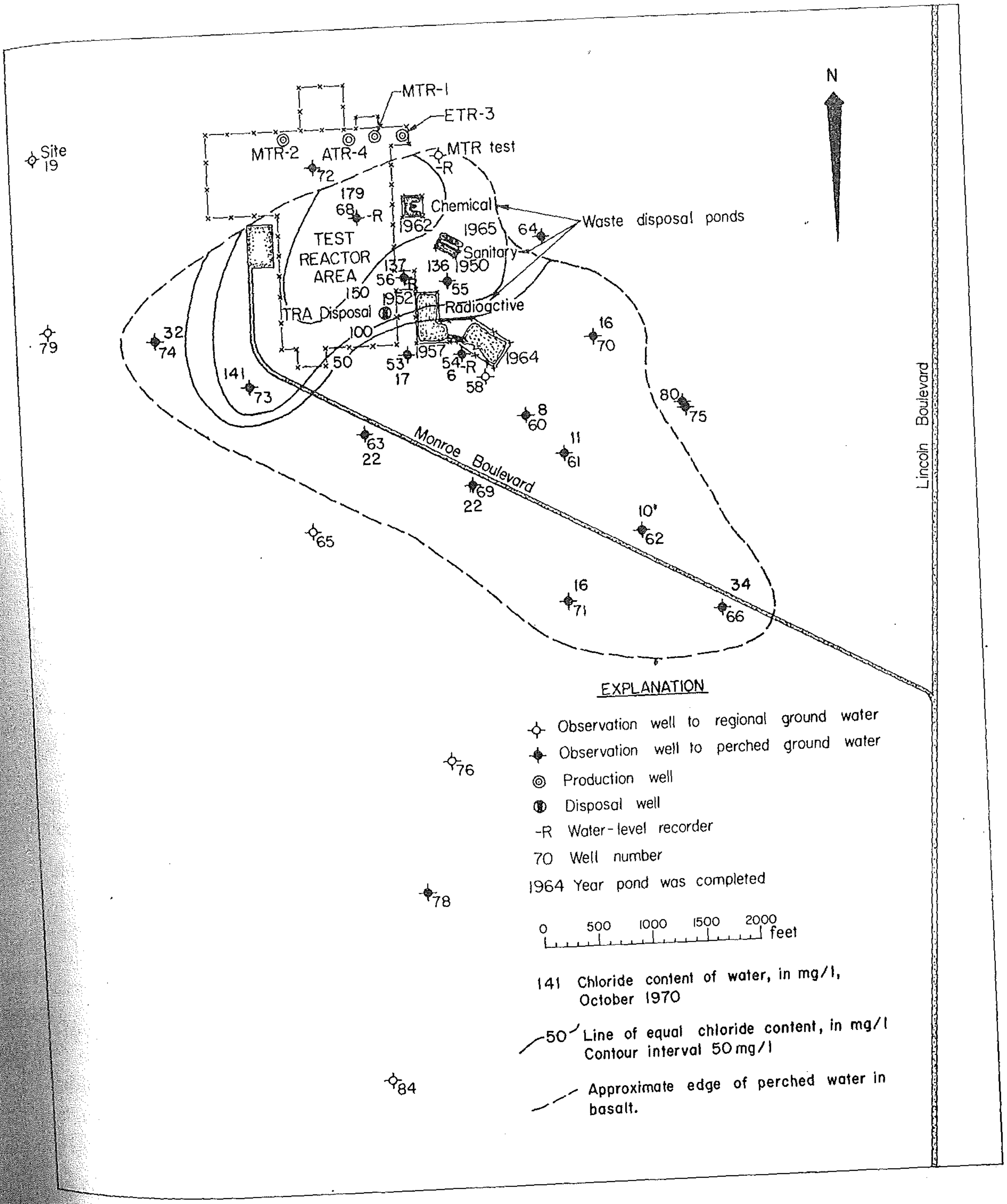


Fig. 47 Map of the Test Reactor Area showing the chloride content in the perched groundwater in the basalt, October 1970.

69. Cr(VI) was detected in every perched water well except Well 69. The complex distribution of Cr(VI) in the perched water in the basalt is poorly understood, partly because its discharge history is not known.

In October 1970, total chromium content ranged from 0.01 to 0.80 mg/l in 15 samples of the perched water in the basalt. The least chromium was in water from Well 66 and the most chromium was in water from Well 63. The average chromium content in the water samples was 0.30 mg/l. The concentration of total chromium was variable but all perched water samples contained detectable amounts of total chromium. Additional information is needed concerning current average input amounts of chromium to the TRA ponds before subsurface effects are adequately understood. Chromium discharge to the pond is not currently monitored and thus cannot be correlated quantitatively with subsurface effects.

2. ICPP LIQUID WASTE DISPOSAL

Since disposal operations began in 1952 at the ICPP, volume and characteristics of liquid wastes discharged to the subsurface have varied considerably. Continuous data on the complete waste composition of effluents are not available. For example, tritium, in the form of tritiated water, is the principal radioactive component in the ICPP waste, but was not discovered and monitored until 1961 (Barraclough, Teasdale, Robertson, and Jensen, 1967), although it had been a significant waste product since 1952. With these types of limitations, it is not possible to list a complete and accurate description of the quantities and characteristics of all ICPP waste products which have been discharged to the subsurface. However, in many cases where direct data are lacking, estimates based on indirect information will be presented. Most of the data have been collected and compiled by the AEC (for example, Osloond, 1970) and the Idaho Nuclear Corporation. Certain parts of the data were collected by the U. S. Geological Survey.

The general layout of the ICPP is shown in Figure 48. The map indicates locations of significant buildings and facilities, the disposal well, and the supply wells.

2.1 Volume and Radioactive Components

2.11 Sources of ICPP Radioactive Wastes. A proper understanding of ICPP waste products and their effects should include some understanding of the origin of the wastes. Nearly all of the radioactive wastes discharged down the ICPP well are fission and activation products originating from spent fuel elements which are processed in the plant. Additional, but minor, sources are the sink drains from the laboratories where various radioisotopes are used.

All the high-level radioactive liquid wastes are first concentrated by evaporation and stored for an interim period prior to solidification by calcination. The bulk of the low level

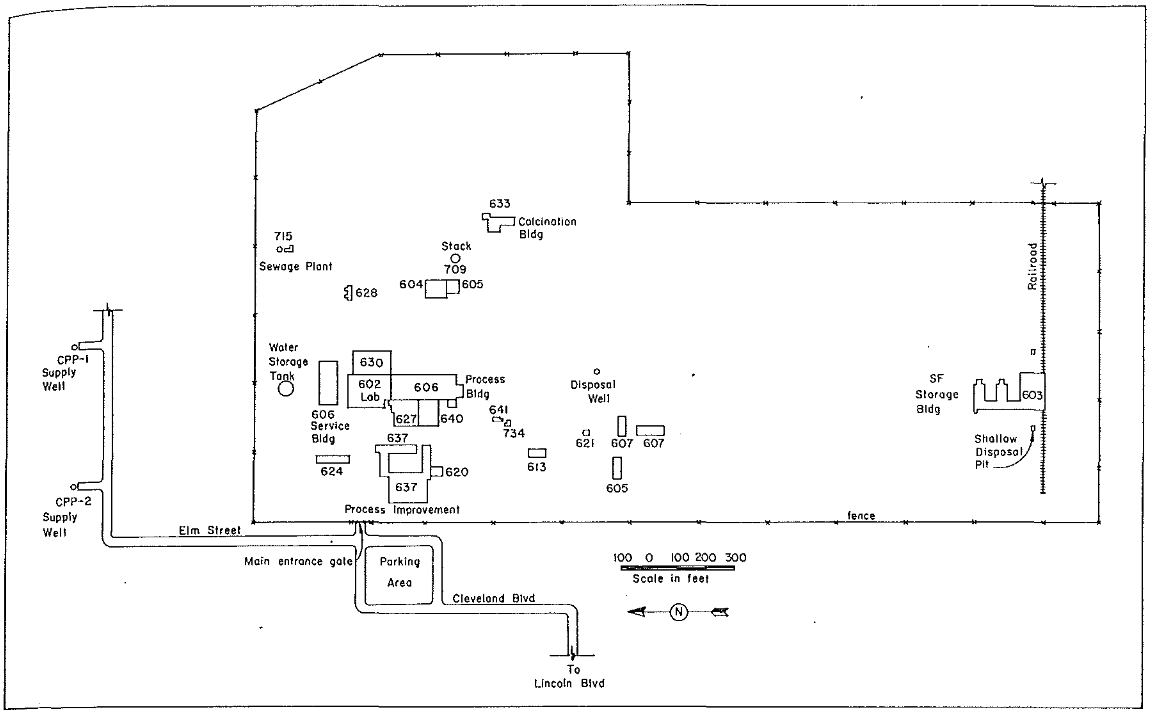


Fig. 48 Map showing principal features of the ICPP area.

activity that is discharged down the well is that which is carried over in the condensate from the boil-off treatment. Before it is discharged to the well, the effluent passes through an ion exchange system to remove most of the cationic radioisotopes. In other words, most of the low-level radioactive liquid wastes have been purified by distillation before discharge. Tritiated water behaves similar to normal water, so that the distillation process does little to reduce the tritium concentration. This explains one reason why tritium is the most abundant isotope in the waste.

Because of its relative abundance, some attention will be focused on tritium and its origins. In a nuclear reactor, tritium can be created by several processes (Jacobs, 1968). First, it can be formed as a ternary fission product within the reactor fuel. According to Jacobs (1968), fission accounts for most of the tritium produced in light-water cooled reactors. Second, tritium can be produced by neutron irradiation of other elements, especially deuterium (H-2), lithium, boron, and nitrogen. Of the neutron irradiation reactions, the first two reactions are the most important. Lithium was a primary source of tritium when it was used as a brazing flux in the fuel-element cladding. However, this use has apparently been discontinued. The formation of tritium from deuterium is more significant in heavy-water cooled reactors (not used at the NRTS). In light-water reactors, such as those at the NRTS, the natural abundance of deuterium is about 0.015% (Jacobs, 1968). However, deuterium can be produced from protium (ordinary H-1) by neutron capture. This reaction can cause a significant increase in the deuterium in the cooling water of light-water reactors which in turn leads to more tritium production in the cooling water.

At the present time, most of the waste tritium produced at the ICPP is apparently of fission-product origin; however, before 1962 the neutron-gamma reaction with lithium-6 in the old-style fuel elements was probably the most important source. That is one reason why more waste tritium was produced in those earlier years (see Figure 50).

2.12 Quantities. Table IX summaries the available records on the volumes and radioactive composition of the liquid wastes discharged to the ICPP disposal well and pit. Most of the data are based on the analysis of monthly composite samples of the effluents. A quantitative appraisal of the accuracy and completeness of the data is not possible. Especially in the earlier years, the limited analytical techniques undoubtedly failed to detect activity of some low-energy beta emitters such as tritium. It is fairly certain that relatively large, but undetected, quantities of tritium were carried in the effluents from 1953 to December 1961 (Barraclough, Teasdale, Robertson, and Jensen, 1967).

The post-1961 data appear more complete and accurate than the earlier data in the table. Also, a number of changes have occurred over the years in the materials and processes which produce the wastes and the techniques by which the wastes are handled; the post-1961 data are therefore considered more representative of the modern ICPP waste disposal situation than is the total record from 1952.

As indicated by Table IX, a total of 5.4 x 10^9 gallons of liquid waste have been discharged to the well and 4.8 x 10^7 gallons to the covered pit, or a combined total of more than 5.4 x 10^9 gallons discharged to the subsurface in 18 years. This is an average of about 300 million gallons per year for the 18 years, or nearly 1 million gallons per day. This discharge has carried a reported total of 6,756 Ci of $\beta+\gamma$ radioactivity into the ground (plus a reported trace of α activity). The average for 18 years comes to 375 Ci per year or slightly more than 1 Ci per day. Since 1961, the discharge of radioactivity has averaged about 600 Ci per year (almost 2 Ci/day), due primarily to the inclusion of tritium into the monitored isotopes. The average concentration of radioactivity in waste water has been 330 pCi/ml for the period of record. The post-1961 data indicate an average of 540 pCi/ml, again reflecting the contribution of tritium. Figure 49 shows graphically the yearly total of volume discharged and beta-gamma activity for the period of record. Note the total activity discharged has been declining since 1967.

The data in the table indicate that tritium, at least since 1961, has been the principal component of the radioactive waste. Of the 6,756 Ci reported as the total $\beta+\gamma$ discharge, 5,690 Ci, or 84.4%, have been tritium. Since December 1961, tritium has composed 95.5% of the monitored radioactivity in the waste. Although the waste monitoring techniques were not capable of detecting tritium before 1961, it is assumed that the relative levels of tritium

TABLE IX

SUMMARY OF REPORTED DATA ON THE VOLUME AND RADIOACTIVE CHARACTERISTICS OF LIQUID WASTES DISCHARGED TO THE ICPP DISPOSAL WELL AND PIT; DATA FROM AEC REPORTS (Osloond, 1965, 1967, and 1970; Osloond and Newcomb, 1968 and 1969; Osloond and Schmalz, 1966; Horan and others, 1962 and 1963) AND AEC FILES

Year	Effluent volume in millions of gallons		Total β+γ activity reported in curies		Total reported activity (Well+Pit) Curies	Measured or Computed Radioisotopic content, in curies (half-lives in parentheses)									Average concentration of reported activity pci/ml	
						H^3	Sr^{89}	Sr^{90}	$Zr^{95}-Nb^{95}$	$Rh^{106}-Ru^{106}$	I^{131}	Cs^{137}	Ce^{144}	Other or unidentified		
	Well	Pit	Well	Pit		(12.3 yrs)	(50.8 days)	(28.9 yrs)	(65 days)	(368 days)	(8.06 days)	(30 yrs)	(284 days)	Isotopes	H^3	Total β+γ
1952	?	?	In-sig.	In-sig.	Insig.											
1953	396		15		15									15		10
1954	229	5	8	2	10				1.8				0.5	7.8		11
1955	396	5	15	5	20				4					16		13
1956	351	6	22	5	27				5.6					21.6		20
1957	231	5	285	5	289				6		273			9.9		323
1958	273	7	339	5	344		2.7	1.9	19.4	3.5	251	3.5	48	13.7		324
1959	328	8	47	13	59			2.5	7.4	6.1	15.7		21.6	5.9		46
1960	190	2	32	4	36		0.7	1.1		4.0	16.6	1.4	4.0	7.9		50
1961	188		624		624	590**	2.2	0.3	1.2	3.4	18.1	0.5	4.5	3.5	6000**	876
1962	262	4.8	176	244	420	340	2.3	23.2	1	0.5	24	20.5	0.7	8	342	423
1963	257	2.5	1025	86	1111	1080		10.0	0.7	0.2	0.4	13.4	0.3	2.2	1100	1130
1964	344	1.3	1720	73	1793	1769		1.2	8.5	1.0		2.5	6.3	1.1	1340	1360
1965	416	0.7	78	38	116	96		2.8		0.5	0.8	2.0	8.0	2.5	61	73
1966	364	0.5	249	16	265	250		1.6	4.3	1.0	2.3	1.9	0.6	3.0	181	192
1967	301		865		865	857		1.6		0.2	1.0	0.6		5.5	752	758
1968	271		517		517	510		1.1	1.2	0.5		0.6	0.5	2.7	497	502
1969	328		164		164	124		5.1	0.7	1.9		4.4	0.5	26.8	100	130
1970	278		81		81	75		0.5				1.2	0.4	3.2	72	73
Totals	5403	48	6261	495	6756	5690	8	53	62	23	603	52	96	156		
Percent of Total	99.1	0.9	92.6	7.4	100	84.2***	0.12	0.78	0.93	0.34	9.0	0.76	1.4	2.3	95.5	100
Yearly Average	300	3.9	348	41	375	569	0.47	2.9	3.6	1.3	35.5	2.9	5.4	8.7	526	Total record: 326 Post'61 record: 540

* It is estimated that tritium releases from 1952 to 1961 were between 10,000 and 20,000 Ci. Robertson used a value of 16,000 (Barraclough and others, 1967) and Hawkins and Schmalz (1965) used a value of 11,000 Ci to 12,000 Ci.

** December only.

*** This percentage becomes 95.5 when only the post-1961 records are considered.

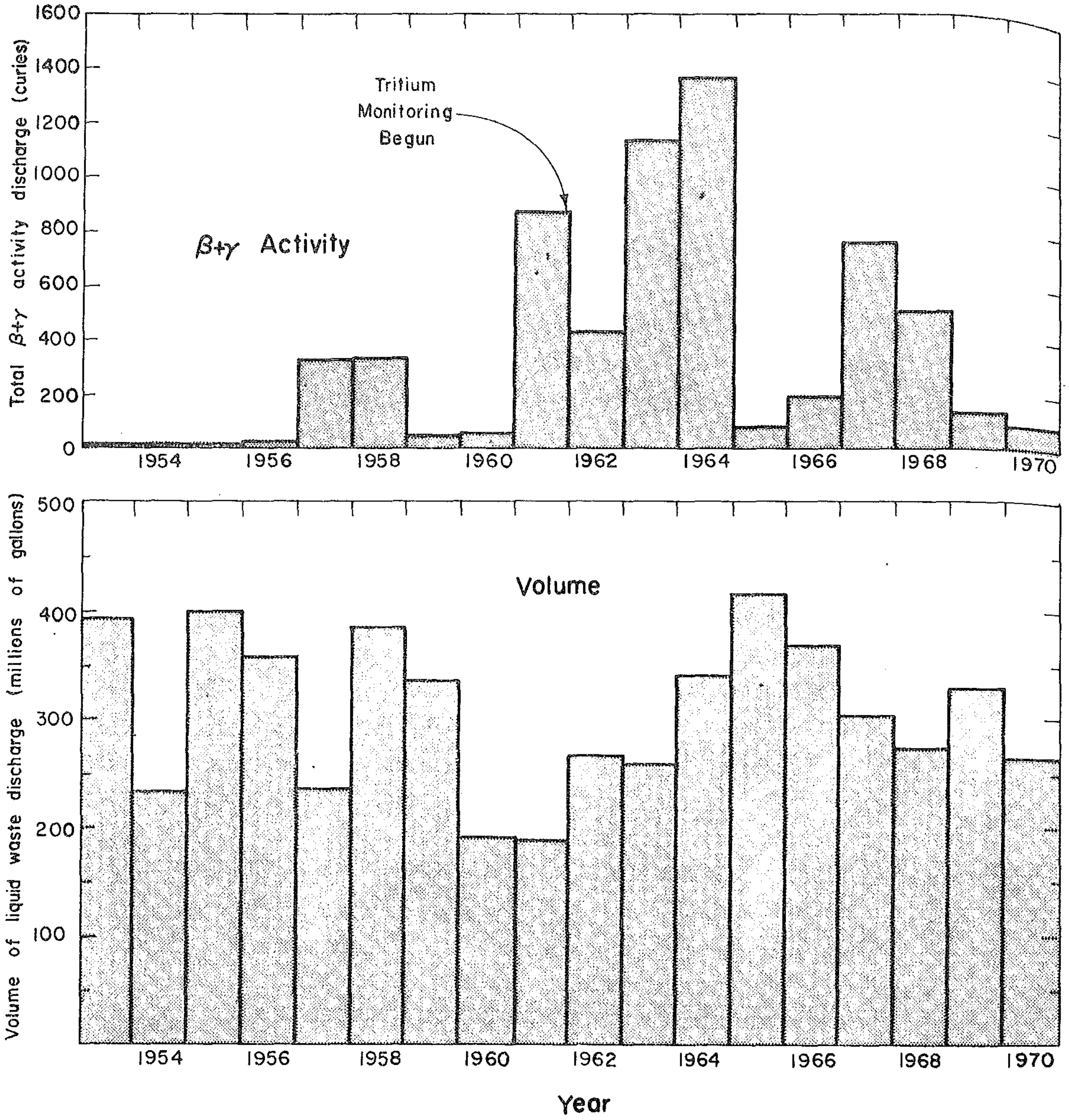


Fig. 49 Graphs showing yearly volumes and $\beta+\gamma$ radioactivity of the ICPP liquid wastes discharged to the subsurface.

in pre-1961 waste were similar to those observed since 1961. There is little reason to believe otherwise. It has been estimated that 10,000 to 20,000 Ci of tritium were discharged at the ICPP between 1952 and December 1961 (Barraclough, Teasdale, Robertson, and Jensen, 1967; Hawkins and Schmalz. 1965). This, of course, would have been in addition to the 5,690 Ci measured since then. If the figure from Barraclough, Teasdale, Robertson, and Jensen (1967) of 16,000 Ci (pre-1961) is used, then a total of approximately 22,000 Ci of tritium have been disposed. Radioactive decay would have reduced this amount to about 14,000 Ci at the present (tritium half-life = 12.3 years). Figure 50 shows monthly discharges

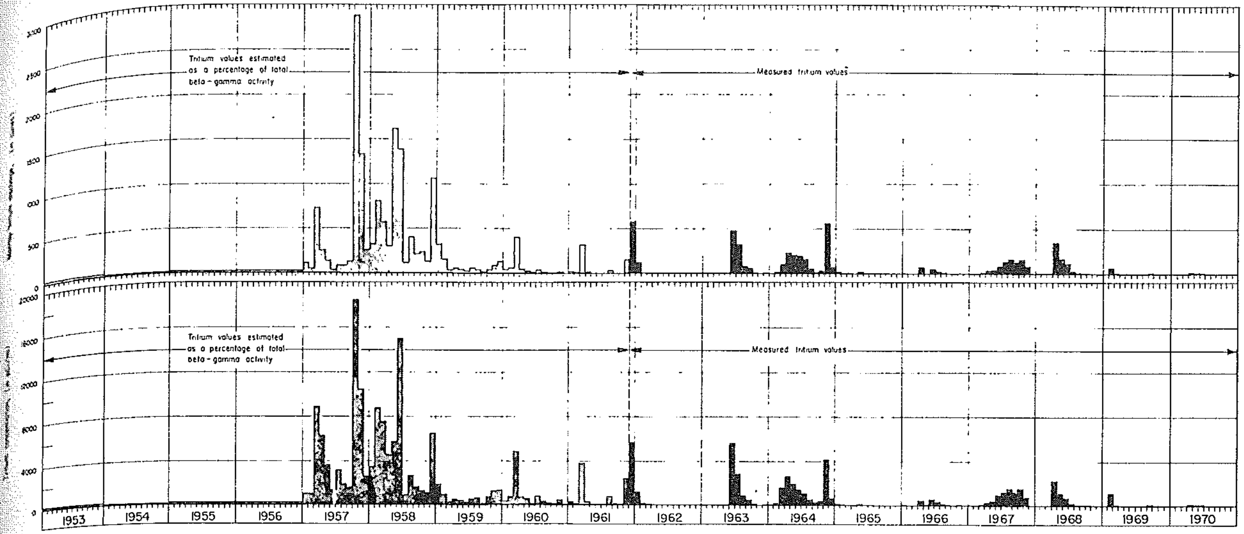


Fig. 50 Graph showing monthly quantities of tritiated water discharged by the ICPP to the subsurface.

of tritium over the period of record, including the pre-1961 estimates of Barraclough, Teasdale, Robertson, and Jensen (1967). Figure 51 shows a cumulative graph of tritium discharged using the same pre-1961 estimates, with decay losses deducted. The 14,000 Ci total agrees reasonably well with the amount of waste tritium that appears to be present in the ground water, according to an estimated materials balance on tritium (Barraclough, Teasdale, Robertson, and Jensen, 1967). The behavior and distribution of tritium and other waste products in the groundwater is discussed in detail in the next section of this report.

Perhaps the next most significant radioactive components of the waste are Sr-90 and Cs-137, because of their longer half-lives and low biological tolerances. Although other isotopes have been discharged in larger quantities (such as H-3, I-131, and Ce-144) their relatively short half-lives or low energy reduce their long-term significance.

Table IX lists a total of 53 Ci of Sr-90 disposed at the ICPP. Of this total, 33 Ci were discharged to the shallow pit in 1962 and 1963. Similarly, 34 Ci out of the total 52 Ci of Cs-137 were discharged to the pit during the same two years. In order for any of these isotopes to reach the regional water table, they would have to be carried downward by percolating water through about 425 feet of basalt and interbedded sediments. This provides an opportunity for some of the Sr-90 and Cs-137 cations to be adsorbed or exchanged on the sedimentary material. It is therefore unlikely that significant portions of the Sr-90 and Cs-137 would migrate to the regional groundwater. Some laboratory and field studies have been made on the adsorption of these isotopes by ICPP sediments (Hawkins and Short, 1965; Morris and others, 1964; W. L. Polzer, written communication, 1971). Data from

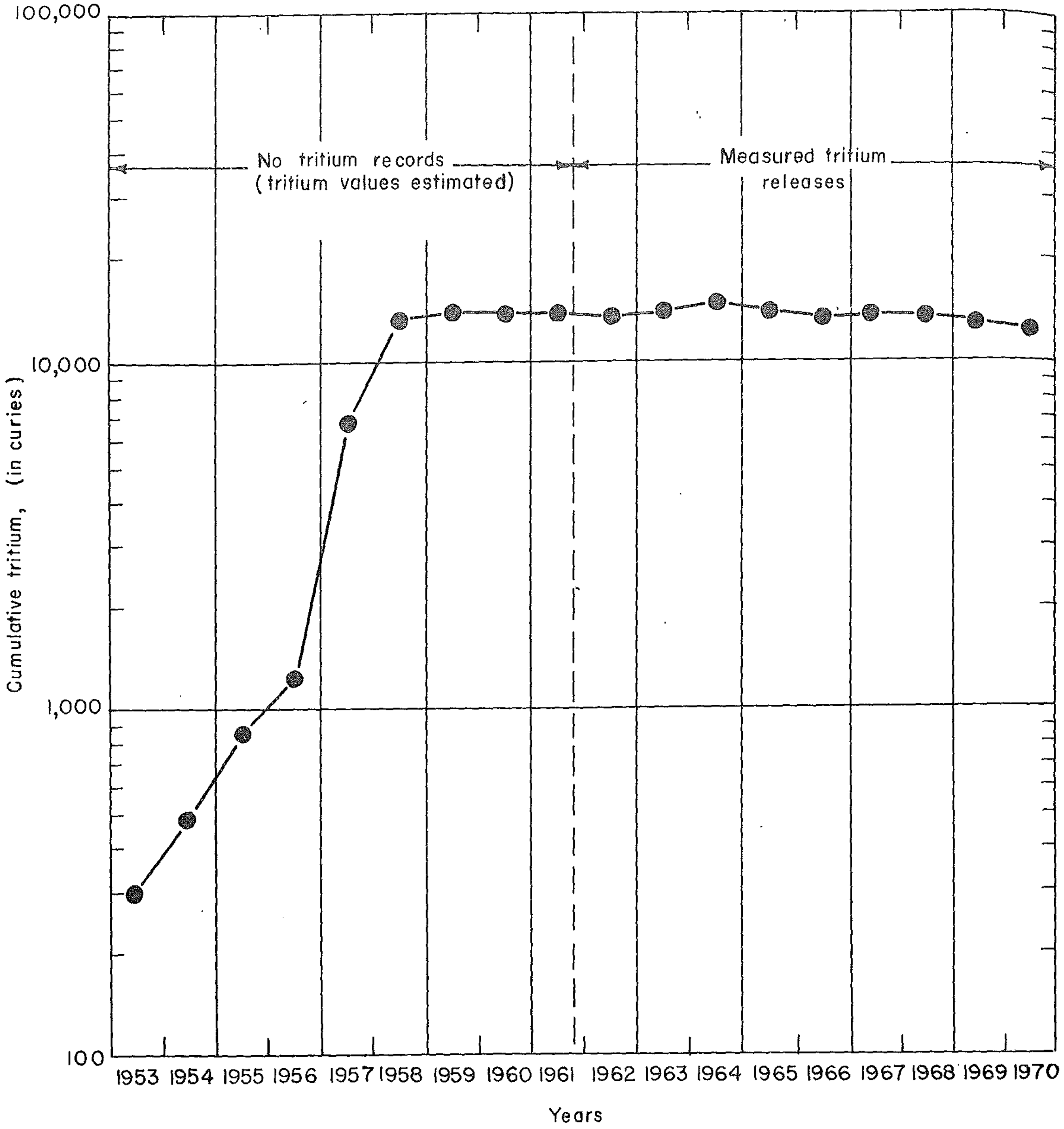


Fig. 51 Graph showing estimated cumulative waste tritium discharged to the subsurface by the ICPP, with radioactive decay subtracted out.

Hawkins and Short (1965) indicate that the cation exchange capacity of the interbedded sediments might be on the order of 10 to 15 meq/100g. W. L. Polzer (written communication, 1971) concluded that essentially all the Cs-137 (34 Ci) remained adsorbed on sediments within 15 feet (vertically) of the disposal pit. He also concluded that most of the Sr-90 had probably passed through the upper sediments, into the basalt.

In 1963, an ion exchange system was installed at the ICPP to reduce the discharge of cationic radionuclides such as Sr-90. In 1970, a new ion exchange system was installed to reduce further the concentrations of these wastes. The new system should eliminate significant discharges of these nuclides in the future. If course it will not reduce nonionic tritium or anionic products such as I-131.

AEC regulations define the permissible radionuclide concentrations in drinking water supplies resulting from AEC licensed operations (U.S. Atomic Energy Commission, 1968). These regulations specify allowable concentration limits for most of the known radioactive isotopes in drinking water for a controlled area such as the NRTS, in accordance with radiation protection guides recommended by the Federal Radiation Council. Table X lists these limits for certain radionuclides pertinent to NRTS operations, together with their average concentrations in the ICPP effluent.

As indicated by both the AEC and U.S. Public Health Service (1962) concentration guide limits, Sr-90 is by far the waste product requiring the most stringent restriction. According to Table X, Sr-90 is the only radioisotope in the ICPP effluent whose concentration exceeds the limits for drinking water. The long-term average concentrations of all the other isotopes listed in Table IX are below the maximum permissible. After the wastes are discharged into the regional groundwater supply, the concentrations are reduced by dispersion, decay, and, for some, sorption; small concentrations of a few isotopes do reach some of the on-site drinking water supply wells. The distribution of these waste products in the groundwater are discussed in detail in the next section.

2.2 Nonradioactive Industrial Waste Components

In addition to the radioactive components, the ICPP liquid waste effluents also carry a certain amount of nonradioactive chemical and industrial wastes. The nature and quantities of these wastes have not been completely or continuously monitored in the waste stream. However, records have been kept on the quantities of the significant chemicals consumed at the plant, nearly all of which end up as waste products. Available data indicate that the most abundant chemical waste product going down the disposal well is sodium chloride. A rather good record is available for the amount of NaCl consumed at the ICPP. Other waste components in the effluent include heat, sulfuric acid, sulfite, and phosphate. According to the Idaho Nuclear Corporation, the operating contractor until 1971 (G. E. Lohse, oral communication, 1970), the approximate quantities of various compounds which are used in the plant, and which ultimately are discharged in the liquid waste, are those listed in Table XI. These quantities are based on operations over one year's time (1969) and are not necessarily representative for previous years. In addition to the listings in Table XI, small (probably insignificant) amounts of the following products are reportedly disposed of: ammonium nitrate, acetic acid, ammonium oxalate, aluminum nitrate, ethel acetate, ethanol, oxalic acid, lead, and carbon tetrachloride. It should be reemphasized that the above data are only estimates.

TABLE X

MAXIMUM PERMISSIBLE CONCENTRATIONS OF RADIOISOTOPES IN DRINKING WATER (in a restricted area) RESULTING FROM AEC OPERATIONS (U. S. Atomic Energy Commission, 1968), COMPARED TO AVERAGE CONCENTRATIONS IN ICPP DISPOSAL WELL EFFLUENT

Isotope	AEC limits, pCi/ml	Average long-term concentration in ICPP effluent, pCi/ml
Cerium - 144	10	4.5
Cesium - 137	20	2.4
Cobalt - 60	50	-
Hydrogen - 3 (tritium)	$3x10^3$	526
Ruthenium - 106	10	1.1
Strontium - 89	3	0.39
Strontium - 90	0.3[a]	2.4
Zirconium - 95	60	3.0

---

[a] U. S. Public Health Service (1962) placed a maximum allowable limit of 0.01 pCi/ml for Sr-90 in public drinking water. Of the above listed isotopes, Sr-90 is the only one specifically restricted by U. S. Public Health Service.

TABLE XI

APPROXIMATE MONTHLY CONSUMPTION OF CHEMICALS AT THE ICPP, IN 1969

Compound	Approximate Quantity Consumed Per Month
NaCl	65,000 lb
H_2SO4	6,600 lb
NaOH	2,300 lb
Na_2SO_3	430 lb
Na_3PO_4	430 lb
Acetone	300 gal
HCl	100 lb

A large quantity of the ICPP process water is softened by conventional ion-exchange softeners. Hence, relatively large amounts of waste NaCl result from the frequent regeneration of the softeners. The waste sulfuric acid and sodium hydroxide result principally from the regeneration of cationic and anionic ion-exchangers which are used for producing demineralized water.

Some approximate concentrations may be calculated using the figures in Table XI and the average discharge volumes (Table IX). In 1969 the discharge to the disposal well was about 9.0 x 10^5 gpd, or about 27 x 10^6 gallon per month, which carried about 74,000 pounds of dissolved wastes per month. This yields an average waste concentration of about 310 mg/l. In addition to the waste solutes, the effluent is also assumed to contain the normal amount of natural dissolved solids, about 210 mg/l. Accordingly, the total solute content of the effluent would then be near 520 mg/l. This appears to be a reasonable figure, based on some of the observation well data near the ICPP. A section later in this report describes the distribution of dissolved waste products and specific conductance values of the groundwater in the vicinity of the ICPP. These data indicate that the groundwater has an average dissolved solids content of about 400 mg/l in the downstream observation wells nearest the disposal (Wells 41, 47, and 40). Values as high as 508 mg/l dissolved solids have been measured in Well 47. Because of dilution and dispersion, the monitor wells will generally reflect concentrations lower than those in the disposal well effluent. Therefore, it would seem safe to assume that the effluent has an average dissolved solids content somewhat higher than the average 400 mg/l in the three most responsive observation wells.

Peckham (1959) studied the waste chloride content of the effluent for 1956-58. His data indicate that average dissolved-solids content of the discharge should have been about 600 mg/l, which is fairly consistent with the 520 mg/l value, above. On the basis of all available data, especially Peckham's, the average dissolved-solids content of the effluent over the past 17 years is assumed to be near 600 mg/l.

Based on the Table XI values, the average waste sodium ion concentration in the effluent water should be about 110 mg/l. Similarly, the waste chloride concentration should approach 170 mg/l. With the addition of the natural sodium and chloride concentrations of 8 and 10 mg/l, respectively, the total concentrations are raised to 120 and 180 mg/l. Peckham (1959) concluded that the average chloride content of the effluent from 1956 through 1958 was about 245 mg/l. The corresponding sodium content would have been about 160 mg/l. This Na^+ concentration is in reasonable agreement with an analysis performed by Idaho Nuclear Corporation on a composite sample of the effluent collected during the month of May 1969, in which a sodium concentration of 183 mg/l was obtained. This sample also indicated a total dissolved solids content of 786 mg/l which is in fair agreement with the estimated average of 600 mg/l.

The range of waste solute concentrations in the effluent are not well known. Peckham's data (1959) indicate that the weekly average chloride concentration varies from about 100 to 400 mg/l. Based on the variability in the processes which control the waste concentration, it appears feasible that the individual waste concentrations may vary by factors of 0.1 to 10 times the average.

The average waste sulfate concentration is estimated to be about 25 mg/l, and the average sulfite and phosphate concentration about 1 mg/l. Natural sulfate concentration is about 20 mg/l, making the total estimated effluent concentration near 45 mg/l.

With the exception of one recent measurement, no direct data could be located on the pH of the effluent; however, it is believed to be slightly acidic, based on the fuel processing operations which produce some acid wastes. The pH of a composite effluent sample collected during the month of July 1970 was measured as 6.7. The plant was relatively idle during that time except for decontamination procedures. The measured pH is therefore not necessarily representative of the combined effluent when fuel processing or calcining operations are in progress. The calcining process does not appear to have a large effect on the pH. Groundwater samples from nearby downgradient wells have always exhibited pH values near the normal natural range of 7.8 to 8.2. Since these wells normally reflect a strong influence from ICPP disposal practices, it is assumed that pH of the disposal well wastes is near the natural level, or is at least close enough so that its effects are buffered by the natural chemistry of the groundwater and minerals of the aquifer.

A principal waste product of the ICPP is heat. Much of the waste heat is transferred to the plant process waste waters which are discharged down the well. The only known direct temperature measurements on the effluent were made only recently, at the disposal wellhead (Figure 52). The temperatures averaged 67°F (19.5°C), with a maximum reading of 77°F (25°C) and a minimum of 59°F (15°C) from January through June 1970. The data indicate a roughly inverse correlation between quantity of discharge and temperature -- lower temperatures are associated with highest discharges, and vice versa. The highest water temperatures observed in the nearby observation wells have generally been from 58 to 65°F (14 to 18°C). Jones (1961) reports a maximum observation temperature of 64°F (18°C) in 1961. These data would indicate that the average effluent temperature has probably been 65°F (18°C) or higher. A heat balance analysis on the system (later in this report) indicates that the average temperature may have been closer to 70°F (21°C) which would also be reasonable.

2.3 Sanitary Wastes

One other source of liquid waste discharge to the ground at the ICPP is the sewage system. The main system is an Imhoff process with chlorination from which the final treated effluent is allowed to seep underground. According to Schmalz (1968), approximately 26,000 gpd flow through the system. Another 1,000 gpd (estimated) flow through additional minor septic tank systems. No effects from these rather minor quantities of waste have been noted in the regional groundwater.

2.4 Unaccountable Liquid Discharges

In addition to the above mentioned liquid waste releases, various quantities of leakage and other unmeasured waste waters enter the subsurface at ICPP. A crude water budget of the facility, described in Appendix C, indicated that as much as 15% of the water used is unaccounted for over the past 10 years.

2.5 Perched Waste Water at the ICPP

Shallow disposal above the Snake River Plain aquifer has been only a minor practice at the ICPP. Nevertheless, significant quantities of perched waste waters have been observed beneath the plant-area over the years. The origins of these waters are varied and manifold and consequently are not well defined. Some of the known contributors to the perched waste water include the following: discharges to the seepage pit (discontinued in 1966), leaks in some low-level waste transport lines, leaks in subsurface fire water lines, collapsed and plugged disposal well, and other minor leaks and discharges.

2.51 Shallow Perched Water. The first level of perched water at the ICPP occurs within the Big Lost River alluvium on the upper surface of the basalt. Water in this zone has reportedly been an occasional nuisance to some of the facilities by causing basement leaks. The shallow perched waste water was first investigated near the fuel element cutting and

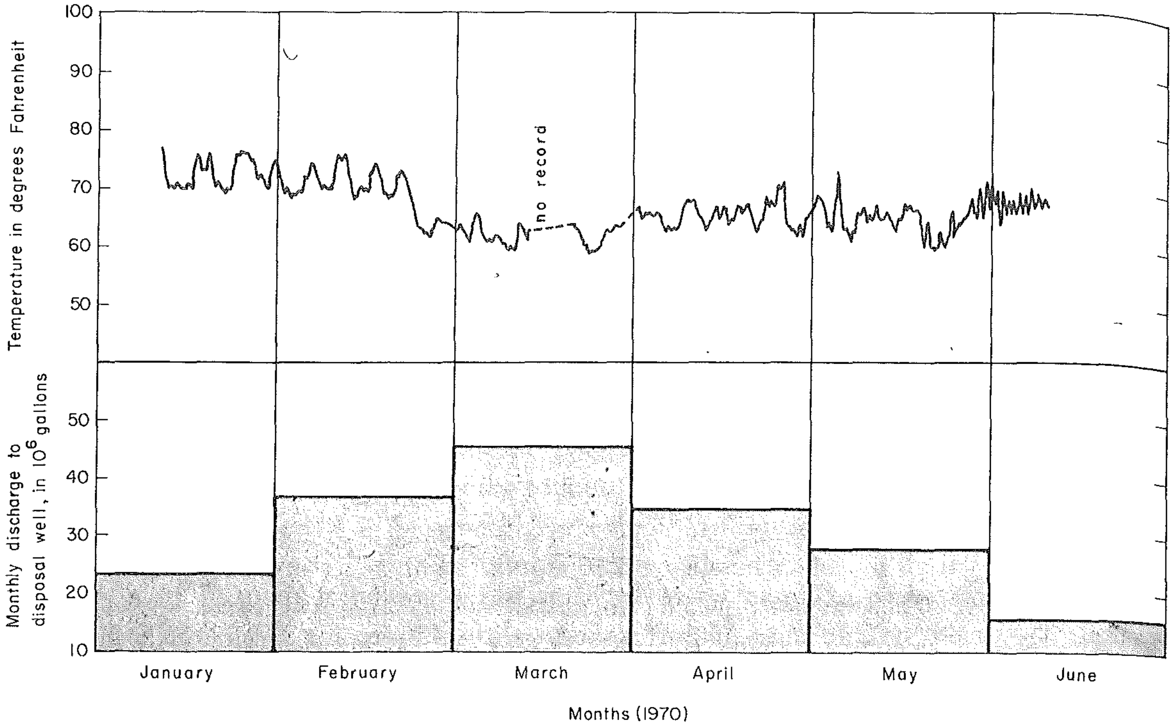


Fig. 52 Graph showing measured temperature variations of the ICPP liquid waste disposal well effluent.

storage facility (building CPP-603, Figure 48) in 1962 (Morris and others, 1963). This perched water resulted principally from waste discharges to the shallow seepage pit on the west side of the building. Nine auger holes were drilled around the bulding during the 1962 investigation, six of which encountered perched water in the alluvium near the top of the basalt. The augering and sampling study was expanded in 1963 (Morris, Teasdale, and others, 1964) to provide a total of 27 observation holes in alluvium near CPP-603. A small zone of perched water was found at a depth of about 22 feet and the larger zone was encountered directly on the basalt surface at a depth of about 32 feet.

Although some of the original auger holes have been destroyed, the remaining ones have been used occasionally to measure and sample the perched water since 1963. From 1962 through 1963 the liquid waste discharge to the pit averaged about 10,000 gpd. Morris, Teasdale, and others (1964) calculated that approximately 10,000 gallons of waste were contained in the alluvial perched water beneath the pit. In other words, the shallow perched water contained only one day's discharge of waste. Under these conditions, the perched water body should reflect short-term variations in the discharge rates or compositions. The Sr-90 data presented by Morris, Teasdale, and others (1964) indicated that such variation and other similar short-term variations have been observed.

A permanent or long-term cessation in discharge to the pit should show dramatically in the perched water. Although discharge to the pit was reportedly permanently discontinued in October 1966, the perched water has not reflected the corresponding response that would be expected. It has, in fact, remained a dynamic body with its post-1966 behavior very similar to that of the pre-1966 period, as indicated by water-level contour maps [Figures 53(a), (b), (c), and (d)]. The 1966 and 1968 maps indicate there was actually an enlargement in this perched body of water after the 1966 cessation.

Although there is only a very limited body of chemical quality data available on the water, some interesting comparisons can be made for some waste products, such as Sr-90 [Figures 54(a), and (b)]. The high concentrations in 1963 reflect the high Sr-90 releases to the pit in 1962 and 1963 when more than 33 Ci were discharged. The 1970 concentrations would be attributed either to continued minor discharges or to desorption from sediments of previously discharged and sorbed Sr-90. Figures 55(a) and (b) show the tritium concentrations for the same two times. There has been a large decline in all the tritium concentrations from the 1963 sampling to the 1970 sampling. The high values in 1963 again reflect the relatively high waste discharges to the pit in 1962 and 1963. This decline in tritium content from 1963 to 1970 is much too great to be caused by radioactive decay. Also, tritiated water should be little affected by sorption reactions. The average tritium concentration discharged to the pit in 1963 was about 6,000 pCi/ml, which agrees fairly well with the concentrations in Figure 53(a) in the range of 6,000 to 7,000 pCi/ml. The last recorded discharges to the pit were in 1966 and averaged about 8,000 pCi/ml (although the total volume was less than for previous years). Assuming this waste was the last discharged to the pit, the tritium presently in the perched water would have to be a residual of the 1966 discharge. This would further mean that the perched body has remained rather stagnant since 1966 and that the concentration of radioactive waste components contained within it should have declined by radioactive decay. It is apparent, however, that water levels in some of the perched water wells have risen since 1966. In addition, it is evident that the tritium concentrations in all the wells have declined by factors several times greater than the amount due to radioactive decay. These data suggest, then, that there have been some liquid discharges to the pit since 1966. The decline in tritium concentration could possibly be explained by the discharge of nonradioactive liquid wastes to the system which would percolate down to the perched water and dilute the radioisotopes contained therein.

According to Morris, Teasdale, and others (1964) sewage wastes (nonradioactive) from the building are also discharged into the pit from a nearby septic tank. It is not known how the sewage discharge volumes have compared to the radioactive waste volumes. It is assumed that the sewage discharges have continued since 1966 and are partially responsible for maintaining the perched water body below. The radioactive waste disposal system was designed so that wastes entered an intermediate underground sump tank before passing into the seepage pit. The sewage wastes, however, bypass the intermediate sump.

Because of the questionable source of the more recent radioactive wastes in the shallow perched water, the seepage pit and intermediate sump were sampled in June 1970.

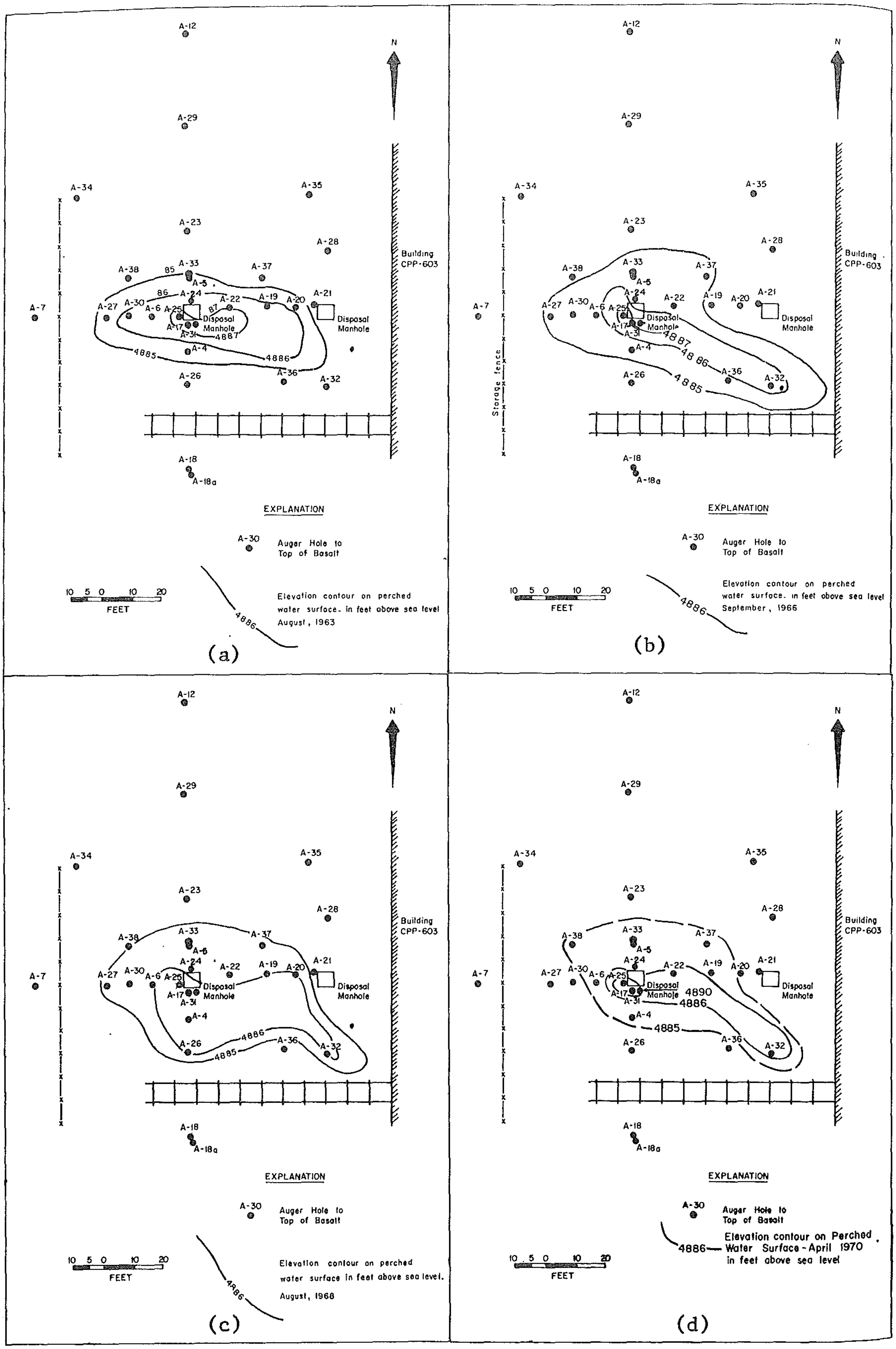


Fig. 53 Map showing water-level contours on shallow perched waste water at ICPP for four different times.

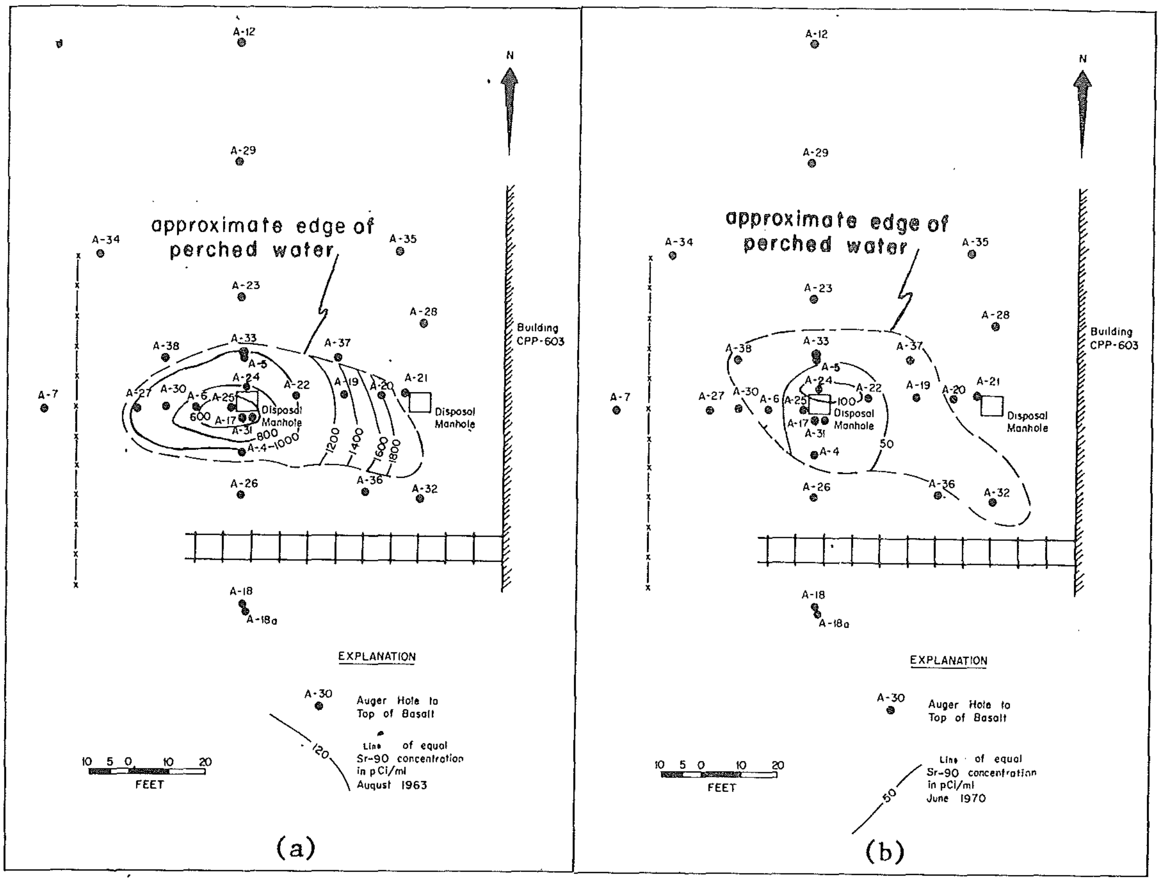


Fig. 54 Map showing distribution of strontium-90 in shallow perched water at ICPP for two different times.

The presence of water in the intermediate sump suggested that waste were still entering from some source other than the sewage system. Analyses of the samples collected showed significant quantities of radioactive wastes. The sump sample analyses indicated concentrations of 79 pCi/ml tritium and 61 pCi/ml Sr-90, whereas the seepage pit sample showed 95 pCi/ml tritium and 56 pCi/ml Sr-90. These data indicate that liquid radioactive waste are still entering this disposal system. The similarity of the two samples would suggest that waste in the two pits came from the same source. The source of this waste remains unknown but it may be due to leakage in piping or storage systems or it could be due to unintentional and unknown releases from the plant. Whatever the source may be, it remains evident that discharges to the system were not completely curtailed in 1966.

2.52 Deeper Basalt. In addition to the relatively small amount of perched waste water in the shallow alluvium, a much more extensive system of perched waste water has been observed deeper, in the basalt, below the ICPP. This water was first discovered in 1956 during the drilling of Well 40. Perched water was encountered at a depth of 348 feet. An analysis of this water (Olmsted, 1962) showed abnormally high total dissolved solids (303 mg/l), sodium (25 mg/l), and chloride (81 mg/l). These characteristics, particularly the high

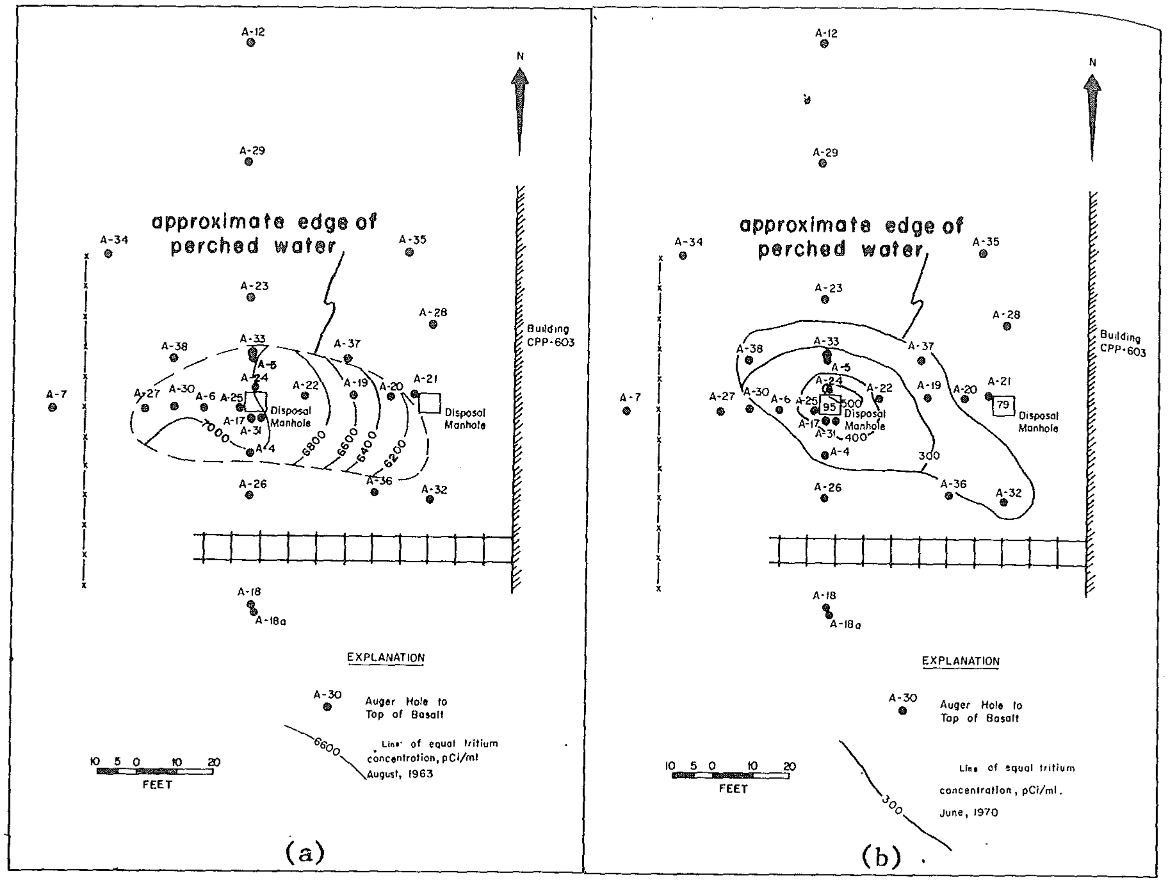


Fig. 55 Map showing tritium distribution in shallow perched water at ICPP for two different times.

chloride, indicate that the water was of waste origin. This is a reasonable level for perched water to accumulate, as there is a prominent clay bed (aquitard) 370 feet below land surface. Perched water was also encountered later in several other nearby wells during drilling. Table XII summarizes the available perched-water information from these wells.

One of the first conclusions evident from Table XII is that all the wells listed encountered perched water in the zone between 340 and 400 feet. This would imply a single, extensive perched water body in that interval. Data from Wells 50 and 52 indicate that other less extensive perched water zones were also present at shallower depths. Radioactive and chemical data on the waters from all wells except 41 and 43 show definite waste contamination. The apparent normal or natural composition of water from Wells 41 and 43 was caused by the introduction of fresh natural water into the hole during drilling. Under these circumstances, the sample would be from the drilling water rather than from the undisturbed perched water. It could also be due to fresh water recharge from fire lines

TABLE XII

DEPTH OF PERCHED WATER ZONES ENCOUNTERED DURING THE DRILLING OF WELLS IN THE ICPP VICINITY

Well number	Date drilled	Depths to perched water (ft)	Characteristics of the water	Depth of perching clay layer (ft)
40	9-56	348 (rose to 340)	high Na^+, Cl^-	370
41	12-56	396 (rose to 384)	high Cl^-	?
43	3-57	367 (rose to 362)	normal chemical composition	370
44	9-57	385	normal chemical composition	?
50	9-59	84		110 ?
		126	high sodium, β activity Ru-106, Rh-106 present	135
	deepened to 405 ft 10-62	390	high tritium	392
52	12-59	174	slightly high Na^+, high β & γ activity, I-131, Ru-106, Rh-106 present	195
	deepened to 650 ft 10-60	320		345
		385	slightly high Na^+, high β activity, Ru-106 present	410

which were known to have been leaking in this area. Figure 56 shows water contours on the deeper perched water zone, interpreted as a single continuous body. This is a purely schematic representation because the water level was tapped and measured at a different time in each well from 1956 through 1962. The contours on this map suggest a possible source of the water near Well 40. However, this contour configuration is probably due to an overall decline in the perched water level between the time Well 40 was drilled and the time the others were drilled, rather than a source of recharge near Well 40. However, it could also have been due to recharge from the leaking fire lines mentioned above.

Every well in Figure 56 except Well 50 was eventually drilled into the regional water table of the Snake River Plain aquifer (about 450 feet deep) and presently taps only the water of that aquifer. Well 50, however, was bottomed about 45 feet above the Snake River Plain aquifer. Consequently, it presently is the only well in the ICPP area that exclusively taps the deep perched water. The well was drilled to a depth of 282 feet in 1959 and later deepened to 405 feet in 1962. The regional water table in the vicinity is about 450 feet deep. Water level and sample data collected on the well over the years indicate that it has continuously contained perched waste water except for the period March-April 1960 when it was dry (before it was deepened). Every water sample that has been collected from the well has contained high amounts of waste products (chemical and radioactive). A sample collected after the well was completed to a depth of 282 feet in 1959 contained 424 mg/l sodium and a significant amount of beta activity. After the well was deepened in 1962 the water level and tritium content were monitored periodically. The graphs in Figure 57 indicate the perched reservoir is quite dynamic and apparently responds rapidly to changes in its recharge. The tritium graph indicates that perched water has continuously contained significant amounts of waste tritium. The concentration of 4,180 pCi/ml measured on the April 1970 sample is the highest tritium content ever measured on any groundwater sample from the NRTS. When the striking rise in the water level of Well 50 was discovered in the summer of 1968, a water level recorder was installed on the well in hopes of learning more about the cause of the rise. At that time, essentially nothing was known about the source (or sources) and extent of this perched water. In 1968, some unusual increases in tritium, chloride, and other waste products were noted in the two ICPP production wells. (See the subsequent section in this report describing waste effects on the regional groundwater.) By early 1970, the chloride content of production well CPP-1 had increased to about 90 mg/l. Chloride concentrations in excess of 50 mg/l pose a corrosion threat to some of ICPP processes. The increasing contamination of the production water therefore generated a considerable amount of concern. A likely source of the production well contamination was the perched water, based on the similarity in waste products contained in both waters and the apparent correlation of increased production well contamination with increased perched water in 1968.

The ICPP disposal well was considered to be one likely source of the perched water. In June 1970 an attempt was made to replace a defective measuring line in the disposal well so

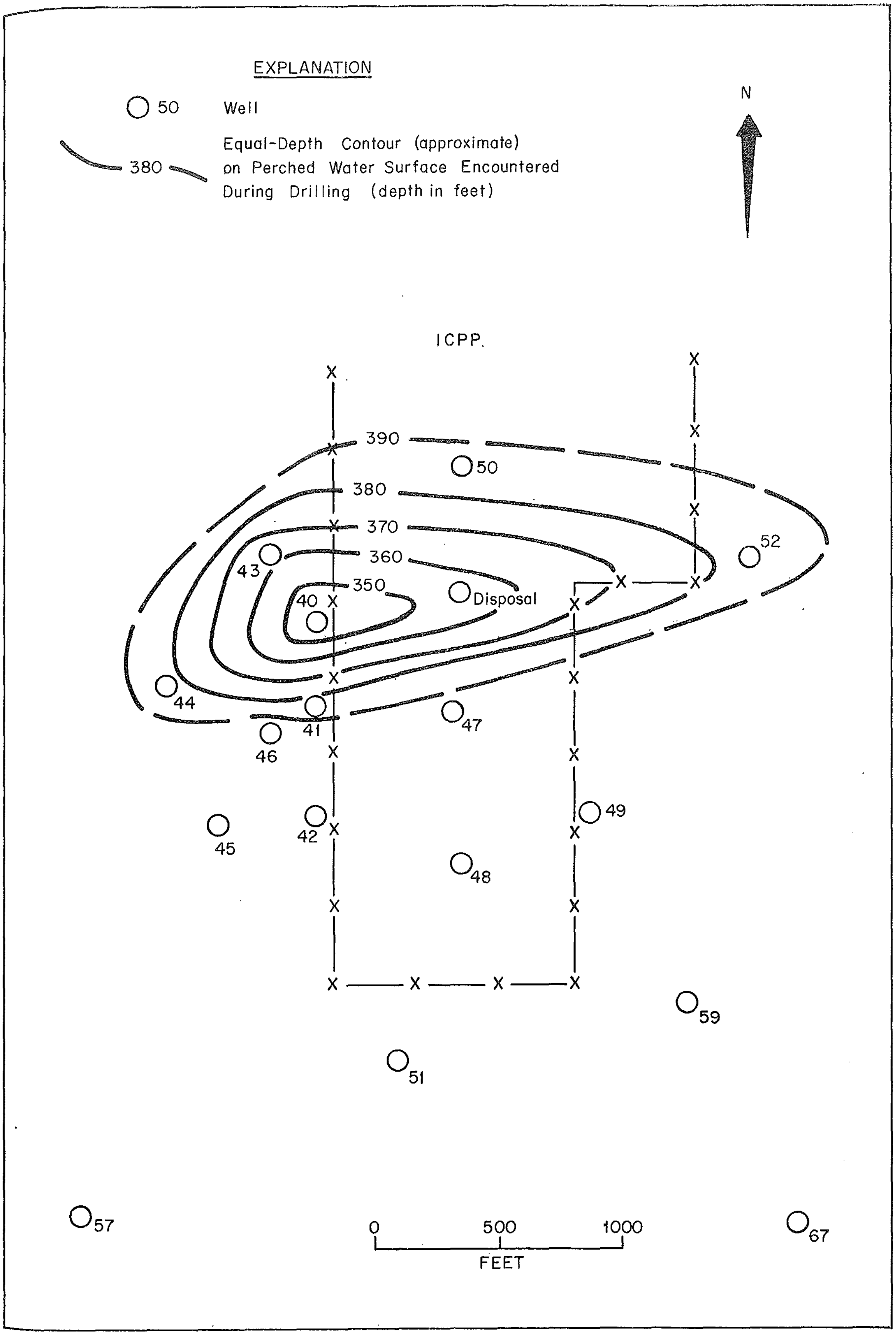


Fig. 56 Map showing water levels of deep perched water at the ICPP as encountered during well drilling.

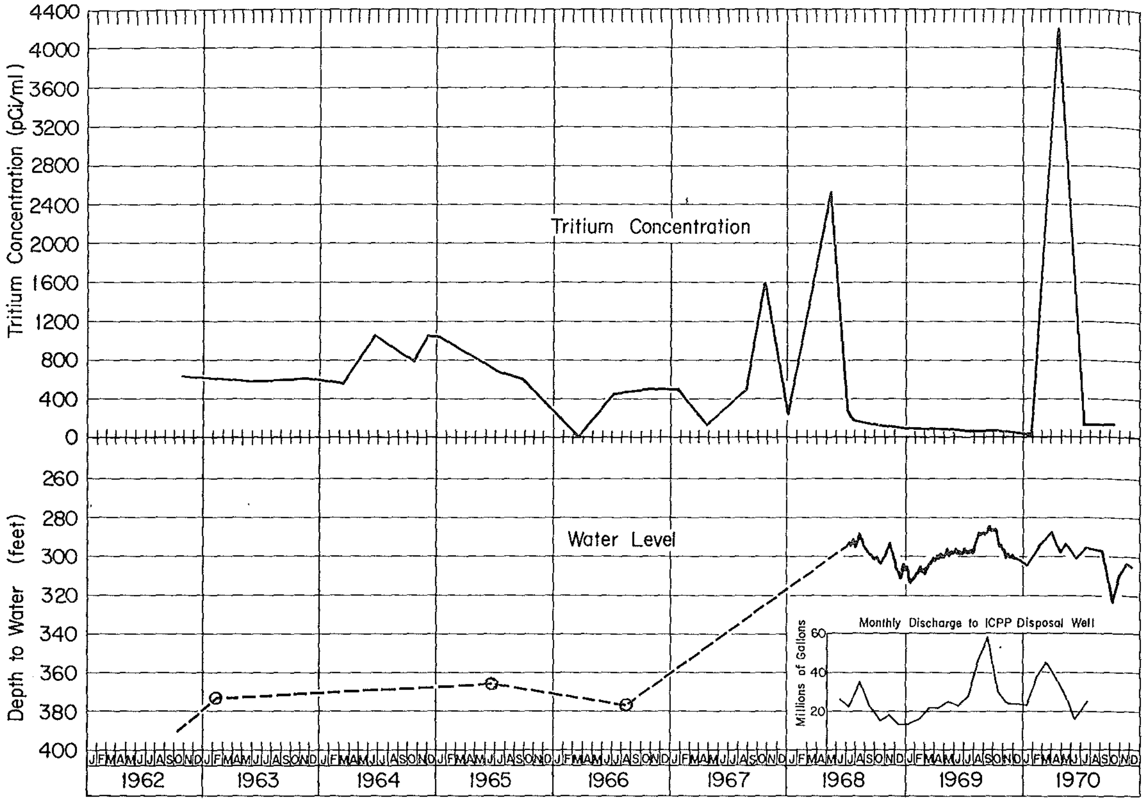


Fig. 57 Graphs showing hydrograph of Well 50 (deep perched water), tritium concentration of Well 50 samples, and discharge rate of the ICPP disposal well.

that the water level could be measured. It was then discovered that the well had collapsed and was plugged at a depth of 226 feet and that all the waste water was being injected into the unsaturated zone above that level. The original well was 598 feet with a natural water level at about 455 feet. The well was originally 24 inches in diameter, cased with 16-inch steel casing, and gravel packed. The salty, aerated waste water apparently corroded the casing until it collapsed, allowing the gravel pack and intruding sediments to fill the well up to the 226-foot depth. It was indicated by caliper logs and first attempts at cleaning the well that only fragmentary corroded pieces were left of the original 16-inch casing. The last previous depth measurements made in 1966 showed that the well was still intact. It is therefore estimated that most of the collapse took place in 1967 or early 1968. This correlates well with the 1968 rise in perched water in Well 50 and the increased contamination in the production wells noted in 1968. This evidence together with the excellent correlation of the two hydrographs in Figure 57 leaves little question that the disposal well has been the principal source of the perched water for the past two to three years. However, there undoubtedly are other contributions coming from sources such as the previously mentioned seepage pit and plant and pipeline leakages. These secondary sources were probably maintaining the deep perched water to a lesser extent before the disposal well went bad and will most likely continue to do so. An interpretive cross-sectional diagram of the perched water body in the basalt is shown in Figure 58.

In September 1970, a drilling contractor began to redrill and reline the disposal well to its original depth. By October, deepening had progressed to about 500 feet and the water level in the well had resumed its normal water table depth at about 455 feet. This, of course, removed the primary recharge source from the perched water, and the water level in Well 50 began a sharp decline (Figure 57). The October depth to water (320 feet) in Well 50 is the lowest since 1966. However, during development operations, a short time later in October the well collapsed again. Consequently the waste again began to recharge the perched water, as the sharp rise on the Well 50 hydrograph indicates. The well was reopened to the water table early in 1971, allowing the perched water body to contract to a significantly smaller size. However, during this contraction period, waste products will continue to seep downward from the perched water into the Snake River Plain aquifer where they can be captured by the two production wells. Under these conditions, the contamination in production well CPP-1 will probably gradually decline to the pre-1966 levels. (Use of the CPP-1 well for water supply has been temporarily discontinued until the water quality returns to a desirable level.) It may take several months, therefore, before the production well contamination declines to a relatively minor level. Regular monitoring of Well 50 and the two production wells will be necessary to define the longer term fate and effects of the perched water beneath the ICPP.

If the disposal well became plugged in mid-1967, approximately 900 million gallons of waste water would have been injected into the basalt above the 226-foot plug by September 1970. If all of this water were perched by an impermeable layer at the 390-foot depth, it could form a saturated cone-shaped lens 165 feet thick in the center and extending outward to a radius of over 4,000 feet from the disposal well. The production wells are only 2,000 feet away. This calculation is based on an effective basalt porosity of 8% which was found to be reasonable in a previous study (Barraclough and others, 1967). It is unrealistic to assume that all the water became perched; there certainly would be some leakage downward through the perching layers to the Snake River Plain aquifer. The Well 50 hydrograph (Figure 57) indicates that there was not a continual buildup in the perched water level but rather that there were fluctuations to maintain an equilibrium level, which suggests that water was leaking through the perching layer. Samples from nearby observation wells in the Snake River Plain aquifer, downgradient from the disposal wells (Wells 46 and 47), have continuously contained waste products, again indicating that at least some of the waste water has been reaching the aquifer while the disposal well was plugged. The 8,000-foot diameter perched water lens hypothesized above is only to illustrate that it is reasonable for the perched water to have extended to the production wells, entered them, and flowed down the casing. However, it is not necessary for the perched water to have entered the wells directly; more significant quantities of waste probably contaminated the production wells by percolating downward into the Snake River Plain aquifer within the cones of influence (or cones of capture) of the pumping wells.

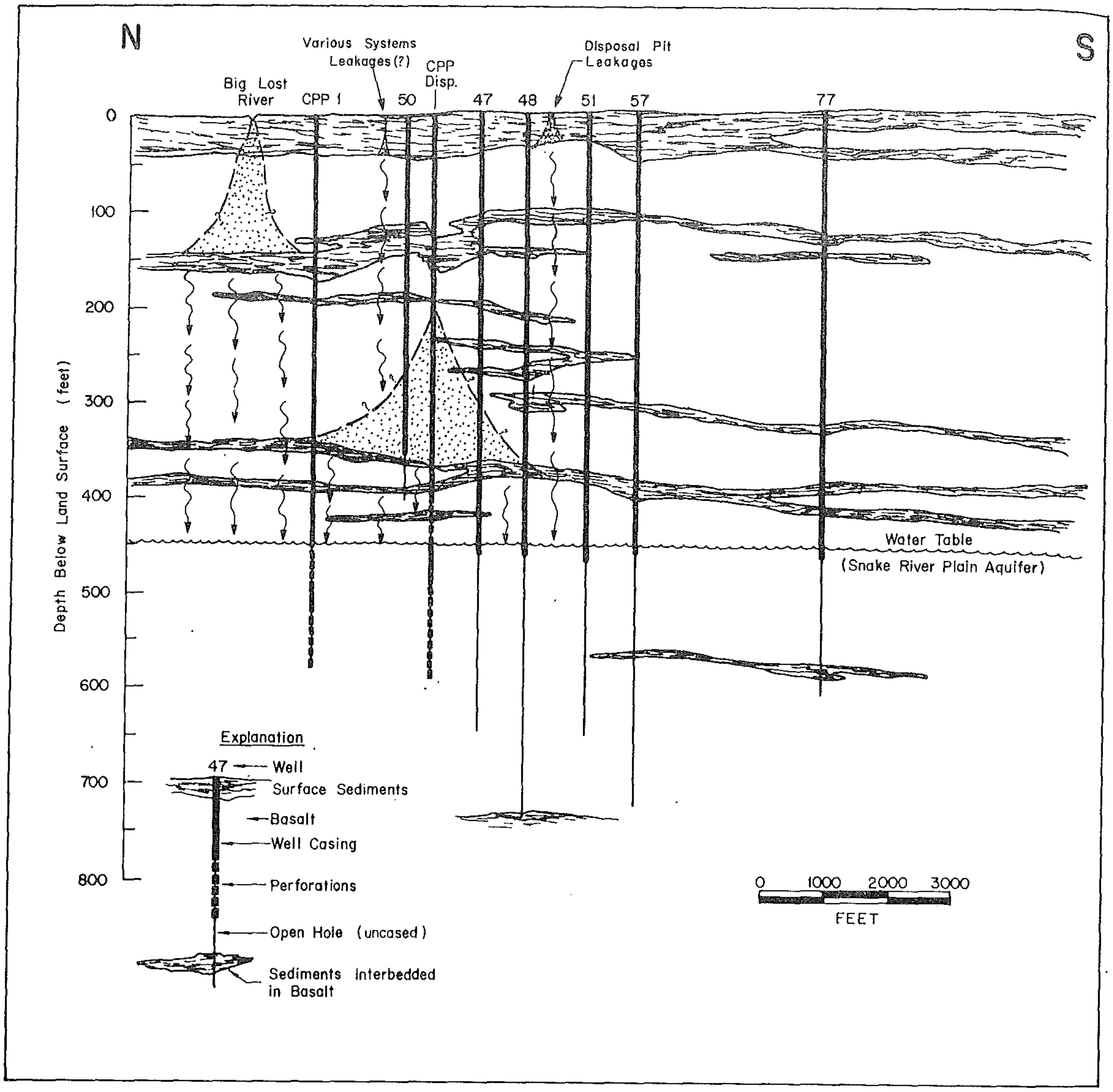


Fig. 58 Geologic cross section through the ICPP area showing generalized stratigraphy, perched water, wells, and regional water table.

A similar contamination episode occurred in 1959, when ruthenium-106 contamination was found in the two ICPP production wells. Mundorff (in Horan and others, 1960) studied the problem and showed that it was possible (with high pumping and disposal rates) for the hydraulic gradient between the disposal well and the production wells to become reversed so that waste water would flow directly from the disposal well to the production wells. However, he also concluded that a perched water source could be responsible for the contamination and that there was insufficient evidence to show which of the two mechanisms was responsible. Minor amounts of waste products, principally tritium, have occasionally been observed in ICPP production well samples in other years which again could be attributed either to perched water percolation or direct flow from the disposal well to the pumping wells through the aquifer.

A few other characteristics of the perched water from Well 50 have been determined, such as sodium concentration, specific conductance, and strontium-90 concentration (Figure 59). A borehole temperature log made in 1968 indicated that the Well 50 water temperature was 66 to 67°F (19 to 19.5°C). This is considerably warmer than natural water should be, again indicating the perched water had a high rate of recharge by warm waste water. All the data in Figure 59 are indicative of ICPP waste effluent. Further investigations are needed on the poorly understood ICPP perched water system so that its future effects and changes can be more fully evaluated.

3. OTHER SOURCES OF LIQUID WASTE DISCHARGES

The combined TRA-ICPP liquid waste discharges comprise more than 75% of the total volume of NRTS liquid waste and about 99% of the total radioactivity discharged. It is also apparent from limited data that the ICPP-TRA liquid waste effluents carry most of the total on-site chemical waste products.

Other facilities which discharge smaller but significant quantities of liquid wastes include NRF, CFA, EBR-II, TAN, SPERT, and ARA, as indicated on Table XII. NRF is the most significant of these contributors, discharging almost as much chemical waste as the ICPP.

3.1 Perched Waste Water at Other Areas

Perched waste water undoubtedly exists at several of the other NRTS facilities in addition to the TRA and ICPP. The only other area where significant studies of perched waste water have been made is the NRF. Prior to 1964 radioactive liquid wastes were discharged to the ground at two locations at the NRF, the ECF-A1W crib and the S1W pond (Figure 60). Since 1965, however, the S1W pond has been used almost exclusively, with the old ECF-A1W crib being used only occasionally for unusual operational wastes. In 1963, a field study was made of shallow perched water beneath these disposal sites (Morris, Teasdale, and others, 1964). Water percolates from each site to the top of the basalt where a small perched body forms because of the reduced permeability at the basalt-sediment interface, much as it does in the TRA pond system. The water then percolates through the basalt sequence to the regional water table at a depth of about 360 feet. Presumably one or more other perched water zones occur in the basalt (as occurs at the TRA).

In the 1963 study, 25 holes were augered to the basalt to study the small perched zone on top of the basalt beneath each pond (Figure 61). The basalt surface is 10 to 20 feet deep at the ECF-A1W crib and 30 to 40 feet deep at the S1W pond. Samples from the ECF-A1W perched water indicated tritium concentrations from 427 to 822 pCi/ml whereas S1W perched water contained 90 to 150 pCi/ml tritium. Since 1963, the perched water

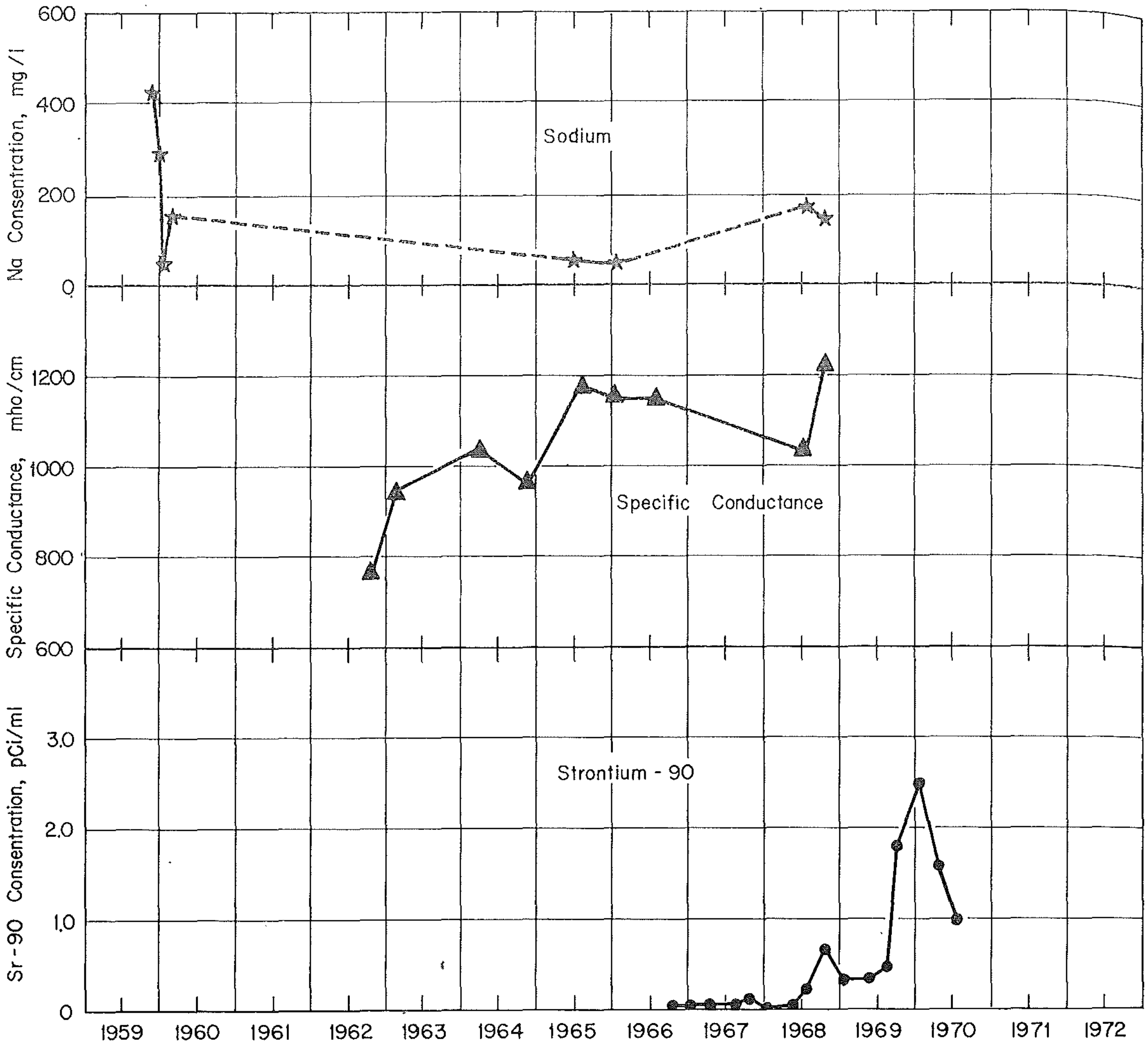


Fig. 59 Graph showing sodium and strontium-90 concentration, and specific conductance of perched water samples from Well 50.

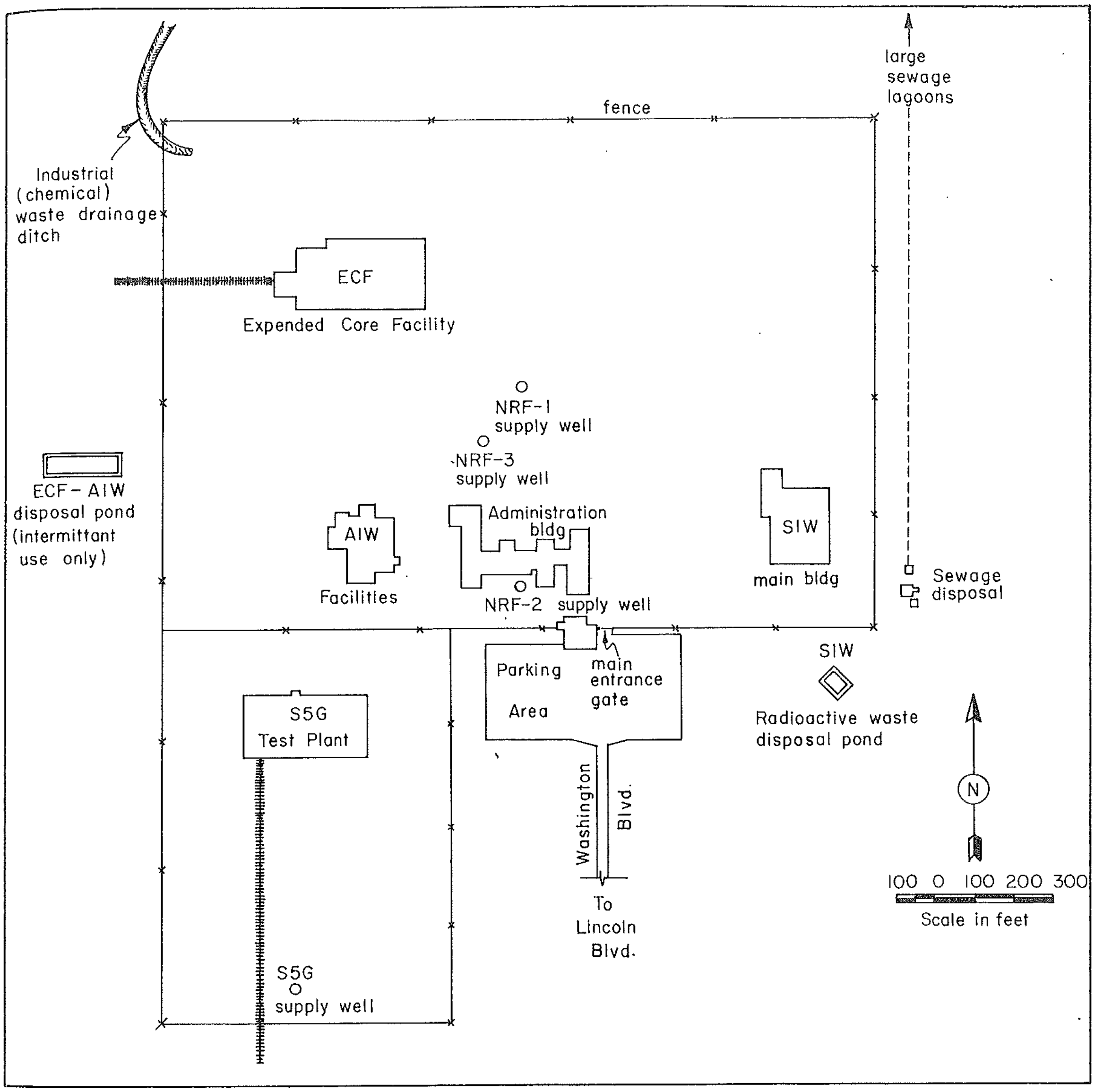


Fig. 60 Map of the NRF vicinity showing location of waste disposal ponds and other principal features.

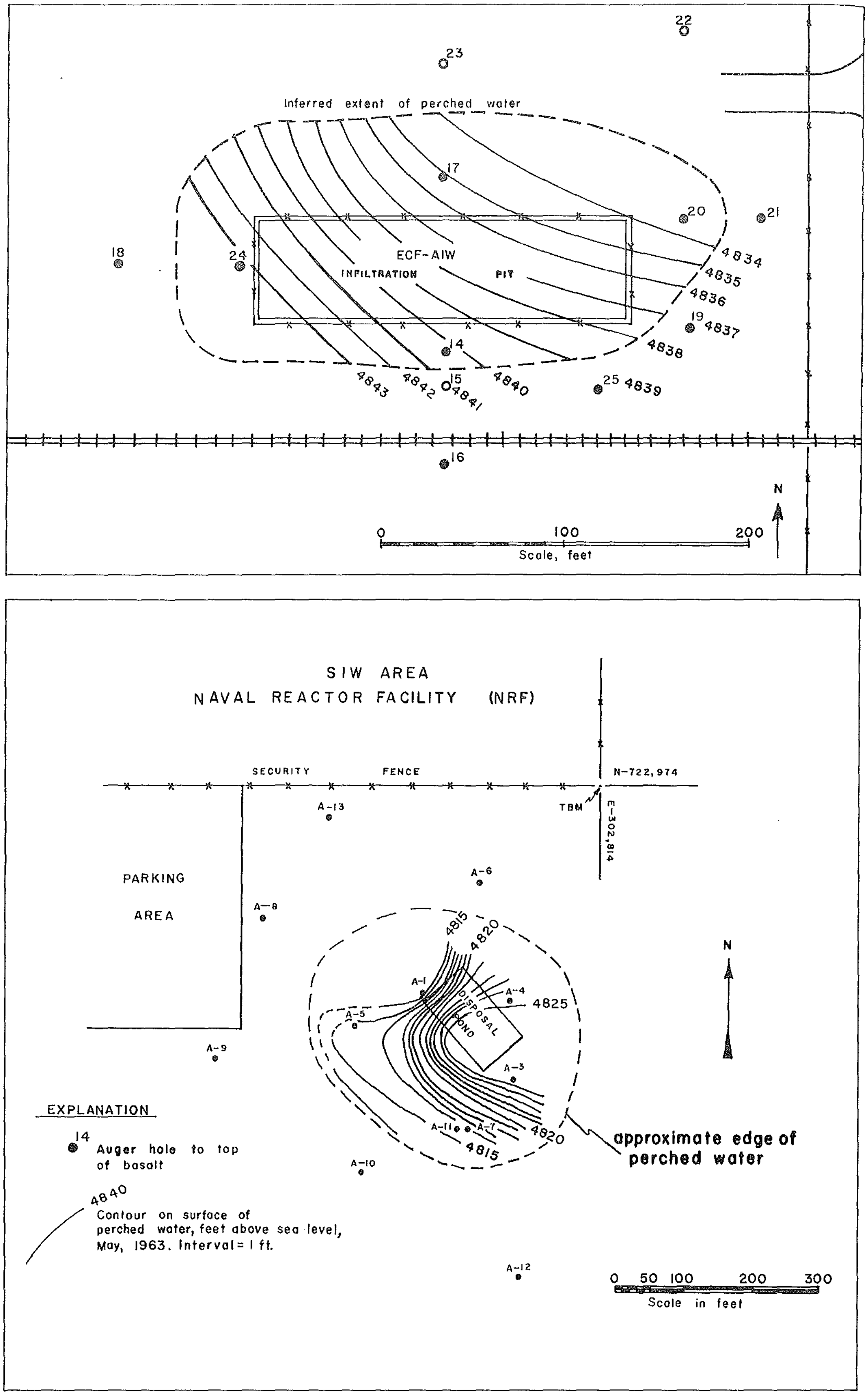


Fig. 61 Map showing contours on the shallow perched water surface beneath the NRF disposal ponds for 1963.

beneath the S1W pond has probably increased because of the increased discharge to the pond, whereas the ECF-A1W perched water has no doubt declined. In addition to the perched water beneath the pond and crib, it is likely to occur also beneath the liquid industrial waste drainage-seepage ditch northwest of NRF. Studies at the NRF have not been included in the Geological Survey program since 1963.

Another area where perched water probably occurs is the Experimental Breeder Reactor II (EBR-II) site, where liquid wastes are discharged to seepage ponds. The discharge rates are relatively low so that any perched water system would be correspondingly small.

A likely area for small quantities of perched water in the future is the Power Burst Facility (PBF), near SPERT area. Construction of this facility has only recently been completed. When it becomes operational, PBF will use two shallow wells, 110 and 115 feet deep, to dispose of low-level radioactive liquid wastes and corrosive liquid wastes, respectively. The wells were purposely designed to allow the waste water to perch, thus retarding percolation to the regional water table, which is about 450 feet deep.

The Loss-of-Fluid Test (LOFT) facility at TAN will use a seepage pond for disposal of its low-level radioactive and chemical liquid wastes, when the project becomes operational; however, only small volumes are anticipated so that no extensive perched-water bodies should result.

It is unlikely that significant zones of perched waste water occur at any facilities other than those discussed, because of their lack of significant waste discharges to the ground above the Snake River Plain aquifer.

4. SUMMARY OF LIQUID WASTE DISPOSAL

Table XIII summarizes the site-wide liquid disposal situation on a yearly basis. Under current conditions about 5.5×10^8 gallons of waste water containing 4,100 Ci of radionuclides are discharged to the ground in an average year. About 2.9×10^8 gallons of water containing about 6.7×10^6 pounds of waste chemical compounds are discharged per year. By the end of 1970, an approximate total of 1.6×10^{10} gallons of liquid waste had been discharged to the ground since NRTS operations began.

It is estimated that a total of at least 70,000 Ci of liquid radioactive waste has been discharged to the ground from 1952 through 1970. Most of this activity has been short-lived isotopes (half-lives less than 30 days) from the TRA so that an estimated quantity of only 13,000 Ci remains in the ground at present (Osloond, 1970), most of which is tritium.

For the same period of time (1952-70), it is estimated that nearly 100 million pounds of nonradioactive waste chemicals have been discharged to the ground in aqueous solution.

TABLE XIII

COMPARATIVE LIST OF SOME AVERAGE OR TYPICAL LIQUID WASTE DISCHARGE DATA FOR THE MOST SIGNIFICANT NRTS FACILITIES

		Radioactive Waste			Industrial or Chemical Wastes				Sewage Wastes		Comments
Facility	Year in which major operation began	Volume (gallons per year)	Radioactivity (curies per year)	Disposal method	Volume (gallons per year)	Major dissolved waste products	Estimated quantity (pounds per year	Disposal method	Estimated volume (gallons per year)	Disposal method	
TRA	1952	190×10^6	3,440*	seepage pond	42×10^6	NaCl, H_2SO_4, NaOH	4.710^6	seepage pond	9.9×10^6	Imhoff process	* Includes about 70 percent very short-lived, unidentified isotopes
					168×10^6	chromate, fungicide	(included above)	disposal well (1,271 ft deep)			
ICPP	1953	300×10^6	600	disposal well (598 ft deep)**	(mixed with radioactive waste	NaCl, sulfates, heat	0.92×10^6	disposal well (598 ft deep)	10.2×10^6	Imhoff process plus 4 septic tanks	**ICPP disposal well was found to be collapsed at a depth of 226 ft in 1970
NRF	1953	30×10^6	27	seepage pond	60×10^6	NaCl, H_2SO_4, poly phosphate	0.72×10^6	drainage ditch	21.9×10^6	2 sewage lagoons	
TAN	1954	23×10^6	6	disposal well (310 ft deep)	insignificant		insignificant		6.6×10^6	Imhoff process plus 3 septic tanks	
CFA	1952	(included with sewage)	2	(sewage system)	insignificant		insignificant		56×10^6	Settling basin, digester	
EBR II	1961	0.10×10^6	5	(sewage system)	23.7×10^6	H_2SO_4, NaOH, sulfates, chromate	0.43×10^6	seepage pond	7.3×10^6	Sewage lagoon plus 2 septic tank systems	
SPERT	1955	1.0×10^6	insignificant	seepage pond	insignificant		insignificant		1.8×10^6	8 septic tanks	
ARA	1957	insignificant	insignificant		insignificant		insignificant		1.3×10^6	6 septic tank systems	
Totals		550×10^6	4,100		290×10^6		6.7×10^6		110×10^6		

These consist mostly of NaCl, H_2SO_4, and NaOH. In addition, an estimated 1.8×10^{14} calories or more of waste heat have been added directly to the Snake River Plain aquifer, mostly through the ICPP disposal well.

5. WASTE DISTRIBUTION AND BEHAVIOR IN THE SNAKE RIVER PLAIN AQUIFER

5.1 Introduction

After waste products enter the regional groundwater of the Snake River Plain aquifer, their fate is controlled by two general influences -- the natural properties of the aquifer system and artificial, or man-induced, influences. Natural factors which control the movement and behavior of waste products include velocity and direction of groundwater flow, dispersion properties of the aquifer, degree and distribution of anisotropy and heterogeneity in the aquifer system, sorption and heat-transfer properties of the aquifer minerals, chemical equilibria of the aquifer system, and others. The man-induced influences consist primarily of the hydraulic effects on the aquifer from pumping and injecting wells. Secondary effects might include upsets in the natural chemical equilibrium by waste water and changes in the viscosity of the aquifer water by the injection of warmer waste water. The latter could cause an increase in the hydraulic conductivity of the aquifer in the zone transmitting the warmer water.

The overall observation well system for the Snake River Plain aquifer at NRTS (Figure 7) is the product of several studies of special localized problems. A good example of a localized "anomaly" in the well distribution is a string of six wells, numbers 34 through 39, southwest of the ICPP. This series was drilled in 1955 to intercept the waste "plume" flowing downgradient from the ICPP disposal well. As it turned out, because of the heterogeneity and anisotropy of the aquifer the plume flowed more to the south with a much wider dispersion effect than was originally anticipated. Consequently, the string of Wells 34 to 39 intercepts only the northwestern edge of the ICPP waste plume, as will be shown below. Additional concentrated clusters of wells occur at areas around the ICPP and the TRA. These wells were intended to provide more detailed monitoring near the major waste disposal installations. Many of these wells proved to be poorly located, primarily because of the heterogeneity in the aquifer, or a lack of knowledge of the local aquifer characteristics. A total of 114 production, test, and observation wells is available in the NRTS vicinity to serve as Snake River Plain aquifer testing and monitoring points. Table XIV lists these wells and some of their characteristics. In addition to the wells listed, a few other wells are available at greater distances from the NRTS, should a need for them ever arise. The distribution pattern of these 114 wells is certainly less than ideal. With comprehensive hindsight, it is easy to visualize better locations for most of the wells (for the purpose of monitoring long-term, large scale waste movement patterns). However, the wells are also used to study other parameters such as elevation of the water-table surface, recharge

TABLE XIV

LIST OF ALL AVAILABLE SNAKE RIVER PLAIN AQUIFER MONITOR WELLS IN THE NRTS VICINITY

Active Production Wells			
Well Identification	Year drilled	Penetration below water table, in ft	Remarks
CFA-1	1942	106	
CFA-2	1944	103	
EBR-I	1949	499	
CPP-1	1950	140	
CPP-2	1951	158	
MTR-1	1950	147	
ETR-3	1957	138	
ATR-4	1963	426	
NRF-1	1950	176	
NRF-2	1951	167	
NRF-3	1956	178	
S5G Production	1963	124	
ANP-1	1953	158	
ANP-2	1953	135	
ANP-8	1956	100	
FET-1	1958	140	
FET-2	1958	260	
SPERT-1	1955	187	
SPERT-IV	1960	752	
OMRE	1957	463	
SL-1	1959	181	
GCRE	1958	146	
EOCR	1960	748	
EBR-II-1	1959	123	
EBR-II-2	1959	121	
Site 4	1956	100	Dairy farm supply
Fire Station-2	1957	95	
Atomic City	1952	55	Private supply
Leo Rogers	1966	105	Private supply

TABLE XIV (contd.)

Miscellaneous Open Wells			
Well Identification	Year drilled	Penetration below water table, in ft	Remarks
Cerro Grande	1922 or earlier	111	Abandoned railroad supply well
2nd Owsley	1928 or earlier	113	Abandoned private irrigation well
MTR-Test	1949	114	
Highway-1	1950 (deepened in 1969)	piezometer pipes installed separately to 3 different depths	Originally a construction supply well, presently a special USBR test well
Highway-2	1950	82	Former construction supply well
Highway-3	1967	112	Supply well for roadside rest area
ANP-5	1956	104	
ANP-6	1956	92	
ANP-7	1956	85	
ANP-9	1956	99	
ANP-10	1959	461	
PSTF	1957	112	
P&W-1	1957	117	
P&W-2	1957	75	
P&W-3	1957	100	
Arbor Test	1958	115	
Area-II	1960	215	
Site 6	1959	170	
Site 9	1960	490	
Site 14	1956	444	
Site 16	1957	127	
Site 17	1960	189	
Site 19	1960	398	

TABLE XIV (contd.)

USGS Observation Wells			
Well Number	Year drilled	Penetration below water table, in ft	Remarks
1	1949	50	
2	1950	50	
4	1950	300	
5	1950	35	Needs to be cleaned
6	1950	188	
7	1950	1,000	
8	1950	46	
9	1951	50	
11	1950	45	
12	1950	360	
13	1950	214	
14	1951	38	
15	1951	1,185	
16	1951	52	
17	1951	144	
18	1951	61	
19	1951	123	
20	1951	216	
21	1952	75	
22	1951	48	
23	1952	62	
24	1952	112	
25	1952	53	
26	1952	58	
27	1952	88	
28	1953	105	
29	1953	41	
30	1953	41	
31	1953	177	
32	1953	108	

TABLE XIV (contd.)

USGS Observation Wells			
Well Number	Year drilled	Penetration below water table, in ft	Remarks
33	1953	150	Presently collapsed above water table
34	1954	232	
35	1955	110	
36	1955	100	
37	1955	104	
38	1956	262	
39	1955	102	
40	1956	225	
41	1956	221	
42	1957	223	
43	1957	195	
44	1957	195	
45	1957	195	
46	1958	197	
47	1958	199	
48	1958	296	
49	1959	207	
51	1960	203	
52	1960	194	
57	1960	269	
58	1961	14	
59	1960	203	
65	1960	37	
67	1961	239	
76	1962	244	
77	1962	144	
79	1962	228	
82	1962	250	
83	1962	153	

TABLE XIV (contd.)

USGS Observation Wells			
Well Number	Year drilled	Penetration below water table, in ft	Remarks
84	1962	24	
85	1962	153	
86	1966	50	
Total: 114		average aquifer penetration: 185 ft.	

effects, and seismic water-level fluctuations. Each of these multiple purposes would require a different arrangement of the wells for the most ideal data network. The proper number and location of the monitor wells could thus be debated endlessly, depending on point of view, desired degree of accuracy, and economics.

Regardless of whatever shortcomings the NRTS observation-well system may have, it is probably as good as or better than most groundwater systems in the country of comparable area and use. It is with this well network that all the following waste distribution patterns are interpreted.

Table XIV indicates that the penetration below the water table of most of the wells is near the average of 185 feet, with a maximum of 1,185 feet (Well 15) and a minimum of 14 feet (Well 58). The average thickness of the aquifer is believed to be from 2,000 to 5,000 feet, although little is known of it beneath the upper 1,200 feet. This means that the NRTS observation wells are only "skimming" wells -- they tap only the upper 200 feet or so of the total aquifer. G. H. Chase (written communication, 1966) indicates the aquifer consists of two separate parts -- the upper, highly permeable, basaltic part (above depths of 600 to 800 feet) and the lower, much less permeable, sediment-dominated part (below the 600-to 800-foot depth). This would mean that the upper 250 feet or so of the aquifer has the most effective hydraulic properties. The deepest well in the NRTS vicinity is only about 1,500 feet deep, so it is not clear what the characteristics of the aquifer may be below this depth. It is quite possible the section below 1,500 feet may become basalt dominated again and that another highly transmissive zone may occur there. If this is true, the lower transmissive zone should probably be considered a separate aquifer or subaquifer because it would be effectively separated from the upper permeable zone by the thick sedimentary sequence from 800 to 1,500 feet deep. In addition, the large-scale vertical lithologic heterogeneity of the aquifer system as well as other physical characteristics contribute to a high degree of vertical-versus-horizontal anisotropy. It is believed most of the permeability of the basaltic portions of the aquifer can be attributed to large voids, fissures, crevices, and other macroscopic openings associated with the inter-flow zones -- the zones separating individual thin lava flows. These zones undulate on a roughly horizontal plane, therefore contributing much more to the horizontal permeability of the aquifer than to the vertical permeability. Therefore, the so-called "skimming" effects of the NRTS observation wells may very well be insignificant. The materials and heat balances discussed later in this section of the report support this concept.

The NRTS liquid wastes which reach the Snake River Plain aquifer, either by percolation from ponds or by direct injection through wells, are received only into the upper surface of the aquifer. The percolating wastes obviously enter the aquifer at the water table surface. The ICPP disposal well penetrates only 150 feet below the water table. It is concluded, therefore, that the NRTS observation wells provide reasonable representation of the part of the aquifer system that is effected by waste disposal activities.

The method and depth at which samples are collected from observation wells is another problem. The most ideal method of sampling is probably the packer-pump method. In this technique, inflatable packers are used to isolate the portion of the well from which the sample is desired. A submersible pump placed in the isolated zone is then used to pump out the aquifer water for sampling. The packers provide greater assurance that the sample comes from the desired depth interval and the water is pumped from a representative aquifer zone surrounding the well. Unfortunately, this sampling method is very difficult and expensive for a large number of wells. Nevertheless, it has had considerable use at the NRTS for several wells at various times, especially by Jones (1961). Since 1961, packers and pumps have had little use on the site in sampling observation wells.

The sampling technique most commonly used for the NRTS wells is the Föerst thief sampler. This is a static sampler which is lowered on a cable to the desired depth in a well, then remotely closed to trap a water sample from that depth. The method has been very satisfactory for most cases in the NRTS observation well system. Of most critical concern is the selection of the appropriate sampling depth or depths for each well. Several factors are considered in selecting a representative sampling point for a particular well. The first consideration is that the sampling point be a permeable zone in the aquifer. In an uncased well, such a zone would be selected by the use of various borehole geophysical logs together with the lithologic log. Generally, a good dynamic permeable zone would occur in a fractured basalt section that contains large voids or openings. This would be shown on the gamma, gamma-gamma, and caliper logs. A tracejector log or other flow-meter logs can be used to show the velocity and general flow direction (up, down, horizontal, stagnant) of the borehole water at any depth. Thus, a permeable zone displaying good cross-flow of groundwater would make an appropriate sampling point. In cased wells, the sampling point is always selected in a perforated zone, preferably one that shows significant flow-through.

In many of the wells, a vertical series of thief samples have been collected throughout the saturated portion of the hole, then analyzed and correlated with the borehole flow logs. A good example of this is described by Barraclough, Teasdale, Robertson, and Jensen (1967, pp. 73-75) for Wells 42, 43, and 49. In most cases, it was found that samples collected from flowing zones within the well had similar concentrations of waste products, whereas those samples from static or stagnant zones often had considerably different concentrations. These types of studies plus many years of NRTS monitoring experience have shown that thief samples collected from a dynamic part of an observation well are reliably representative of the aquifer water tapped by that part of the well.

5.2 Nonradioactive Wastes

Although many chemical waste products are discharged to the subsurface, only sodium chloride, chromate, and heat have produced significantly detectable changes in the water quality of the Snake River Plain aquifer. These products, plus the parameter of specific conductance, are the only chemical effects analyzed in this study.

In many cases, the effects of a particular waste parameter have been sought to no avail in the downgradient aquifer water. For example, many pH measurements have been made on monitor-well samples but no significant deviations from the normal values have been observed. Available data indicate that there has not been any significant discharge to the aquifer of other more exotic and potentially harmful chemical wastes such as mercury, arsenic, and pesticides at the NRTS.

5.21 Chloride. As mentioned in a previous section of this report, sodium chloride is the most significant chemical waste product disposed to the subsurface at the NRTS. Consequently, sodium and chloride are among the most wide-spread waste products in the regional groundwater. NRTS chloride contamination in the Snake River Plain aquifer was first studied extensively by Peckham (1959).

The normal background or natural chloride concentration in the part of the aquifer near the ICPP is 9 to 10 mg/l (Table III and Figure 24). An anomalously high natural level of about 20 mg/l appeared to be present in the CFA region. However, the CFA concentration declined later in the 1950's. For the purposes of this study, a lower limit of 15 mg/l was selected as representing waste contamination. Because of the variability in this background value, 15 mg/l is probably too high in some areas and may be slightly too low in others, but it generally appears to be reasonable and, in most cases, conservative.

Although sodium chloride has been discharged to the ground continuously since early 1953, the first reasonably complete set of groundwater chloride analyses was collected late in 1958. Two other sets of data, collected in 1960 and 1969, are representative of the distribution changes of waste chloride in the Snake River Plain aquifer after 1958. Chloride concentration lines in the aquifer for the three data sets (Figure 62) indicate that by fall of 1958, waste chloride had traveled southward as far as the CFA-1 well (about 2.5 miles) from the ICPP disposal well. It must be remembered that the lines, particularly the 15 and 20 mg/l, are interpretive approximations based on fairly sparse well data and may be subject to significant error. It appears that even as early as 1958, concentrations of 50 mg/l, or more, chloride were fairly wide spread in the aquifer. These figures cover only the TRA-ICPP-CFA region because this is the only part of the NRTS in which waste disposal has caused significant effects on the Snake River Plain aquifer.

It appears that the first significant waste chloride from the ICPP arrived at the CFA-1 well in about 1958. It therefore traveled a horizontal distance of about 35,000 feet in about 2,000 days, for an approximate velocity of seven feet per day. This agrees very well with the findings of Hawkins and Schmalz (1965) who concluded that waste tritium from the ICPP first arrived at the CFA-1 and -2 wells in 1958. This velocity (seven feet per day) is not necessarily the average groundwater flow rate for this region. The 1958 arrivals of tritium and chloride are first arrivals rather than average arrivals; for this reason the arrival time may indicate a velocity faster than the average. The leading edge of the contamination front travels faster than the average flow as the front disperses longitudinally.

In addition to dispersion effects, three other major factors might cause the travel time from ICPP to CFA to appear to be different from the true average groundwater velocity:

(1) The CFA wells may not be on the most direct flow path from the ICPP. In this case the apparent travel time would be slower than it would be to a well on the most direct flow path. The magnitude of the delay would depend on how far the CFA wells are laterally from the most direct downstream line. Studies by Barraclough, Teasdale, Robertson, and Jensen (1967) indicate that the most direct flow path may be a few thousand feet to the west of CFA.

(2) The ICPP disposal well induces initial high velocities (as much as 5,000 feet per day adjacent to the well) due to the injection effect. However, previous studies (Barraclough, Teasdale, Robertson, and Jensen, 1967) indicate that the effect becomes fairly insignificant at a distance of 1,000 feet or more from the injection well. In addition to the injection effect, the CFA pumping wells produce a similar acceleration of flow as they draw aquifer water toward them. Aqueous waste products that are captured in the field of influence of a pumping well gradually accelerate as they approach the well. This effect of the CFA wells is less significant than that of the ICPP injection well because the CFA wells

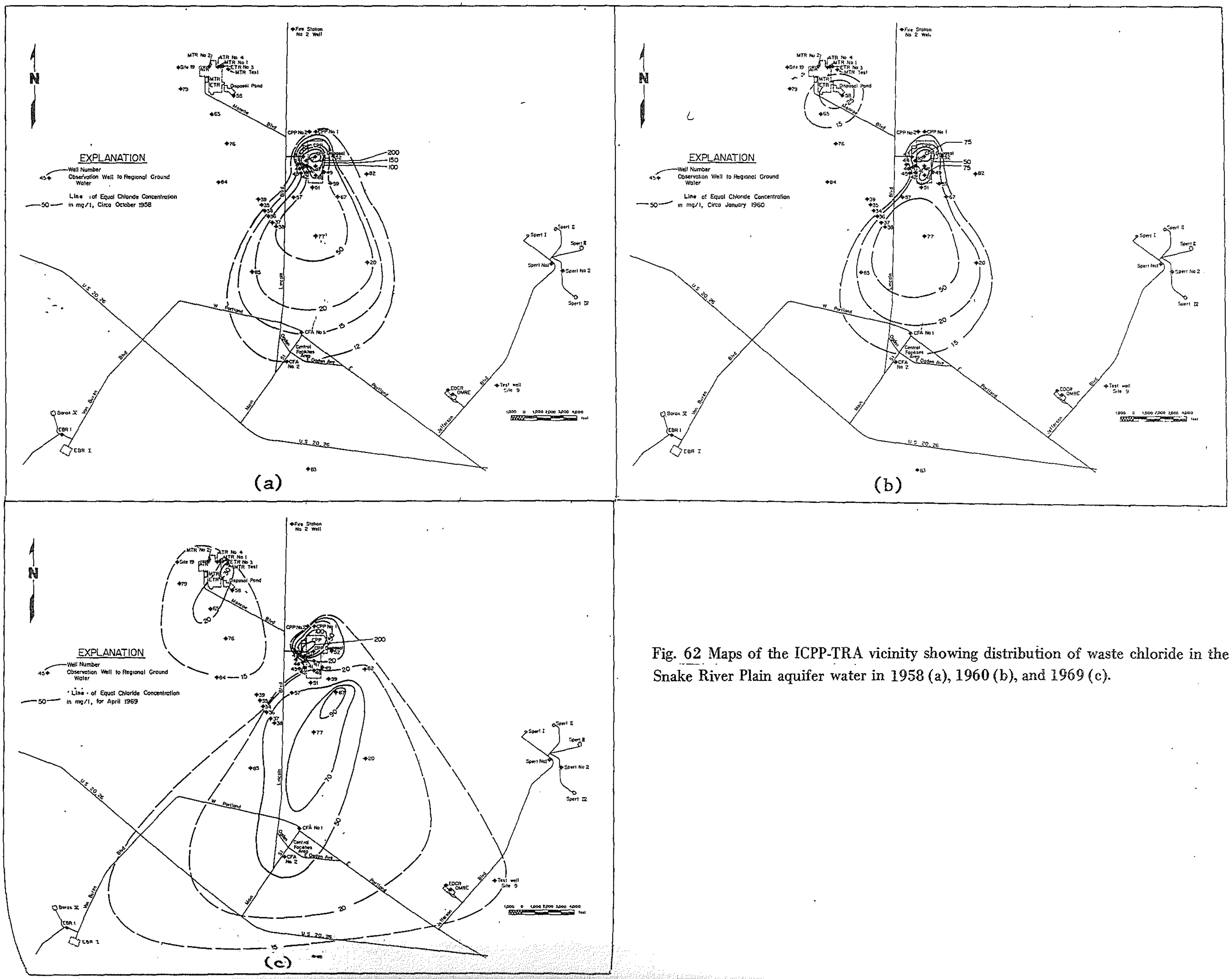
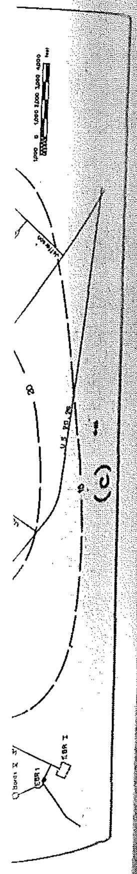


Fig. 62 Maps of the ICPP-TRA vicinity showing distribution of waste chloride in the Snake River Plain aquifer water in 1958 (a), 1960 (b), and 1969 (c).

withdraw only about 1/4 to 1/2 the discharge rate of the disposal well. The influence of the pumping and disposal wells increases the overall velocity of wastes from the ICPP to the CFA above the natural groundwater velocity. The flow lines would also be distorted to flow more directly between the two areas.

(3) Ion exchange or sorption can significantly affect solute flow rates. If a waste ion is reversibly sorbed while flowing through the aquifer, it will travel at a slower rate than the average groundwater flow rate. The permeability (and porosity) features of the Snake River Plain aquifer are large-scale features. Consequently, a very small amount of basalt surface area is exposed to the water, in comparison to, say, a sand aquifer. Sorption or exchange reactions are highly dependent on available mineral surface area. Many other factors control the magnitude of sorption effects such as the species and charge of the ion, the minerals present and their crystal structure, and the total chemical makeup of the water. The sorption effects on chloride are believed to be insignificant for two reasons. First, and most important, the anion exchange capacity of earth materials is much less than the cation exchange capacity; second, is the small amount of available mineral surface area. The latter effect may be somewhat offset by the presence of clay coatings on some of the basalt fracture and void surfaces. This conclusion is supported by other data later in this section such as materials balance studies and comparisons with tritium and other waste product behavior. It should be pointed out however, that the positively charged waste cations, Cs-137, Sr-90, and sodium, do show significant influence by sorption. The principal sorption reactions involved in this case are probably reversible exchange reactions; that is, they generally do not permanently remove solutes from solution.



There is not a great difference between the 1958 and 1960 chloride lines, particularly in the outer ones (15, 20, and 50 mg/l). This is primarily because the two maps are separated in time by little more than a year. The 1960 map shows the appearance of a separate plume of waste chloride from the TRA (Wells 58 and 65). Another apparent change is a decline in concentrations near the disposal well in 1960, which apparently represents a short period of reduced chloride discharge previous to the sampling period. The 1960 map tends to verify the earlier 1958 map. Obvious changes occurred in the ICPP waste chloride plume from 1960 to 1969. Considerable advancement and spreading in the 15, 20, and 50 mg/l lines is evident. The 50 mg/l line advanced past the CFA-1 and -2 wells and concentrations of 70 to 90 mg/l occupied a significant area around Wells 67 and 77.

The wide expansion of the 15 mg/l line is one of the more striking features between 1960 and 1969 (Figure 62). However, not too much significance should be attached to this, as the location of this line is inferred from very few wells. The questionable significance of 15 mg/l being greater than the natural concentration was mentioned previously. The extension of the southwestern lobe of this contour is based on increased chloride concentrations observed in the EBR-I well. It is possible, however, that this increase could be due to minor waste discharges at the EBR-I facility. Likewise the southeastward lobe extension is based on chloride increases in wells EOCR, OMRE, and Site 9. Again it might be argued that these increases are due to minor wastes released at the EOCR, OMRE, and SPERT facilities. Note also that increased chloride levels are indicated at the SPERT area on the 1969 map (Figure 62).

Another prominent feature of the 1969 concentration lines is the apparent separation between the high concentration zone to the north (from Well 47 to the CPP-1 well) and the high concentration zone to the south (from Well 48 to the CFA wells). The two closed 20 mg/l lines outline these zones. At first, one might tend to attribute this separation to a long period of reduced chloride discharges followed by renewed, high discharges. However, no such hiatus occurred in the waste releases. If the ICPP disposal well collapsed in 1967, as was previously concluded, the direct entry of wastes into the aquifer was suddenly curtailed or reduced at that time. Meanwhile, the wastes entered the unsaturated zone above the aquifer, expanding the body of perched waste water. The perched water percolated downward to the aquifer, the rate increasing as the perched body expanded (Figure 63). In time, the perched body reached an equilibrium point at which it lost water downward through the perching layers as fast as it gained water from the disposal well. During the period the perched body was expanding to its equilibrium size, few wastes were reaching the aquifer. This permitted the zone directly beneath the ICPP to be flushed by fresh, southward-flowing aquifer water. Finally, the perched water began to enter the aquifer in larger quantities, recontaminating the zone beneath the ICPP, and leaving the "fresh" water gap near Wells 42 and 49. This "gap" is also seen in some of the other waste products in the figures following. The presence of the perched water body also explains why the upper high chloride zone has apparently moved north to the CPP-1 production well and is no longer centered around the disposal well.

Generally, then, the three chloride maps and the cross section (Figures 62 and 63) behavior appear reasonable. The observed concentration range of about 15 to 200 mg/l is compatible with the average discharge concentration of 200 to 250 mg/l. These patterns compare favorably with those of other waste products discussed below.

5.22 Sodium. Sodium analyses have been conducted on a more frequent basis than the chlorides. Again, the first good set of samples was collected and analyzed in 1958. The sodium concentration patterns for four years, 1958, 1960, 1965, and 1968 (Figure 64), resemble some of the chloride patterns and are roughly in proportionate concentrations. The concentration ratio of sodium to chloride for dissolved sodium chloride is approximately 2:3. For example, a concentration of 30 mg/l chloride should be accompanied by about 20 mg/l sodium. The natural background sodium concentration of the Snake River Plain aquifer water in the ICPP-CFA region is 7 to 9 mg/l (Table III and Figure 23). On this

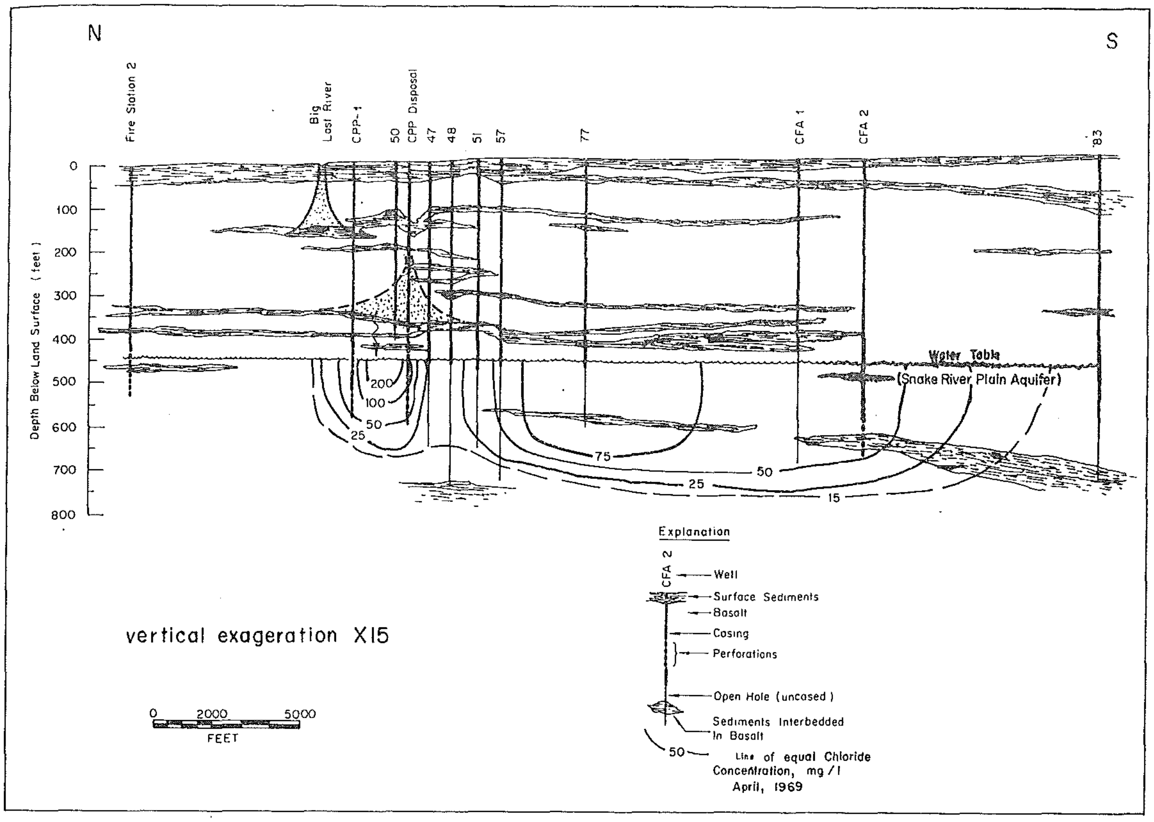


Fig. 63 Cross section through the ICPP area showing the distribution of waste chloride in the regional groundwater.

basis a lower limit of 10 mg/l was selected as indicative of waste contamination. Like chloride, sodium appears to have arrived at the CFA-1 well during or before 1958.

One striking change on the 1960 sodium map (Figure 64) which was not evident on the 1958 map is the depressed concentration zone around Well 51, which had not yet been drilled in 1958. On the 1965 map, a similar depression remains evident. The explanation for this reduced concentration area is not clear. Well 51 generally yields anomalously low concentration of other waste products. (See the following section on distribution of specific conductance values, tritium, and Sr-90.) Jones (1961) concluded that Well 51 was located in a zone of very low permeability, compared with zones to the east and west. This conclusion is supported by the tritium studies of Barraclough, Teasdale, Robertson, and Jensen (1967). If the water tapped by Well 51 is very slow moving, waste products might take many years to gradually enter the less-permeable zone near the well. The hydraulic characteristics of the well offer another probable explanation. It is quite possible that the lower part of the well penetrates less contaminated water flowing beneath the major waste-carrying layer in the top 150 to 200 feet of the aquifer. Well 51 is 659 feet deep and penetrates about 203 feet below the water table. A tracejector log (which measures borehole flow) was made on Well

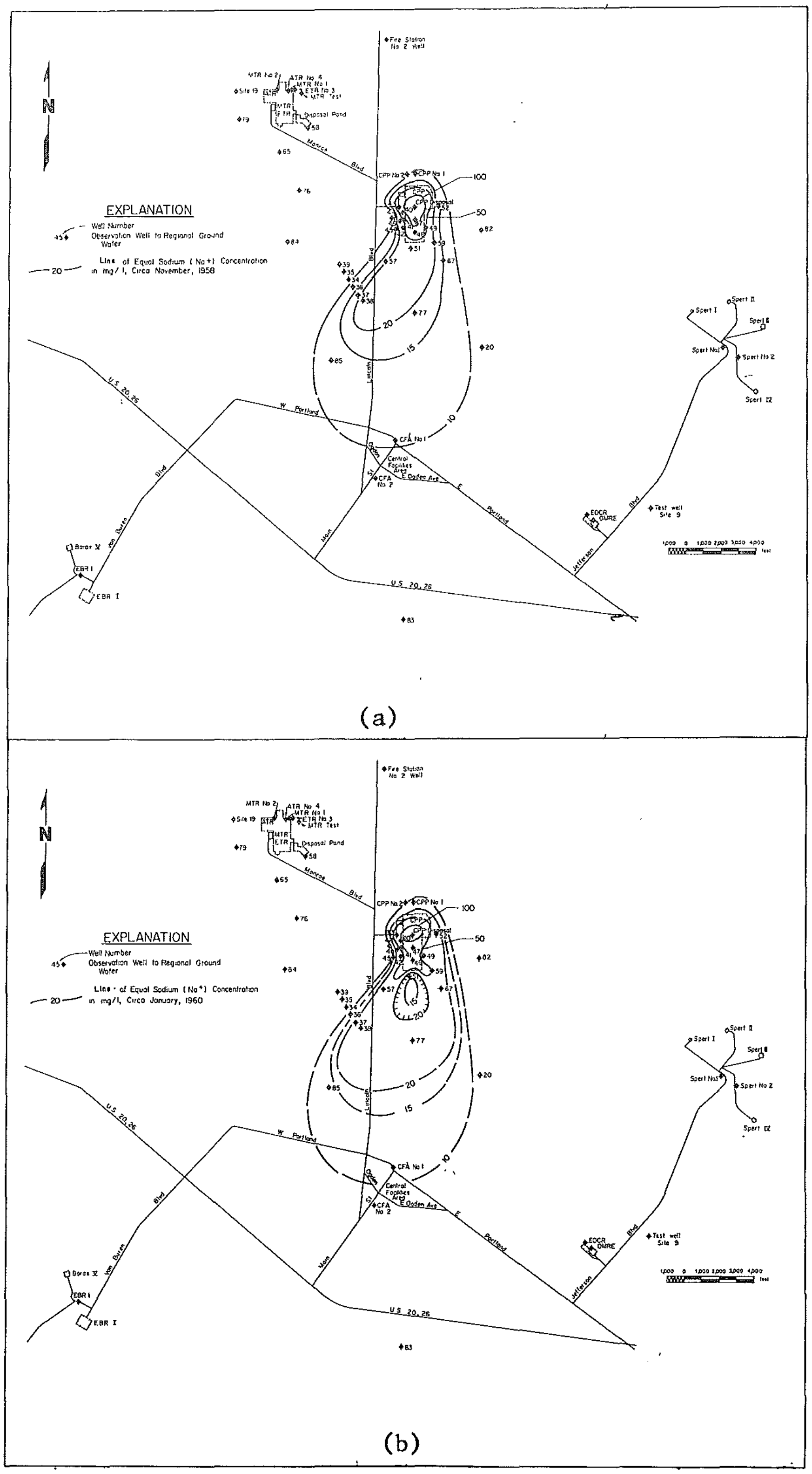


Fig. 64 Maps of the ICPP-TRA vicinity showing distribution of waste sodium in the Snake River Plain aquifer water in 1958 (a), 1960 (b), 1965 (c), and 1968 (d).

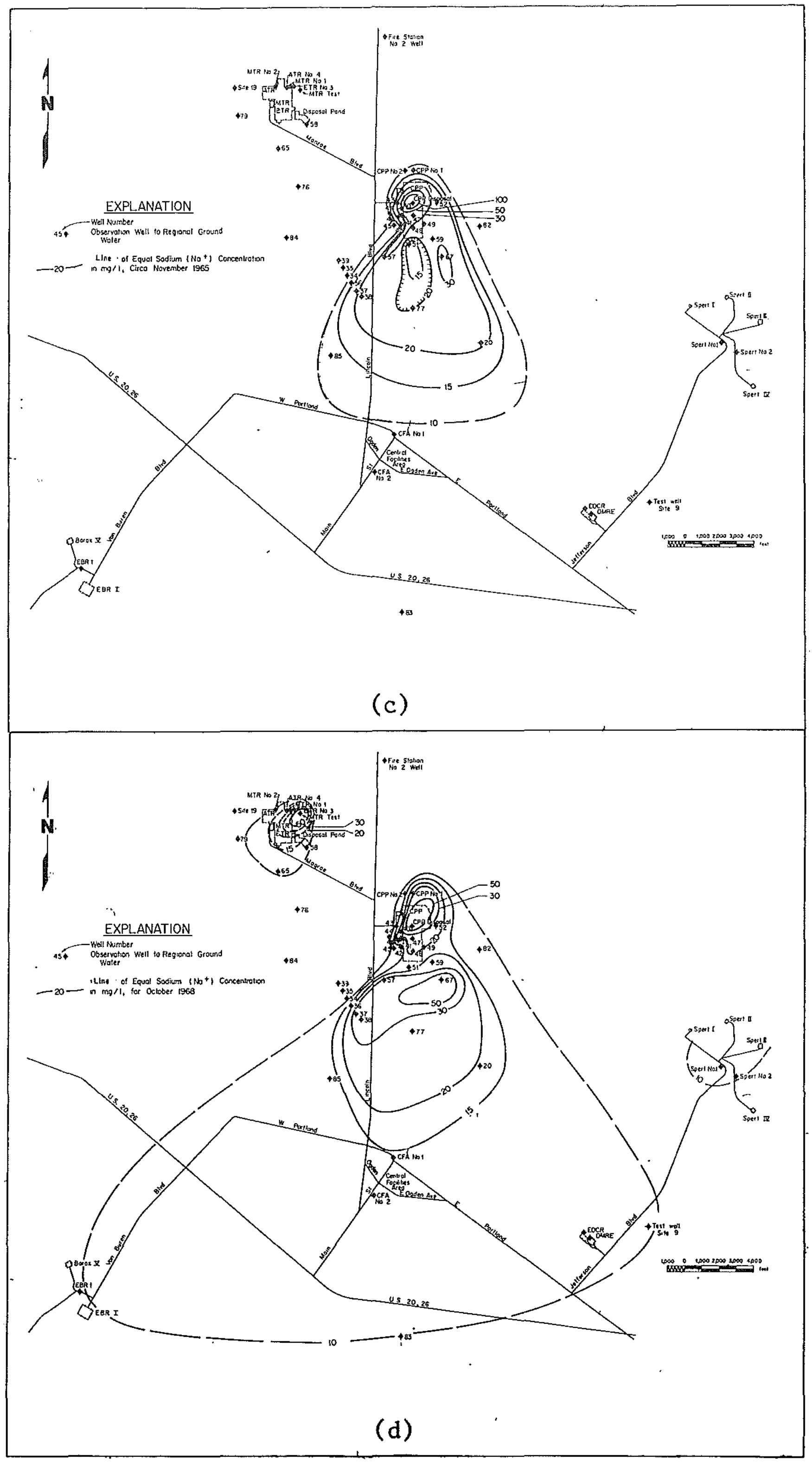

N
EXPLANATION
45 Well Number
Observation Well to Regional Ground Water
20 Line of Equal Sodium (Na+) Concentration in mg/l, Circa November 1965
Fire Station No 2 Well
MTR No 2
ATR No 4
MTR No 1
ETR No 3
MTR Test
Site 19
Disposal Pond
Monroe Blvd
CPP No 2
CPP No 1
CPP
100
50
30
20
15
10
Lincoln Blvd
W Portland
U.S. 20, 26
CFA No 1
CFA No 2
Central Facilities Area
Ogden Ave
E Portland
Main
Van Buren Blvd
Jefferson Blvd
Borax V
EBR 1
EBR I
EOCR
OMRE
Test well Site 9
Spert I
Spert II
Spert III
Spert IV
Spert No 1
Spert No 2
1,000 0 1,000 2,000 3,000 4,000 Feet
(c)
EXPLANATION
45 Well Number
Observation Well to Regional Ground Water
20 Line of Equal Sodium (Na+) Concentration in mg/l, for October 1968
(d)

Fig. 64.

51 in 1965. The log indicated slow upward flow from a depth of 600 feet to about 500 feet due to a small vertical head gradient. The well is normally sampled at 500 feet. Therefore a sample at this depth probably represents water which enters the well at the 600-foot depth (150 feet below the water table). Because of the closeness of Well 51 to the disposal well, the waste contamination zone may very well be limited to the upper 150 feet or so of the aquifer. Jones' data (1961) indicates that most of the waste water is injected in the 60-foot permeable interval of the disposal well between depths of 475 and 535 feet. This would be within the upper 100 feet of the aquifer. The water 150 feet below the water table would therefore be less contaminated than the water 100 feet below. Minor vertical borehole flows caused by vertical head variations have been observed in many other NRTS wells. However most of these wells have not shown a continuous flow over as great a bore length as has Well 51. It is not possible at this time to analyze the effects of these vertical flows in all the wells. Borehole flow was considered in selecting the sampling point in each well. In most cases, the borehole flow effects are probably negligible in analyzing the large-scale waste distribution picture.

The 1960 map shows expected sodium increases over the 1958 concentration regions around Wells 57 and 59. The most notable change evident in the 1965 pattern is the expansion of the 20 mg/l line to Well 20, which is accompanied by a concentration increase around Well 67. The 1968 map shows significant increases in the area enclosed by Wells 57, 67, 77, and 37, but concentration declines are noted in the near-in Wells 41, 42, 47, 48, and 49. This is attributable to the collapse of the disposal well (see Subsection 5.21, Chloride). One of the most obvious features of the 1968 map is the broad extension of the 10 mg/l line. This appears particularly anomalous when compared to the 1965 and 1960 maps. In fact, the 10 mg/l line in 1965 appears more anomalous than in 1968. The 1968 sodium map is reasonably compatible with the 1969 chloride pattern. The 1965 sodium map, however, actually shows a recession in the 10 mg/l line from the 1960 map. Because of the low concentration levels involved, it is believed that the anomalous 1965 pattern may be based on erroneous data; Several of the 1965 samples were from wells that normally contain no waste sodium. Even these "background" samples yielded values 3 to 5 mg/l below their normal levels. For these reasons, the set of samples (analyzed as a batch) on which the 1965 map is based are believed to be 3 to 5 mg/l below their real values. On the other hand, it is quite possible that the 1968 values are 1 or 2 mg/l high. It becomes evident, then, that little reliance can be placed on the exact position of the 10 mg/l sodium line. Because of the analytical methods used, the chloride data are considered more reliable and accurate than the sodium data.

Although the sodium data generally follow patterns similar to the chloride data, the sodium concentrations generally are lower than the normal 3:2 chloride-sodium ratio. The apparent ratios are more near 4:2, in most cases. The reasons for this are uncertain; however, ion exchange or other sorptive reactions are probably responsible. Cationic sodium is more retarded by ion exchange on the basalt and sediments than anionic chloride. No quantitative information is known about the ion exchange characteristics of the aquifer, primarily because of its large-scale features. It is not feasible to extrapolate the results of laboratory studies on small samples to the whole aquifer. However, exchange or other forms of sorption could adequately account for sodium reduction of this magnitude. Cationic strontium-90 and cesium-137 also appear to have been strongly affected by sorption or ion exchange in the aquifer.

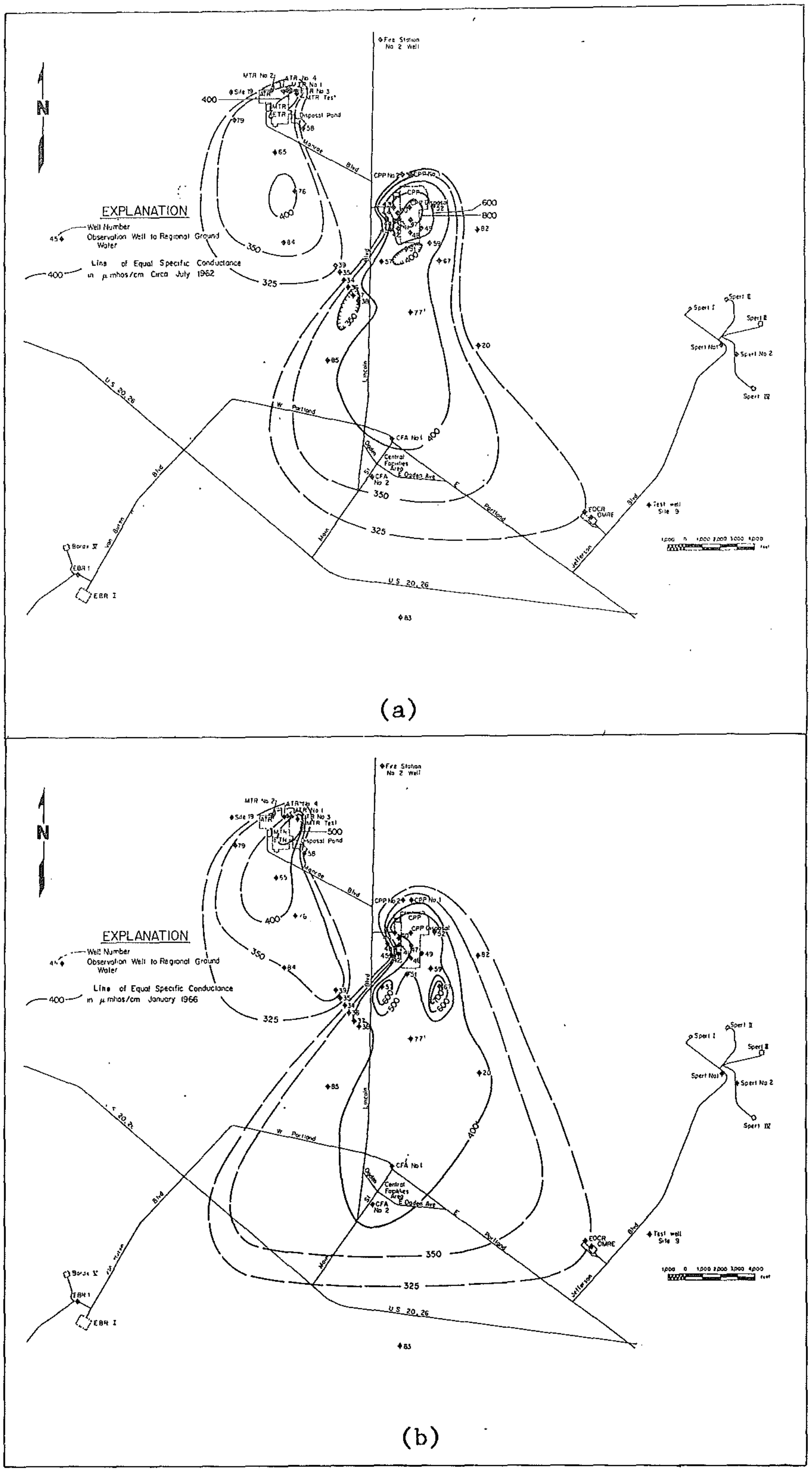
5.23 Specific Conductance. Another chemical indicator of ICPP and TRA wastes is an increase in specific conductance of the contaminated groundwater. This is caused by the increased dissolved solids in the waste effluent (mostly sodium chloride). The first good set of specific conductance data was collected in 1962 and is contoured in Figure 65. The natural specific conductance of the aquifer water generally ranges from about 300 to 325 μmhos/cm at 77°F (25°C) in the TRA-ICPP-CFA region. Therefore, a background level of 325 μmhos/cm is used for this parameter. Conductance data were also collected for three other representative periods -- 1966, 1968, and 1970 (Figure 65).

Specific conductance appears to be a fairly sensitive waste disposal parameter, more so than sodium. For instance, the 1962 map shows the TRA waste plume more extended than was indicated by the chloride or sodium data. The four maps indicate that, in general, it follows much the same pattern as chloride and sodium.

For the natural Snake River Plain aquifer water in the southern part of the NRTS, the ratio of dissolved solids (mg/l) to specific conductance (μmhos/cm) ranges from about 0.59 to 0.63, averaging about 0.61. Wastes from the ICPP and TRA depress the ratio slightly to a minimum of about 0.57 for the more contaminated aquifer waters. For example, a specific conductance of 700 μmhos/cm [near Well 40, Figure 65(d)] would indicate a dissolved-solids content of about 400 mg/l, which is quite reasonable for a near-in sample. The average dissolved solids of the ICPP waste effluent is estimated from about 550 to 650 mg/l with a corresponding specific conductance of 960 to 1,140 μmhos/cm.

There does not appear to be many anomalies in the 1962 map. The extension of the 325 μmhos/cm line southeast to the EOCR area is questionable. The EOCR values could be caused from local waste or merely a higher than normal natural background, or slightly erroneous data.

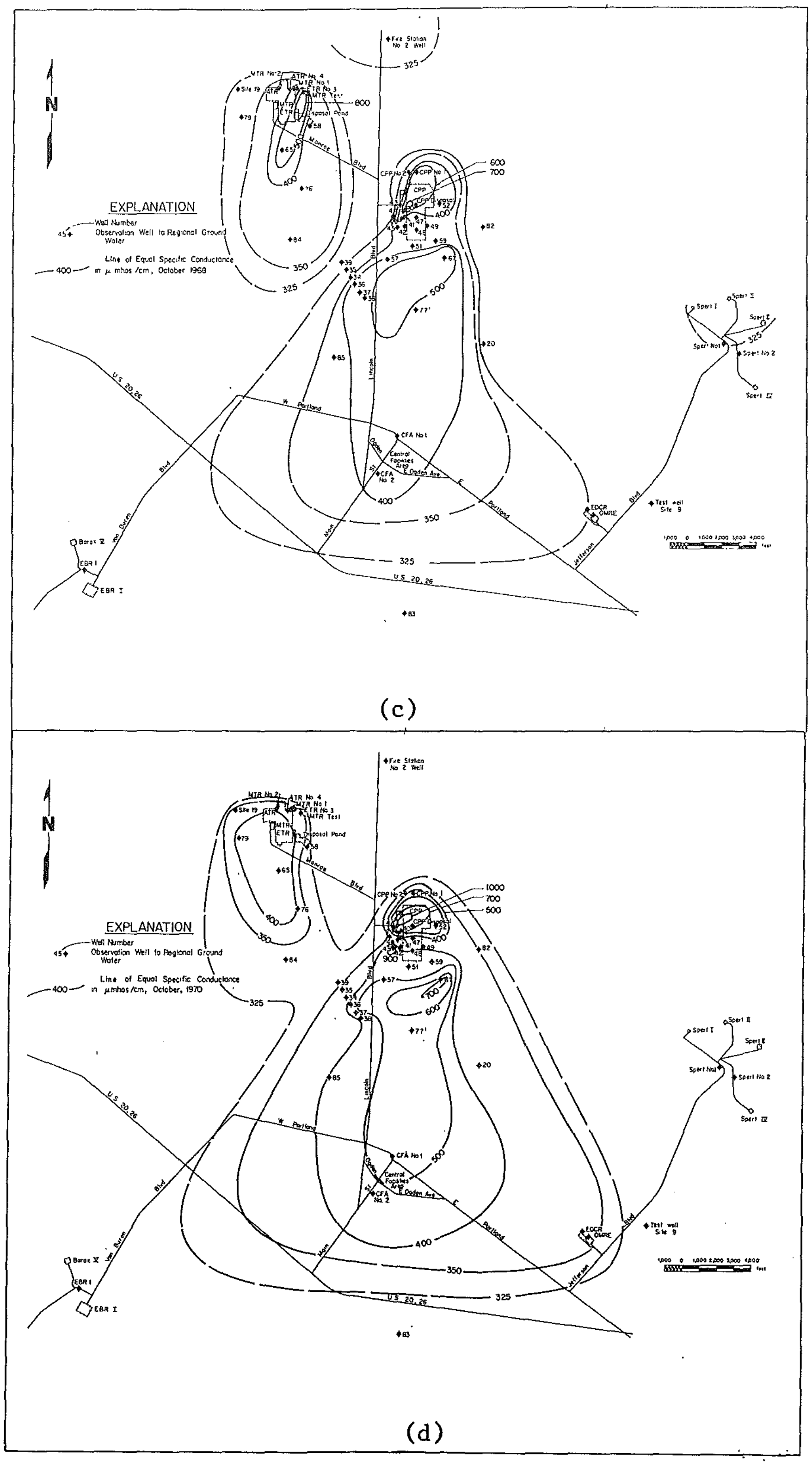
The four maps indicate a reasonable expansion in the 400 to 500 μmhos lines with time. Again, Well 51 demonstrates anomalously low concentrations for all four years. The 1968 conductance map has two noteworthy features. First is the area of reduced concentrations around Wells 42, 47, 48, and 49. This again can be explained by the failure in the disposal well. The second anomalous feature is the apparent decline in concentration at Well 20, which is responsible for the indentation of the 325 μmho line. The reason for



(a)

(b)

Fig. 65 Maps of the ICPP-TRA vicinity showing the distribution of specific conductance in the Snake River Plain aquifer water in 1962 (a), 1966 (b), 1968 (c), and 1970 (d).


N
EXPLANATION
45 Well Number
Observation Well to Regional Ground Water
400 Line of Equal Specific Conductance in µ mhos/cm, October 1968
Fire Station No 2 Well
MTR No 2
MTR No 4
MTR No 1
ETR No 3
MTR Test
Site 19
ETR
MTR
Disposal Pond
Monroe Blvd
CPP No 2
CPP No 1
CPP
Lincoln Blvd
W Portland
E Portland
CFA No 1
CFA No 2
Central Facilities Area
Ogden Ave
Main St
US 20, 26
Van Buren Blvd
Jefferson Blvd
EOCR
OMRE
Test well Site 9
Spert I
Spert II
Spert III
Spert No 1
Spert No 2
Spert IV
Borax V
EBR I
325
350
400
500
600
700
800
(c)
EXPLANATION
45 Well Number
Observation Well to Regional Ground Water
400 Line of Equal Specific Conductance in µmhos/cm, October, 1970
1000
700
500
900
600
400
350
325

(c)

(d)

Fig. 65.

this is unknown; perhaps it is an erroneous value or just a temporary, unusually low value at the time of sampling. The value for Well 20 was back to "normal" in 1970.

The 1970 map, like the 1968 map, shows low conductivity around Wells 41, 42, 47, 48, and 49 (due to the disposal well failure). Other noteworthy features on this map are the extensions of the 500 μmho line and the increase around Wells 40 and 43. The 1970 map indicates that the TRA and ICPP plumes have begun to coalesce. This is also shown in some of the tritium data, which is presented in a following section.

5.24 Temperature. Heat is another significant nonradioactive waste product produced by the ICPP operations and carried down the well in the waste effluent. Few data have been collected on the temperature of the effluent, but indications are that it averages from 65 to 70°F (19 to 21°C). The average natural temperature of the upper 50 to 100 feet of the aquifer in the region is 52 to 54°F (11 to 12°C), as is indicated in Figure 20 in Section III, Geochemistry, and other more recent data. Olmsted (1962) presents a good description of the vertical and areal variations in natural aquifer temperature. The temperature of 53.5°F (12°C) is used here as an appropriate background level for the area. Adequate waste heat distribution data are available for three different periods -- 1958, 1962, and 1969 and are mapped in Figure 66. The temperature measurements in Figure 20 were made by a sensitive down-hole logging probe. Some of the data in Figure 66 were also collected by the down-hole logger, while others represent less-reliable measurements on retrieved samples. In most cases, the accuracy of the data is probably within 0.5°F (0.3°C).

Heat does not appear to be as sensitive a tracer as some of the chemical or radioactive parameters. This is due to several reasons. First, the relative temperature increase caused by the waste is lower, compared to natural background variations, and is much smaller than the increase in other parameters such as chloride and conductivity. Secondly, heat is readily conducted out of the water into the rock, particularly the strata overlying the aquifer. Another limiting factor is the low precision and accuracy in measurements, relative to the more precise chemical and radioactive analyses such as chloride and tritium.

The 1969 temperature shows a logical expansion in the 56°F (13°C) line, but reveals an anomalous recession in the 53.5 and 54°F (11.9 and 11°C) lines away from Well 20.

Perhaps the earlier data represented unusually high natural temperature levels at Well 20, or possibly the 1969 value for Well 20 is in error. It should be kept in mind that a temperature of 54°F (12°C) is not substantially above background.

The principal conclusion drawn from the temperature data is that thermal waste discharges have not caused large or widespread temperature changes in the aquifer. The heat balance described in a following section also indicates that heat effects will continue to be minor because heat dissipates from the groundwater into the overlying strata and maintains

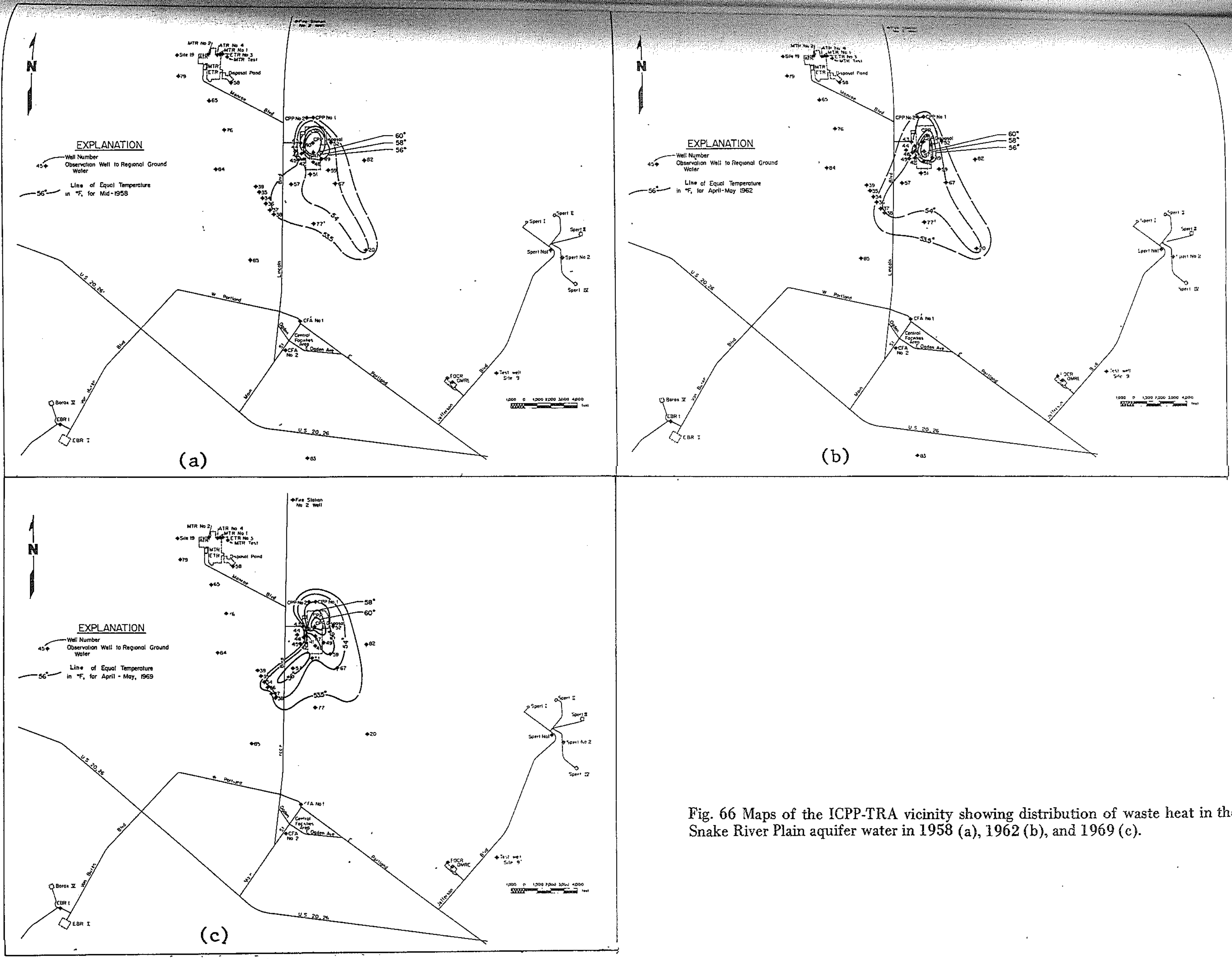


Fig. 66 Maps of the ICPP-TRA vicinity showing distribution of waste heat in the Snake River Plain aquifer water in 1958 (a), 1962 (b), and 1969 (c).

an equilibrium heat content of the aquifer, in which heat is conducted away as fast as it is injected.

5.25 Chromium. Many of the NRTS facilities have discharged dissolved chromate wastes at various times. The TRA, NRF, and EBR-II have been the principal users. In recent years, the TRA has discharged more significant quantities of waste chromates than any other facility. The NRF has changed over from use of a chromate process to a polyphosphate anti-corrosion treatment and the TRA has plans to do the same. EBR-II has installed a chromate reduction system in which hexavalent chromium, Cr(VI), is reduced to the trivalent state.

The only facility from which waste chromium in the aquifer has been observed is TRA. Chromium contamination in the Snake River Plain aquifer at NRTS was first studied by the Geological Survey in 1966 (Barraclough, Teasdale, Robertson, and Jensen, 1967). That study showed that less than 10% of the chromates were reduced from hexavalent form to trivalent or other forms in the ground. For this reason total chromium concentration, which is simpler to analyze for than hexavalent, is considered representative of hexavalent concentration. It also showed that chromium served as a useful tracer to distinguish TRA wastes from ICPP wastes in the aquifer because the ICPP has not discharged any significant amounts. Therefore, the presence of chromium in groundwater downgradient from the TRA and ICPP is indicative of TRA wastes as there is no detectable natural chromium in the water. This is particularly definitive in the area where the TRA and ICPP waste dispersion plumes have mingled or coalesced. Another good tracer property of chromium is that it can easily be detected at concentrations as small as 0.005 mg/l.

Prior to November 1964, the TRA chromate wastes were discharged to the seepage ponds, but since then they have been discharged down the disposal well, directly into the Snake River Plain aquifer. The chromium content of the waste effluent and the quantities discharged are discussed in the foregoing section describing waste characteristics. The normal detection limit for the analysis of chromium in water by the colorimetric method used by the AEC at the NRTS is about 0.005 mg/l. Therefore, on the basis of the detectability, a lower limit of 0.01 mg/l was chosen to be indicative of chromium contamination.

Data for 1966, 1967, and 1970 (Figure 67) indicate that few significant changes have occurred in the distribution patterns over the five-year period. The western and southwestern extent of the plume is only inferred, because appropriate observation wells are not available to define that part. The most significant changes from 1966 to 1970 were the southeastward expansion of 0.01 mg/l line to the CFA-1 and -2 production wells and the 0.05 mg/l line to Wells 35 and 39. The southern extent of the outer line (0.01 mg/l) is not shown on the 1970 map because data were not available. The 1970 data indicate that 0.05 mg/l line had receded to about the 1966 position. Well 65 consistently shows the highest

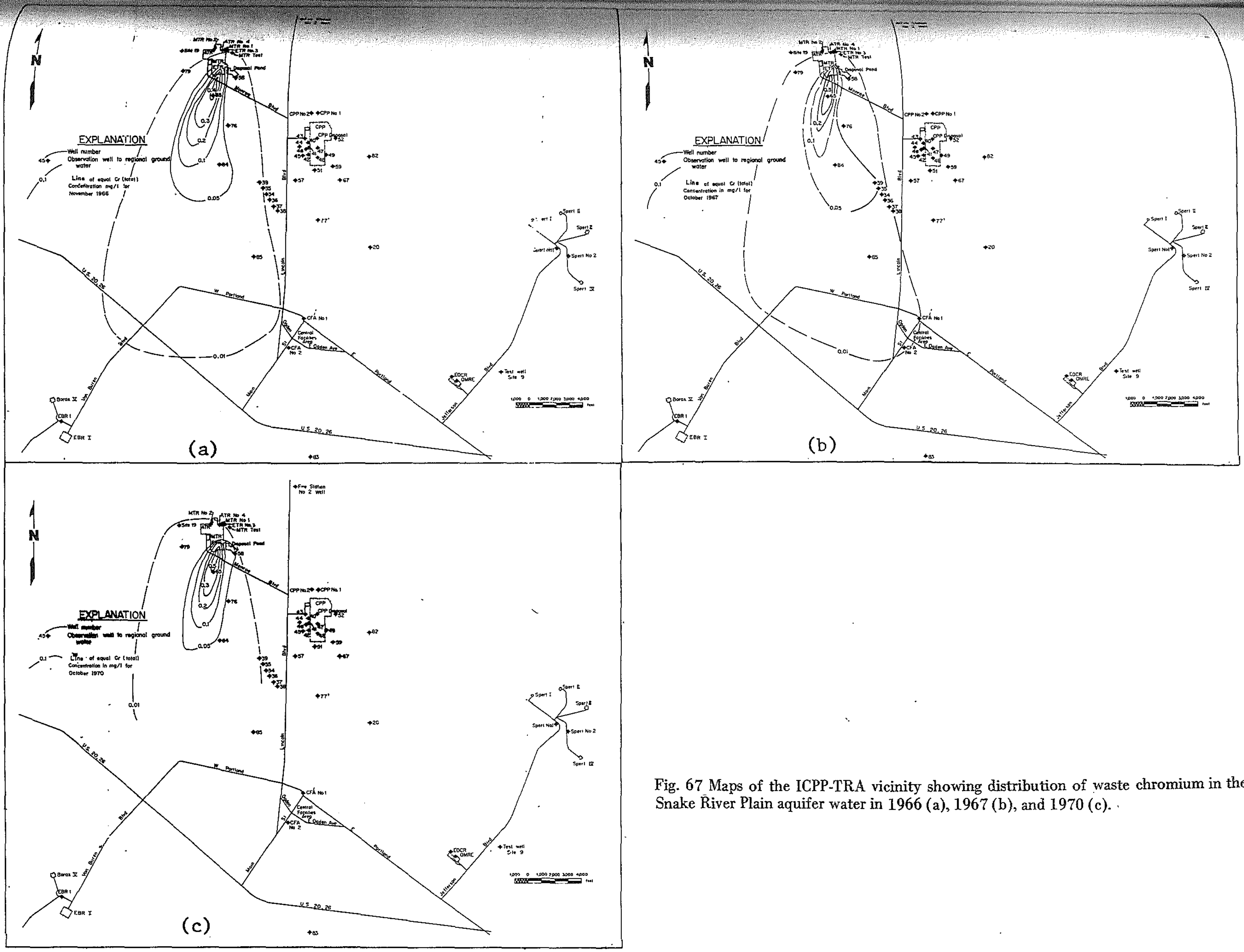


Fig. 67 Maps of the ICPP-TRA vicinity showing distribution of waste chromium in the Snake River Plain aquifer water in 1966 (a), 1967 (b), and 1970 (c).

concentrations of any of the aquifer observation wells. The highest chromium level observed in that well was 0.5 mg/l in 1970.

As Figure 67 indicates, a considerable area of the aquifer (perhaps 1 square mile or more) contains chromium in excess of drinking water limit of 0.05 mg/l However, none of the zone is tapped by supply wells. Above-background concentrations of Cr(VI) are occasionally detected in the two CFA supply wells and in some of the TRA supply wells, but none have exceeded the 0.05 mg/l value.

5.3 Radioactive Components

Only two waste radioisotopes, Sr-90 and tritium, are detectable in the Snake River Plain aquifer over a significant area of distribution. Other radioactive waste products such as Cs-137 are not detectable for one or more of the following reasons: (a) their discharge concentration is too low, (b) their half-life is too short, (c) their concentration is rapidly reduced by sorption reactions.

5.31 Strontium-90 and Cesium-137. Because Sr-90 has a half-life of 28 years and tends to become fixed in the bones if ingested, it has a very low allowable concentration limit (0.01 pCi/ml) in public drinking water. Since 1958, Sr-90 has been a significant waste product at the TRA and ICPP (Table IX). All the TRA Sr-90 has been discharged to the seepage ponds. A little more than half of the ICPP Sr-90 has been discharged to the shallow pit while the remainder was discharged to the deep well. Because of the waste ion-exchange system installed September 1970, Sr-90 and Cs-137, as well as other cationic radionuclides, will probably no longer be discharged to the ICPP well in significant quantities.

The first extensive analysis of Sr-90 in the aquifer was completed in 1964 and subsequent analyses were carried out in 1966 and 1970 (Figure 68). In 1964, the highest concentrations, near the ICPP disposal well, were somewhat greater than 0.06 pCi/ml and the areal extent of the Sr-90 was rather limited. The 1966 data show a similar areal extent, and the concentration around Wells 43 and 47 had risen to about 0.2 pCi/ml. These increases are undoubtedly related to the high Sr-90 discharges in 1962 and 1963 (Table IX). The background Sr-90 content of the aquifer from fallout is below the detection limits of the analytical procedures used for these studies. The detection limit depends on several factors but generally ranges from 0.002 to 0.0045 pCi/ml for these samples. On that basis, the value of 0.005 pCi/ml was chosen to represent detectable waste Sr-90.

In 1970, Sr-90 concentrations had declined to about 0.06 pCi/ml near the disposal well (Figure 68), correlating with the reduction in discharge after 1962 and 1963. Before 1970, only the close-in wells were sampled (Wells 40 through 49, 51, and 59) as it was believed that the Sr-90 was confined only to the aquifer water near to the disposal well.

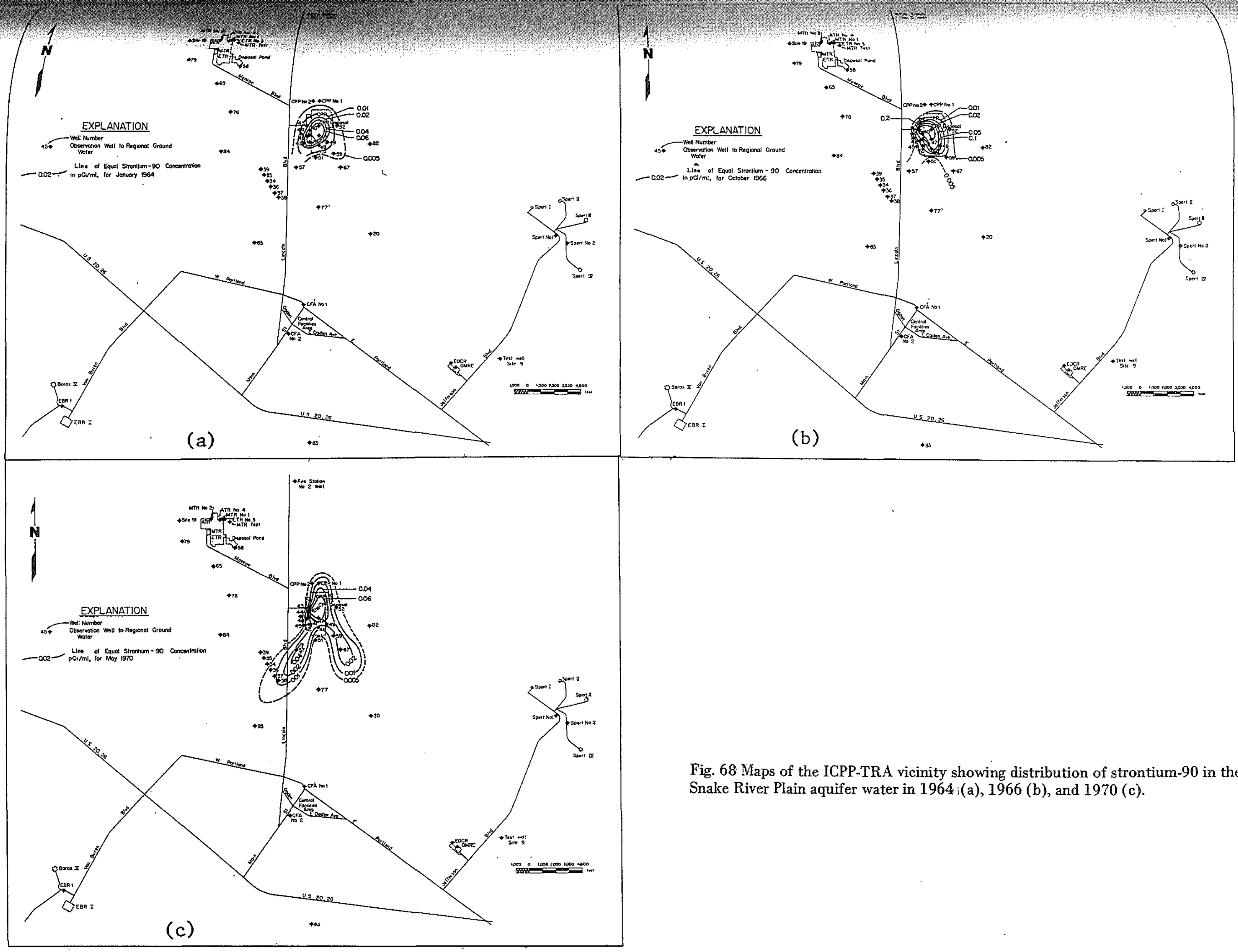


Fig. 68 Maps of the ICPP-TRA vicinity showing distribution of strontium-90 in the Snake River Plain aquifer water in 1964 (a), 1966 (b), and 1970 (c).

Although significant amounts of Sr-90 have also been disposed to the ground at the TRA, none has been detected in the Snake River Plain aquifer from these releases. Thus, none is indicated in the TRA region on Figure 68. The Sr-90 is apparently sorbed on the sediments as it percolates downward from the disposal ponds. Although the Sr-90 has passed through the surface alluvium into the perched water in the basalt, it has not passed through the lower interbedded sediments into the Snake River Plain aquifer.

The ICPP Sr-90 distribution patterns indicate that this waste product has not migrated as far as some of the other solutes such as chloride and tritium. The Sr-90 data more closely resemble the temperature distributions than those of other waste products. This can be explained by several factors. First, the original concentration of the Sr-90 in the effluent is relatively low (normally about 1 to 2 pCi/ml). Second, Sr-90 concentration decreases with time because of radioactive decay. However, the long 28-year half-life diminishes the significance of this factor. Third, and most importantly, Sr-90 is susceptible to ion exchange on earth materials. The mineral exchange sites in the NRTS subsurface are largely calcium saturated because of the relatively high ratio of dissolved calcium content of the water. Dissolved strontium tends to exchange with calcium on exchange sites. Even through a relatively small amount of mineral surface area is available to the groundwater, it is believed that ion-exchange is largely responsible for the retarded migration of waste Sr-90. This belief is strongly supported by the materials balance data in the following section and by the Cs-137 distribution data which are also discussed below.

The 1966 data indicate that Sr-90 concentrations in the aquifer from ICPP have ranged up to about 0.2 pCi/ml. The maximum concentrations observed in 1970 are about 0.06 pCi/ml. The guide concentration for Sr-90 in drinking water for a restricted area such as the NRTS is 0.3 pCi/ml (AEC regulations). For public supply, the Public Health Service (PHS) maximum limit is 0.01 pCi/ml. The only drinking water supply wells which contain detectable Sr-90 are the CPP-1 and -2 wells. Water from the CPP-1 and CPP-2 wells has contained as much as 0.04 and 0.03 pCi/ml Sr-90, respectively. Both AEC and PHS limits are based on Federal Radiation Council recommendations and the difference is based partially on greater monitoring and control and lower per capita intake rate for a restricted supply versus a public supply.

The production of waste cesium-137 (Cs-137) is closely related to Sr-90; consequently, it has been discharged in nearly parallel quantities at the ICPP (Table IX). Cs-137 also has a similar half-life (30 years). Although many analyses have been run, Cs-137 has never been detected in aquifer water below the ICPP region, apparently because of ion exchange. Cesium ions have a greater selectivity coefficient for ion exchange than any other ionic species. The small quantities of Cs-137 injected in the aquifer seem to be almost totally removed from solution by exchange reactions within a distance of a few hundred feet.

On September 10 and 23, 1969, a total of 3.5 Ci each of Sr-90 and Cs-137 was accidently discharged to the ICPP disposal well. Because these were unusually large, short-period releases, it appeared to be a good opportunity to follow tracer slugs of the two isotopes as they migrated past downstream observation wells. About 2 Ci of each isotope were released September 10 and about 1.5 Ci of each were released September 23. Because it was not known that the disposal well had collapsed and plugged, it was assumed that Cs-137 and Sr-90 had entered the aquifer directly and would migrate downgradient. Sampling of the close-in wells (numbers 40, 41, 42, 47, 48, and 49) (Figure 69) showed no apparent effect of the discharge.

It was concluded later, when the poor condition of the disposal well became evident, that the waste containing the Sr-90 and Cs-137 entered the perched water body above the aquifer where it has been retarded from entering the aquifer (Figure 70). The perched water system not only delayed the waste water from entering the aquifer but also provided a much greater opportunity for ion exchange in fine-grained sediment layers.

Sr-90 concentrations in Well 50 (which were not examined until later) show the expected increase from the high Sr-90 discharge entering the perched water (Figure 69). The 2.5 pCi/ml Sr-90 concentration for Well 50 is the highest ever observed in any NRTS groundwater. The maximum concentration peak in Well 50 probably occurred between October 1969 and January 1970 and was therefore missed because of the low frequency of sampling. It is evident that Well 50 concentrations are about an order of magnitude higher than those in the six deeper wells tapping the regional aquifer.

The samples of perched water from Well 50 failed to yield any detectable Cs-137. This is again attributable to the high affinity of cesium to adsorption by ion exchange.

5.32 Tritium. Tritium, by far the most abundant component of the NRTS radioactive waste effluents, is also the most widespread radioactive waste product in the Snake River Plain aquifer. For this reason plus its ease of detectability, it has been studied and analyzed more than any other NRTS waste product. The tritium distributions in the aquifer are more complex and difficult to interpret than the chloride or specific conductance patterns because of the variability in tritium discharges. Another complicating factor is that radioactive decay reduces the content in the aquifer.

The background tritium concentration in the aquifer, due to natural and fallout sources, is variable arealy and temporally and generally averages less than 0.2 pCi/ml per ml. Hawkins and Schmalz (1965) analyzed the earliest data available, 1956, and concluded that the average tritium concentration in the aquifer then was about 0.13 pCi per ml. Barraclough, Teasdale, Robertson, and Jensen (1967) reported an average background of 0.05 to 0.1 pCi per ml for the aquifer in the NRTS vicinity in 1966. Surface water and precipitation samples commonly ranged from 1 to 3 pCi/ml during the 1960's in the Snake

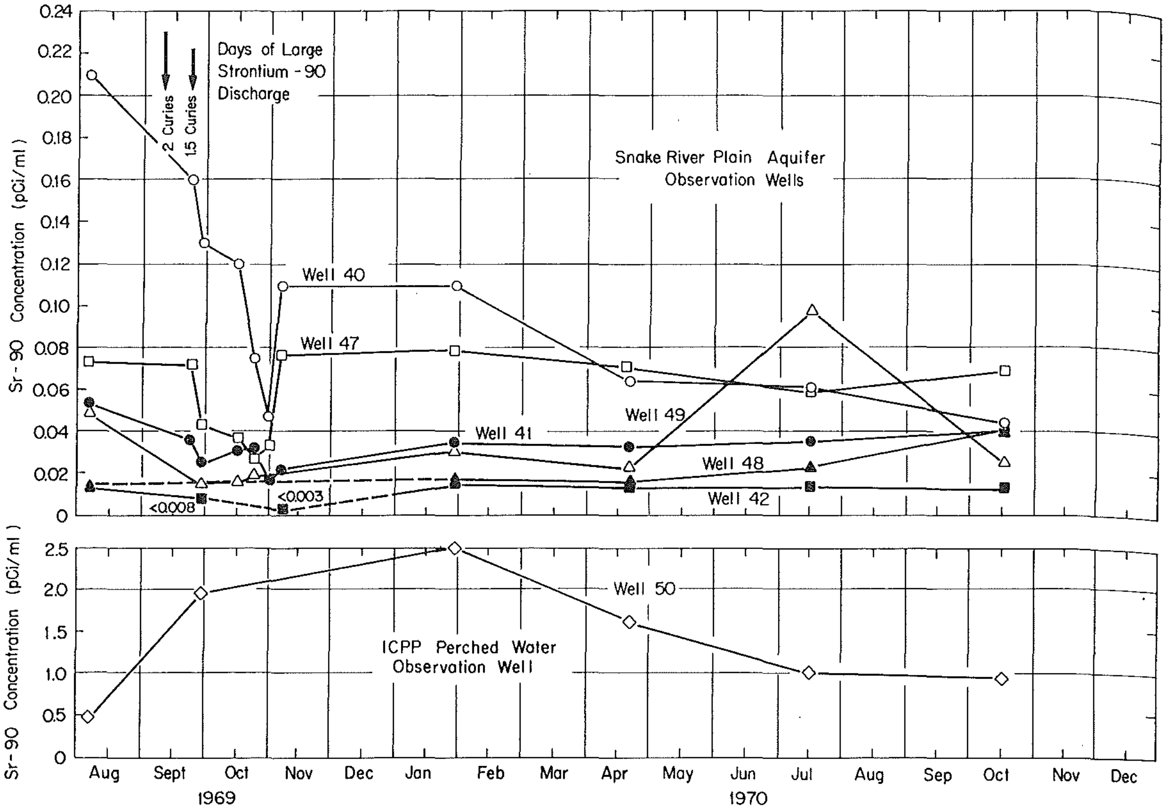


Fig. 69 Graphs of strontium-90 concentration of samples from perched and regional groundwater in the ICPP vicinity.

River Plain vicinity. The first comprehensive analysis of waste tritium distribution in the aquifer was conducted in 1961. The results (Figure 71) indicate that, by 1961, significant concentrations of tritium had spread as far south as the CFA production wells, as had waste sodium and chloride. Hawkins and Schmalz (1965) concluded that the first arrivals of ICPP tritium waste at the CFA-1 and -2 wells occurred in 1958, which is also consistent with Figure 71. Their conclusion was based on tritium analyses of various chemical reagent solutions which had been prepared at various times between 1953 to 1961 from CFA supply water.

The 1961 5-pCi/ml line represents the approximate analytical detection limit at that time. The concentrations greater than 700 pCi/ml at Wells 59 and 38 are among the highest ever observed in the aquifer. They are certainly the highest values observed at those distances from the disposal well, as can be seen from the accompanying maps for later years, 1963, 1968, and 1970 (Figure 71). These high concentrations again verify the conclusion that the largest tritium discharges occurred previously, before monitoring. The detection limit improved from 5 pCi/ml in 1963 to 2 pCi/ml in 1966. This may lead to the mistaken impression that the outer fringe of the waste actually expanded to the extent indicated by the outer lines from 1963 to 1966.

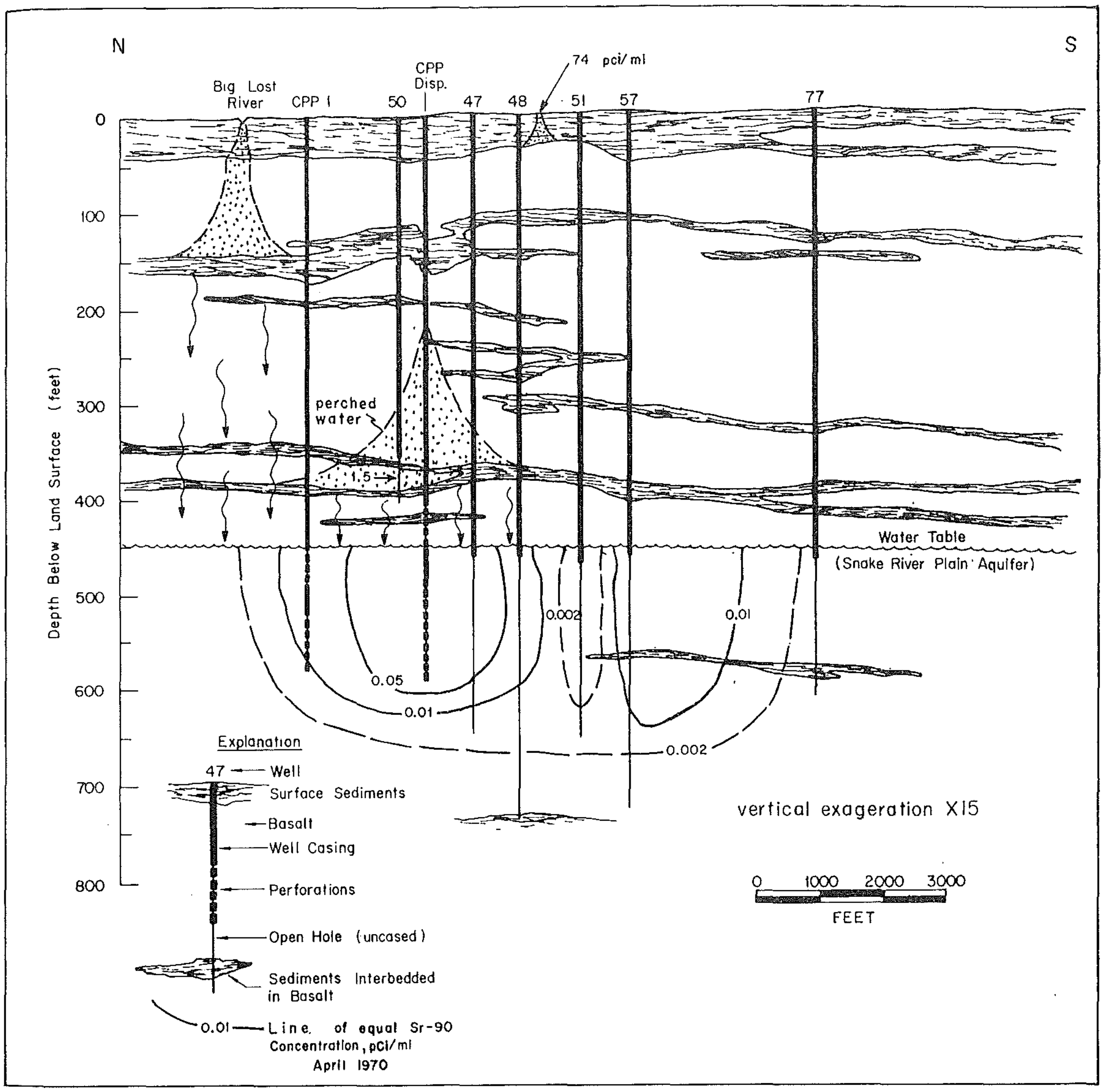


Fig. 70 Cross section through the ICPP area showing distribution of strontium-90 in perched and regional groundwater.

The map for 1963 [Figure 71(b)] shows significant advances in the 25, 50, 100, and 200 pCi/ml lines but declines are indicated in concentrations at Wells 38 and 59. The high concentrations for these two wells on the 1961 map are probably due to a previous period of unusually high tritium discharge.

The 1968 data [Figure 71(c)] do not indicate major downgradient expansion in tritium concentrations from 1963; in fact, the 200 pCi/ml line shows a large decline.

Another significant feature of the 1968 tritium data is the apparent merging of the TRA and ICPP waste plumes in the vicinity of Wells 34 through 39. This coalescence was

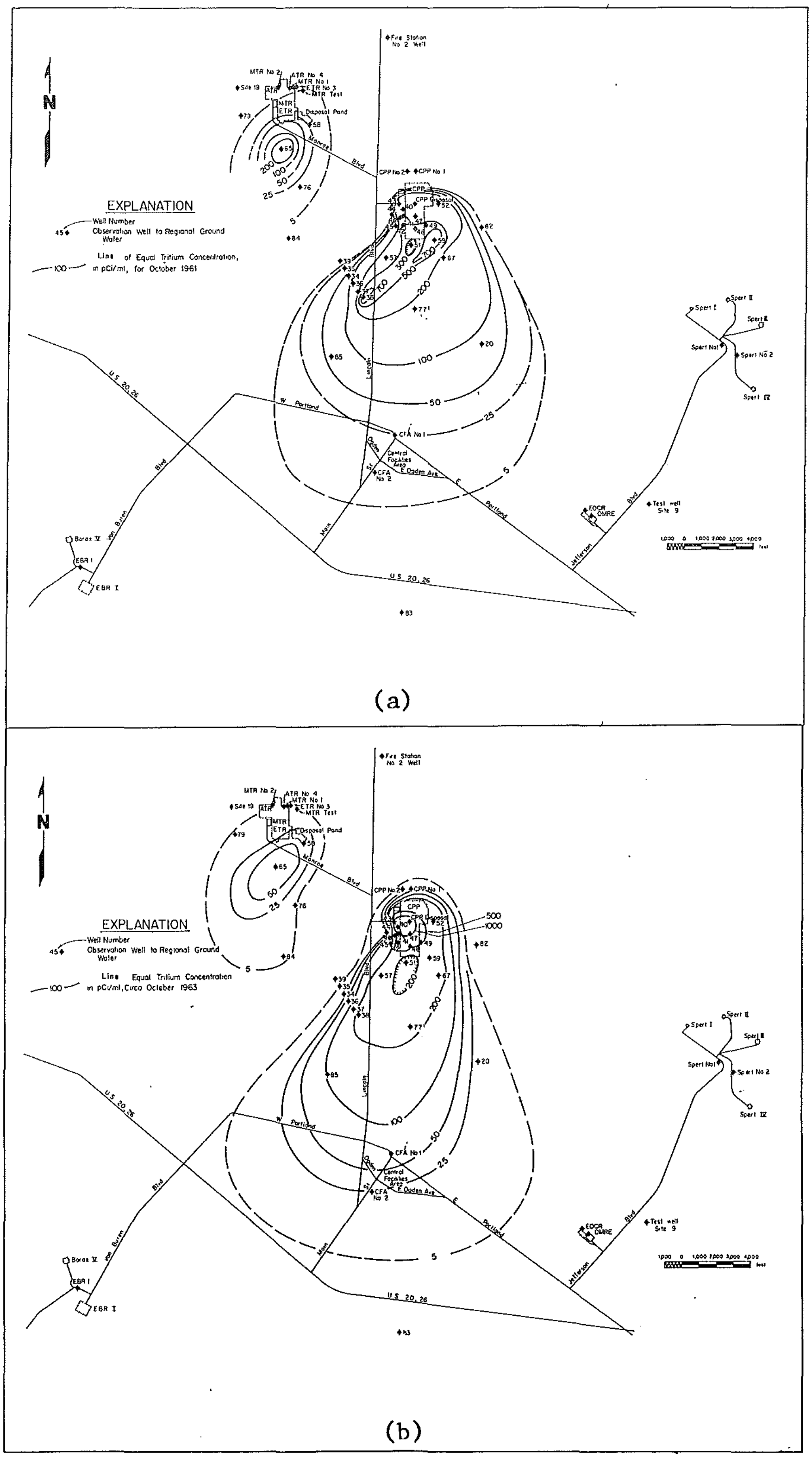


Fig. 71 Maps of the ICPP-TRA vicinity showing distribution of tritium in the Snake River Plain aquifer water in 1961 (a), 1963 (b), 1968 (c), and 1970 (d).

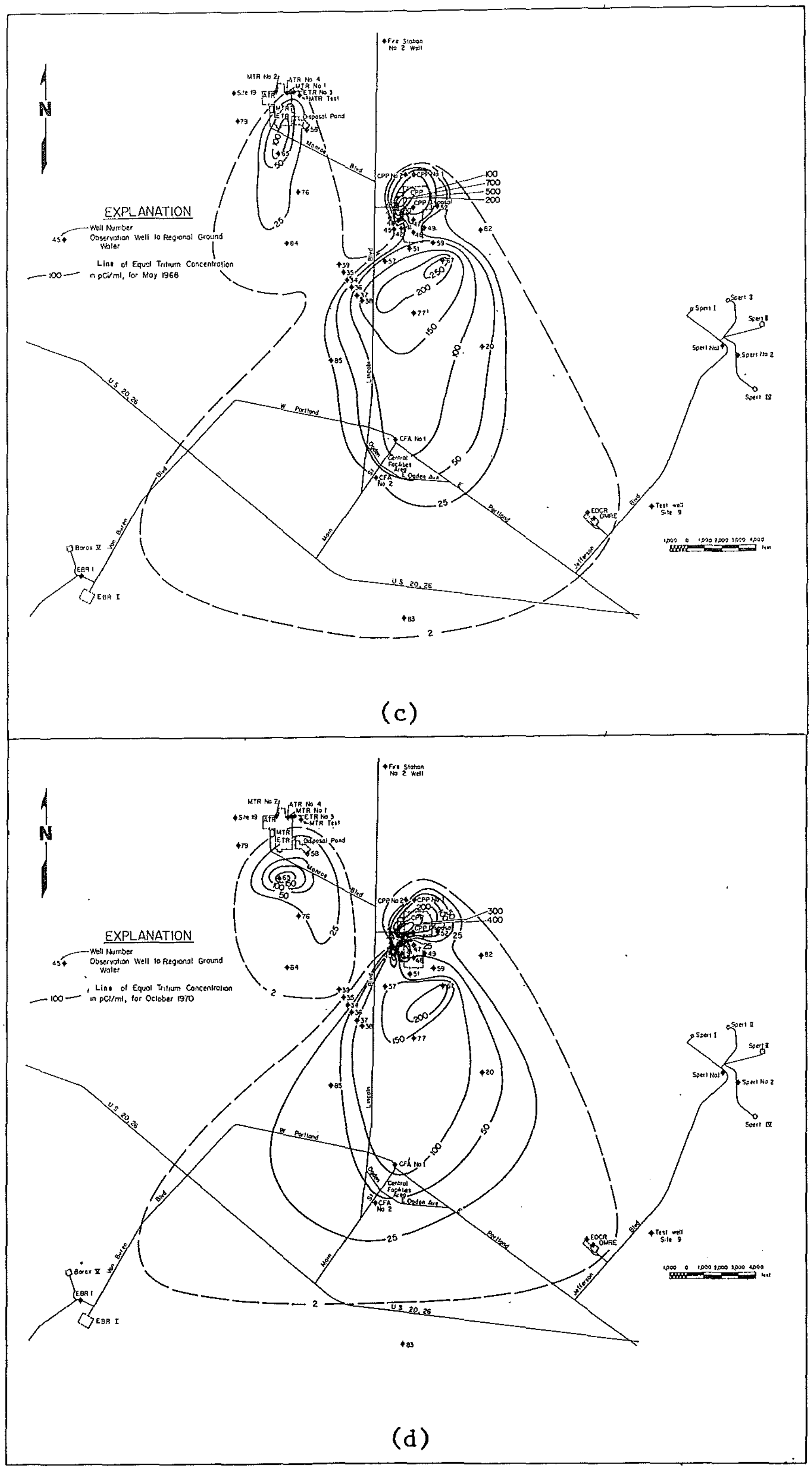

N
EXPLANATION
45
Well Number
Observation Well to Regional Ground Water
100
Line of Equal Tritium Concentration in pCi/ml, for May 1966
Fire Station No 2 Well
MTR No 2
ATR No 4
MTR No 1
ETR No 3
MTR Test
Site 19
ATR
MTR
ETR
Disposal Pond
CPP No 2
CPP No 1
CPP
CPP Disposal
Monroe Blvd
Lincoln Blvd
W Portland
E Portland
U.S. 20, 26
Van Buren Blvd
Jefferson Blvd
Main
Ogden Ave
CFA No 1
CFA No 2
Central Facilities Area
Spert I
Spert II
Spert III
Spert No 1
Spert No 2
Spert IV
EOCR
OMRE
Test well Site 9
Borax V
EBR I
100
700
500
200
250
150
50
25
2
(c)
EXPLANATION
Line of Equal Tritium Concentration in pCi/ml, for October 1970
300
400
(d)

Fig. 71.

observed in several sets of samples collected from 1967 through 1969. The phenomenon was also demonstrated in the 1970 specific conductance data (Figure 65). It is interesting to note that the October 1970 tritium data [Figure 71(d)] again show a slight separation of the two plumes. This verifies two earlier sets of samples collected in May 1970 and October 1969, which showed even greater separations. Apparently the two dispersion plumes first coalesced late in 1967 and continued in that status until the summer of 1969. The explanation for the reseparation is apparently due to local recharge from the Big Lost River, which flows intermittantly in this region. When the river flows in this reach, fresh recharge water percolates down between Wells 39 and 76 and enters the aquifer. This water not only dilutes the waste products but also changes the head distribution in the aquifer which, in turn, diverts the flow patterns. The record high discharge year for the river on the NRTS was 1969. The massive recharge from this flow correlates well with the plume separation beginning in the summer of 1969. The separation increased through the fall of 1969 and spring of 1970 then began to readvance toward coalescence, as indicated in the October 1970 tritium and specific conductance data. Well 78 (Figure 5), which is very close to the river, between Wells 84 and 76, reflects large and rapid recharge effects with any major change in the river's discharge. The well is only 200 feet deep and thus does not tap the Snake River Plain aquifer. It taps only the perched water formed by the percolating river recharge water. Details of the relationship between Well 78 and the Big Lost River and other recharge effects are described in previous reports (Barraclough, Teasdale, Robertson, and Jensen, 1967; and Barraclough, Teasdale, and Jensen, 1967). Although the 25-pCi/ml line shows some expansion in 1970, the 2, 50, and 100 pCi/ml lines remain about the same as on the 1968 map. The 150 and 200 pCi/ml lines (near Wells 57, 67, and 77) continued to show considerable shrinkage in 1970, as they did in 1968. These declines have resulted mainly from the general reduction in total tritium discharge since 1964 (particularly 1965 and 1966) and also from the effects of the collapsed disposal well which has delayed the 1968 through 1970 discharges from entering the aquifer. Tritium data from 1970 were also used to interpret the vertical tritium distribution in relation to lithology and perched water in the TRA-ICPP-CFA regions (Figures 72 and 73).

The materials balance section of this report which follow describes and relates quantitatively the discharge and accumulation of waste tritium in the aquifer.

6. HEAT AND MATERIALS BALANCES

6.1 Introduction

Materials and energy balances provide an assessment of validity and completeness of the preceding interpretations of the underground distributions of the ICPP wastes. These balances are made by comparing the amount of waste product discharged to the aquifer to the amount that appears to be present in the aquifer, minus any known losses. Significant differences point to errors or overlooked aspects of the system.

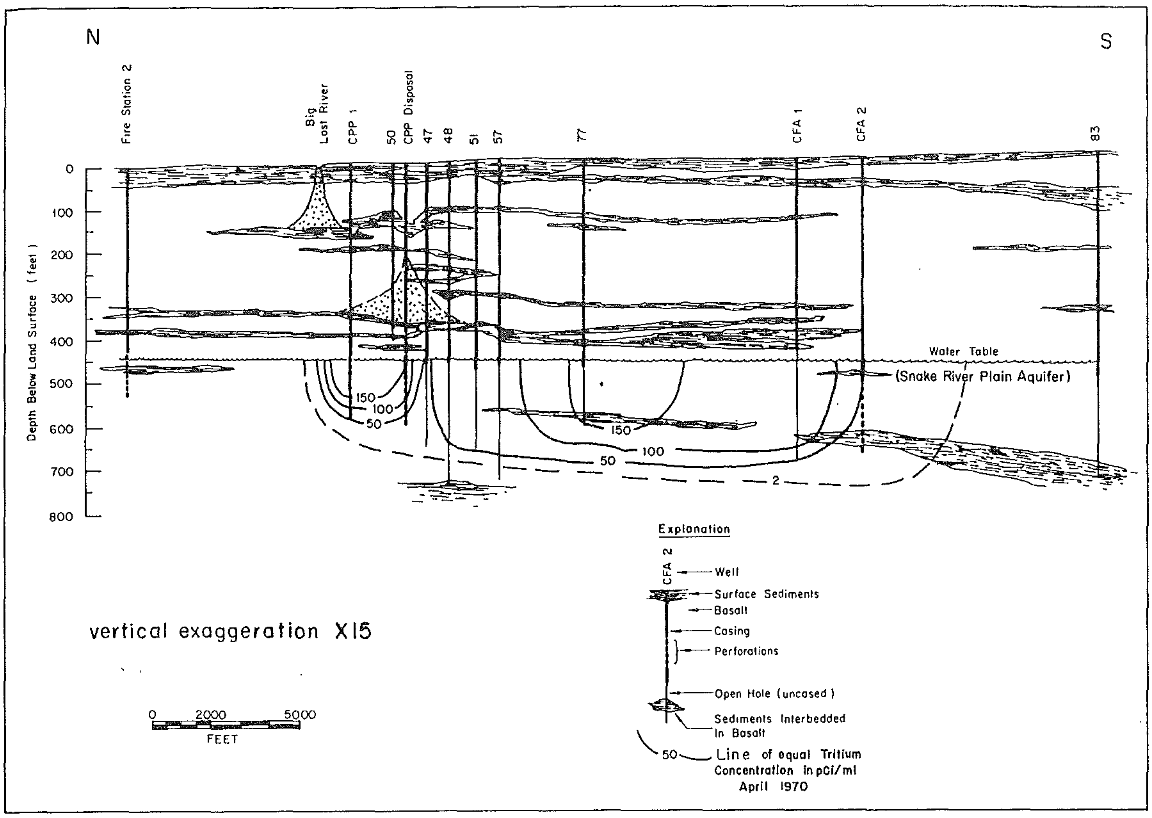


Fig. 72 Cross section through the ICPP-CFA area showing the distribution of tritium in the regional groundwater in 1970.

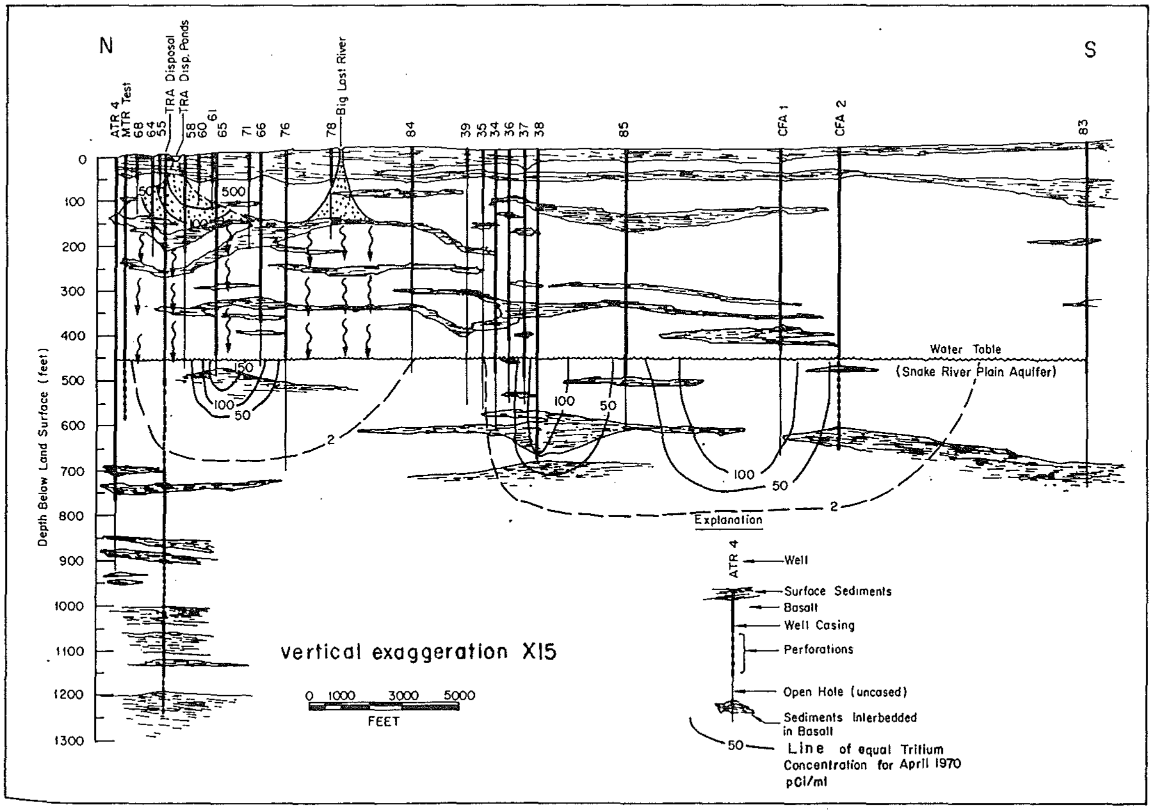


Fig. 73 Cross section through the TRA-CFA area showing the distribution of tritium in the perched and regional groundwater in 1970.

Best estimates of the quantities discharged are obtained from data in Tables X and XI and accompanying discussion. Evaluating the quantities underground is somewhat more complicated and less certain. The available data are plotted on maps (Figures 62 through 66 and Figure 71). The total quantity of the waste product in the aquifer is calculated using incremental volumes of water in the aquifer and multiplying by the average concentration for the increment. The contaminated area (all that within the outer line) is first divided in area increments, considering the area between two consecutive lines to be one increment. The area between the two lines is then measured by planimeter or grid paper and an approximate average concentration assigned to the area. The estimated volume of water beneath the area increment is then calculated with the formula

$$V_n = A_n H_n \Theta_n \tag{17}$$

where V_n is the volume of aquifer water in increment n, A_n is the surface area of the increment, H_n and θ_n the saturated thickness and porosity values, respectively, used for the particular increment. The quantity of waste product in the incremental volumes is then calculated by

$$Q_n = V_n C_n = C_n A_n H_n \Theta_n \tag{18}$$

where Q_n is the total quantity of waste product in V_n and C_n is the average concentration of the waste product within the increment. The total quantity of the contaminant in the aquifer, Q_T, is then calculated by summing the incremental values

$$Q_T = \sum_{n=1}^{k} Q_n = \sum_{n=1}^{k} C_n A_n H_n \Theta_n \tag{19}$$

where k is the total number of area increments used. For the NRTS region, the effective porosity is generally (but not necessarily) assumed constant over the entire area of interest, in which case Equation (19) becomes

$$Q_T = \Theta \sum_{n=1}^{k} C_n A_n H_n \quad . \tag{20}$$

In estimating the average effective porosity of the aquifer, several sources of data were used, including measurements on many samples, well aquifer tests, etc. These data indicated the porosity should be between 5 and 15%. Barraclough, Teasdale, Robertson, and Jensen (1967) used a range of 6 to 10%. An effective porosity of 7% was used for these studies based on the results of previous tritium balances (Barraclough, Teasdale, Robertson, and Jensen, 1967) and other physical data. The contaminated thickness of the aquifer is assumed to range from about 200 feet near the disposal well to perhaps 275 feet in the more extended regions with an average of about 250 feet.

6.2 Tritium

The above materials balance method was used by Barraclough and others (1967) to evaluate NRTS tritium distributions in the regional groundwater. The primary interest was to determine whether or not significant amounts of waste tritium were dispersing downward in the aquifer beneath the observation wells (perhaps 300 feet below the water table). The input part of the balance was difficult to calculate because no tritium discharge records were made from 1953 to 1961. However, the values for that period were estimated from other known characteristics of the waste. Balances were calculated for two different times -- October 1961 and July 1966 (Figure 69). After estimating the pre-1961 discharge, total releases to the well were derived from a graph similar to Figure 51 of the cumulative yearly discharges with decay losses subtracted. According to that graph, a total of about 14,000 Ci of waste tritium should have been present in the aquifer in 1961 and about 13,500 Ci in July 1966. The 1966 value is smaller because more tritium had been lost by decay than had been discharged between 1961 and 1966. With the above method, very good balances, within 10%, were obtained for 1961 and 1966.

The loss of waste from the aquifer by the withdrawal from the CFA production wells was neglected in the 1961 and 1966 tritium balances but should be mentioned at this time. These wells pump out a certain part of the waste carried in the aquifer. Since 1958, when wastes first arrived at these wells, the quantity withdrawn by them is calculated to be about 1 to 2% of the total discharged at the ICPP. This loss is insignificant in relation to the accuracy of the other parameters involved.

It was inferred from the tritium balances that the interpretive tritium concentration lines were reasonably valid and that insignificant quantities of waste migrated below the assumed 250-foot average thickness.

6.3 Chloride

Chloride is now considered the best waste product for mass balance analysis for several reasons. First, it has been discharged more continuously and in larger quantities than any other product since ICPP operations began in late 1952. Consequently, its discharge records, although incomplete, are more reliably estimated than any other waste product. Second, it is easily and accurately determined in groundwater, and nearly complete sets of sample data are available for at least three different times from the NRTS observation wells. Third, chloride is relatively immune to geochemical reactions in the aquifer, such as sorption or precipitation, which would reduce its concentration or movement rate.

Two different times were selected for inventories based on available groundwater sample data -- fall 1958 and April 1969 (Figure 62). From 1952 through October 1958, an average of about 325 million gallons (1.23×10^9 liters) of water per year were metered to the disposal well. The apparent average waste chloride content of this effluent was about 235 mg/l. These data yield a total discharge for the 6.3 years of about 4.0 x 10^6 pounds of chloride. This figure probably has at least 90% accuracy.

Incremental areas, volumes, and chloride contents were calculated and summed to arrive at a total waste chloride content in the aquifer of 4.1 x 10^6 pounds. This agrees quite nicely with the calculated discharge total of 4.0 x 10^6 pounds.

Although only a few chloride determinations were made on the effluent from 1958 to 1969, all indications are that the concentration remained about the same as in the earlier period, but with some decline in total volume. The average metered volume discharge from 1952 through 1969 declined to 301 million gallons per year or 1.15 x 10^9 l/yr. Assuming the same average chloride concentration in the effluent of 235 mg/l, a total of 10.1 x 10^6 pounds is estimated to have been discharged down the well as of April 1969.

The estimated inventory in the aquifer (Figure 62) amounts to 10.9 x 10^6 pounds for April 1969. Again, this figure is very compatible with the calculated 10.1 x 10^6 pounds discharged.

The chloride quantities for both years balance within 8%. This good agreement is as good as could be expected from the accuracy of the data and techniques used. The close results of the two balances indicate that essentially all of the disposed chloride is accounted for in the aquifer and that no significant amounts have migrated deep in the aquifer below the monitor wells or laterally beyond them. These balances are also useful in evaluating those for other waste products. Thus, the chloride results strongly support the more tenuous tritium balances and are useful in interpreting heat and strontium-90 balances that follow.

6.4 Strontium-90

The only time at which a sufficiently complete set of groundwater sample data is available for a materials balance is May 1970 (Figure 68). The total ICPP Sr-90 discharge records are fairly complete but they have not always shown separately the discharges to the shallow pit and the deep well. Table IX indicates that about 53 Ci of Sr-90 have been discharged at the ICPP. More detailed records (Osloond, 1970) indicate that between 15.5 and 18.9 Ci of the 53 were discharged to the disposal well while the remainder was released to the pit. This includes at least 6.2 Ci discharged in 1968 and 1969 after the well became plugged. That part (6.2 Ci) therefore entered the perched water body rather than going directly to the aquifer. The releases to the pit have also been held up in perched water zones. This means that perhaps 12 Ci have been discharged directly to the aquifer while about 40 Ci have been disposed of above the aquifer. It is believed that most of the Sr-90 discharged to the pit (about 34 Ci) has been sorbed on the sedimentary material and basalt between the surface and the water table by ion exchange. Data from Hawkins and Short

(1965) and Dr. W. L. Polzer (oral communication, 1970) indicate that this amount of sorption is reasonable. Polzer (written communication, 1972) estimates that about 6 Ci (20%) is sorbed just in the surface sediments near the pit. It is also likely that a large percentage of the 6 Ci injected into the lower perched water through the plugged well has been, or will be, sorbed before entering the aquifer. However there is also evidence (Figure 68) that some of this Sr-90 has entered the aquifer and increased contamination in the production wells, CPP-1 and -2.

For the purpose of the balance calculations, it is assumed that only the 12 Ci discharged through the well before collapse has entered the aquifer. Correction for radioactive decay up to May 1970 reduces the quantity to 9.5 Ci. Figure 68 was used to calculate the other half of the balance. However, this time an average saturated thickness of 200 feet (instead of 250 feet) was used because the Sr-90 plume is confined to an area much closer to the disposal well.

This inventory indicates that only about 0.25 Ci of Sr-90 was present in the aquifer. This, of course, means that about 97% of the 9.5 Ci discharged is unaccounted for in the balance. This is reasonably attributable to loss by ion exchange (or other sorption process) in the aquifer. This conclusion is strengthened by the Cs-137 data. About 7 Ci of Cs-137 (half-life 30 years) have been discharged to the aquifer through the well and none has ever been detectible in the observation wells, even those closest to the disposal well. This means that there is essentially 100% loss of that isotope. The only plausible mechanism for this loss is sorption. The sorption process is further substantiated by the apparent reduction in cationic sodium in the aquifer, compared to chloride as discussed in the previous section.

These results indicate that the concentrations of Sr-90 and Cs-137 will not likely exceed AEC or PHS recommended limits in the portions of the aquifer tapped by supply wells, if discharges continue at previous or lower rates. The new cation exchange system on the ICPP effluent is designed to reduce significantly the discharge of these isotopes in the future.

Because of sorption, the Sr-90 presently observable in the aquifer (Figure 68) will probably continue to move southward at a very slow rate, compared to tritium or chloride. This will allow radioactive decay to have a greater effect in reducing the concentration. With these effects combined with the diluting effects of dispersion, it is probable that only trace concentrations will ever be detected as far downgradient as the CFA supply wells. Considerably more work would have to be done on the quantitative effects of dispersion and sorption in the aquifer before a more positive statement can be made on the future behavior and distribution of Sr-90 or other sorbable waste products.

6.5 Heat

For several reasons, the waste heat balance was the most difficult of all the balances to calculate; nonetheless, reasonably good results were obtained. The first problem was the lack of a good temperature record on the effluent. The second problem involved determining the increased heat content of the solid portion of the aquifer as well as the liquid. Estimating the heat loss out of the aquifer by conduction was the last major problem.

A waste heat input to the aquifer was considered to result from any discharged waste effluent with a temperature above the average natural aquifer background of 53°F (12°C). Aquifer temperatures greater than this were considered indicative of waste heat (Figure 66). The only significant heat loss from the aquifer was assumed to be upward conduction from the saturated zone. Some downward conduction, no doubt, occurred also, but it was considered insignificant because of the downward positive geothermal temperature gradient. The warmer waste water was assumed to equilibrate rapidly with the cooler aquifer water and rock matrix.

To facilitate computations, cgs-°C units of measurement were used for most of the heat balance calculations. The groundwater temperature data for May 1969 (Figure 66) are considered the best set; the heat balance was thus calculated for that time. The heat input to the aquifer was calculated by the formula

$$Q_T = M(v-53)\ C_{pw} \qquad (21)$$

where Q_T is the total heat added to the aquifer, M is the mass of waste water injected down the well at the average temperature v, and C_{pw} is the heat capacity of the water in calories per gram per degree of temperature. The mass of the discharged effluent was calculated from the metered volume discharge records and the density of water. It is assumed that the 1968 and 1969 discharges entered the perched zone above the aquifer and lost most of their heat there. Therefore only the discharges through 1967 were used as input. The discharge records indicate that 4.53×10^3 million gallons, or 1.72×10^{13} grams, had gone down the well from 1952 through 1967. A value of 68°F (20°C) was assumed for the long-term average effluent temperature (Figure 52 and discussion). The heat capacity of water C_{pw} at this temperature is approximately 0.555 (cal/g)/°F. Therefore,

$$Q_T = (1.72X10^{13})\quad (68-53)\quad (0.555) = 1.43X10^{14}\quad .$$

The balance can be completed by evaluating two more phases -- the waste heat stored in the aquifer and the heat lost by upward conduction. The heat stored in the aquifer can be evaluated in increments as were the dissolved waste products. Assume for instance that an area increment, A_n (Figure 66), had an average groundwater temperature of v_n. It is assumed, then, the solid phase of the aquifer is at the same temperature as the water and the average effected thickness is 200 feet. The waste heat, Q_n, stored in that increment of the aquifer is calculated by

$$Q_n = (v_n - 53) \quad (200A_n) \; \rho_a \; C_{pa} \tag{22}$$

where $(v_n\text{-}53)$ is the temperature increase in the aquifer caused by the waste, $200\,A_n$ is the volume of aquifer increment, ρ_a is the average density of the saturated aquifer, and C_{pa} is the average heat capacity of the saturated aquifer.

v_n and A_n are measured; ρ_a and C_{pa} must be estimated and calculated. The average density of the solid mineral phases making up the basalt was calculated as 2.90 g/cc, based on mineral proportion reported by Chase (written communication, 1966). The heat capacity of most rocks is in the range of 0.19 to 0.23 (cal/g)/^{o}C. For most basalts, the value is probably near 0.20 (cal/g)/^{o}C at 20^{o}C. If the total porosity of the saturated basalt is near 10%, a unit volume of the aquifer would consist of 90% basalt and 10% water and the volumetric heat capacity would be a proportional combination of the values for basalt and water. This combined volumetric heat capacity, C, is calculated as

$$C = (V_w) \; (C_{pw}) \; (\rho_w) + (V_b) \; (C_{pb}) \; (\rho_b) \tag{23}$$

where

V_w = water fraction of total volume = 0.1

C_{pw} = heat capacity of water = 1.0 (cal/g)/^{o}C

ρ_w = density of water = 1.0 g/cc

V_b = basalt fraction of total volume = 0.90

C_{pb} = heat capacity of basalt = 0.20

ρ_b = density of basalt = 2.90 g/cc.

Therefore,

$$C = (0.1)(1)(1)+(0.90)(0.20)(2.90) = 0.622 \text{ (cal/cc)/}^{o}\text{C}.$$

This term, C, is equivalent to the product $\rho_a C_{pa}$ in Equation (22). The above value for C was used to calculate the heat increase in the aquifer by applying Equation (22) to volumetric aquifer increments and them summing. The result indicates 1.40×10^{14} calories of waste heat present in the aquifer as of May 1969. Although this is quite close to the 1.43×10^{14} calories estimated to have been discharged, a valid comparison requires a correction for heat loss from the aquifer. For a simple estimate, assume that the solid layer between the ground surface and the water table can be considered as a homogeneous, semi-infinite solid region, S, bounded only by the water table surface. Assume further that under natural conditions before disposal began, the solid region S was at a constant temperature of 53°F, the same as that of the aquifer immediately below it. Then at some time, t_o , after disposal began, the aquifer was heated to an average temperature, $v = 53^o + \Delta v$, over a large area, A. This would induce heat to flow from the aquifer into the cooler region, S. One form of the solution to this boundary value problem is given by Carslaw and Jaeger (1959). Their solution describes the temperature distribution in the region S at any time after t_o:

$$v_s = \Delta v_a \ \mathrm{erfc} \frac{x}{2\sqrt{kt}} \tag{24}$$

where v_s is the temperature at any point in the region S at distance x above the water table surface (boundary plane); t is the time after the initial temperature increase, Δv_a, of the aquifer; and k is the thermal diffusity of the region, S, (i.e., $k=K/\rho_s C_{ps}$ where K is the thermal conductivity, ρ_s the density, and C_{ps} the heat capacity of the region, S).

If the vertical temperature distribution in S is estimated for any particular time, t, then the increase in heat content for S can also be calculated approximately. This is done by breaking the region S into small vertical increments (a stack of thin, horizontal layers), calculating an average temperature increase for each increment, or layer, and multiplying by the mass and heat capacity of the increment, so that

$$Q_n = AH_n \rho_s C_{ps} \Delta v_n \tag{25}$$

$$Q_T = \sum_{n=1}^{m} AH_n \rho_s C_{ps} \Delta v_n \tag{26}$$

where

Q_n = the increased heat content for layer increment, n

Q_T = the total heat increase of region S

A = the horizontal surface area of the heated portion of the aquifer

H_n = the thickness of layer n

ρ_s = the average density of region S

C_{ps} = the average heat capacity of region S

Δv_n = the average temperature increase at time t for layer n

m = the number of layer-increments used.

The total heat gain, Q_T, of region S is also the total heat loss of the aquifer.

One way to make a conservative estimate of Q_T is to assume that the 1969 waste heat plume in the aquifer (Figure 66) has been the same since 1952 (about 16.5 years); in reality, however, it started as nothing and gradually grew to the 1969 size. The assumed system would thus have lost more heat than the actual system.

The area A enclosed by the outer 1969 line (Figure 66) is about 4.2×10^7 ft^2 or about 4×10^{10} cm^2; the average temperature within the plume, Δv_a, is about 2.2°F (1.2°C) above background. Equations (24) and (26) were evaluated for $t = 16.5$ years (5.2×10^8 sec), and x in increments of 30 or 60 feet (1,000 or 2,000 cm, approximate). The thermal conductivity, K, of most rocks varies from about 2×10^{-3} to 6×10^{-3} (cal/cm)/sec (Carslaw and Jaeger, 1959), and that of NRTS basalt is probably no more than 4×10^{-3}. Although a small piece of dense basalt would have a conductivity of 5×10^{-3} to 6×10^{-3} (cal/cm)/sec, on a massive scale the natural basalt conductivity would be less because of fracturing and other porosity features as well as the anisotropic effects of layering and interbedded sediment zones. Therefore the value of 4×10^{-3} was used, although the actual value might even be lower. The value of $\rho_s C_{ps}$ was previously determined as about 0.522 cal/cc for dry basalt with 10% porosity. Therefore $k = K/\rho_s C_{ps} = 4 \times 10^{-3}/0.52 = 8 \times 10^{-3}$. Equation (24) was then evaluated at several values of x to obtain a temperature profile above the aquifer. According to the calculations the temperature would have been raised 0.8°C at 30 feet above the water table, 0.5°C at 60 feet above, 0.15°C at 120 feet above, 0.04°C at 180 feet above, and 0.005°C at 240 feet above. The results show no significant temperature rises would have occurred higher than 270 feet above the water table. The evaluation of Equation (26) then indicates that approximately 4.5×10^{13} calories of heat would have flowed upward out of the aquifer over the 16.5 year period under the assumed conditions; under actual conditions, something less than that amount should have been lost.

To refine the heat loss estimate, Equations (24) and (26) were reevaluated with a more realistic assumption that the heat plume had been in the aquifer only half the time (8.25 years) of the previously used 16.5 years. This assumption would tend to average the effect of the plume growing from nothing in 1953 to the size and heat content of that shown for 1969.

For that condition, the total heat loss, Q_T, was calculated to be 3.3×10^{13} calories. Adding this figure to the 1.40×10^{14} calories of calculated waste heat storage in the aquifer, a total of 1.73×10^{14} calories is obtained. Recalling that the calculated heat input to the aquifer was 1.43×10^{14} calories, the two sides of the balance agree reasonably well, considering the rather crude precision of the methods used. The heat balance, then, is in general agreement with those of the previous materials balances.

7. APPARENT INFLUENCES OBSERVED ON THE SUBSURFACE BEHAVIOR AND DISTRIBUTION OF WASTES

7.1 Introduction

There are many factors which control the actual and apparent migration and distribution patterns of the waste products underground, both in the unsaturated and saturated zones. Among these factors are: hydraulic dispersion, which is related to the physical and hydraulic characteristics of the aquifer; groundwater flow rates; anisotropy, heterogeneity, and porosity of the aquifer; sorption-desorption reactions; biological activity of algae and bacteria; radioactive decay; chemical equilibria reactions; effects of pumping and injecting wells; natural recharge influences such as seepage from the Big Lost River and local run-off; numbers, locations, construction and hydraulic characteristics of the monitor wells. Many of these effects have been briefly mentioned in the preceding sections. The interdependency and complexity of these factors, combined with limited data or poor understanding of them, prevents complete quantitative assessment of their effects on the disposed NRTS wastes. However, current interpretations and appraisals of these controls are presented below. More intensive study is needed to gain a predictive understanding of the overall behavior of wastes in the aquifer. This could best be accomplished by the development of a digital model of the waste transport system, which is currently underway.

7.2 Hydraulic Dispersion

Hydraulic dispersion has perhaps the most influential control on the distribution of waste tritium and chloride in the Snake River Plain aquifer; it is a much less significant factor in the perched and unsaturated waste zones, because dispersion involves mixing with fresh natural water, which is abundant in the regional aquifer but not in the perched or unsaturated zones.

The effects of dispersion are quite obvious on the patterns of waste products in the Snake River Plain aquifer (Figures 62 through 68), especially those of tritium, chloride, and sodium. These waste plumes have dispersed laterally at an angle 35 to 40 degrees east and west from the north-south centerline. If there were no lateral hydraulic dispersion, the waste water would travel downgradient in the aquifer as a narrow band at about the same concentration as the injected effluent. However, the effects of dispersion cause the waste to mix with and spread out in the natural aquifer water. This, of course, has the beneficial effect of greatly diluting the waste products.

Dispersion also occurs longitudinally, that is, parallel to the direction of flow. As a waste plume advances downgradient, its frontal edge mixes and disperses with the native water and becomes less defined, such that it is an ever-expanding zone rather than a line.

Dispersion is controlled principally by the anisotropy, heterogeneity, and pore geometry of the aquifer and the velocity of the groundwater. In this report, dispersion is defined to include also the effects of molecular diffusion. The rate of dispersion at any point depends on the concentration gradient of the dispersing solute. The effects of molecular diffusion are significant only in very slow moving groundwater with little physical dispersion. In the Snake River Plain aquifer system at the NRTS, molecular diffusion is insignificant. This is due to the relatively high velocity of the groundwater and the physical nature of the aquifer. In other words, the observed dispersion patterns of NRTS wastes are almost entirely due to hydraulic mixing and spreading with essentially no effect from the comparatively slow process of molecular diffusion. However, diffusion may be an important process in mixing a solute uniformly within individual pores.

The lateral dispersion angle of 35 to 40 degrees in the NRTS system is unusually wide, compared with the few documented large-scale dispersion patterns in other aquifers. For instance, Todd (1959) cites a dispersion angle of 3 degrees in one porous media study. Simpson's (1962) data also indicate very narrow lateral dispersion bands in a sandy medium, and similar conclusions were drawn by others such as Bruch and Street (1967) for small-scale studies. Longitudinal dispersion is caused principally by microscopic and macroscopic differential velocities in the groundwater flow, whereas lateral dispersion can be related more to the branching of flow channels and differential vertical anisotropy. Differential velocities and branching effects are both related to the tortuosity of the porous medium. In one-dimensional flow, two dispersion coefficients define the effects of the porous medium on dispersion from a point source (well) -- one for horizontal and one for lateral dispersion. In the case of the NRTS, the horizontal dispersion coefficient must be very large in order to account for the wide dispersion patterns observed.

It is also possible for dispersion to take place in the vertical direction, if the dispersant is not injected over the full thickness of the aquifer. However, in the NRTS system the observed behavior of the wastes and the properties of the aquifer indicate that little vertical dispersion takes place. It is therefore assumed that the NRTS wastes disperse significantly only in the two normal horizontal directions.

Simple two-dimensional dispersion processes in a semi-infinite, homogeneous, isotropic medium can be modeled or described by fairly simple mathematical equations which are specific solutions to the general, more complex, differential equation describing dispersive flow (Simpson, 1962, and Bruch and Street, 1967). However, in media with more complex boundary conditions, input variations, heterogeneity, and anisotropy (such as at the NRTS), the problem of approximating the natural dispersive flow mathematically can become extremely complex. Nevertheless, it is possible to develop mathematically at the NRTS a reasonable approximation to the dispersion system if attention is focused on the general, large-scale effects by means of recently developed digital computer modeling techniques.

7.3 Groundwater Flow Rate and Direction

7.31 General Flow Pattern. The direction and rate at which a waste plume moves in an aquifer is largely dependent on the rate and direction at which the groundwater is flowing in the Snake River Plain aquifer. Thus, in order to understand the general behavior of ICPP and TRA waste plumes, one must first understand something about the aquifer flow system.

Water enters and recharges the aquifer around the fringes of the plain and generally flows southwestward through the aquifer toward the Thousand Springs area (Figure 1). The flow map (Figure 1) is based on the potentiometric surface and other known qualities of the aquifer as presented by Mundorff and others (1964). At a scale this large, the flow system appears fairly uniform and homogeneous. However, when examined in more detail, the system becomes more and more complex (Figure 6). At the scale of Figure 6 the flow pattern appears considerably less uniform but the general flow direction remains to the south-southwest. The ICPP-TRA waste dispersion plume occupies only a small portion of the area in Figure 6. The behavior of these wastes are therefore dependent on the detailed flow characteristics within that small area. In order to define better some of those characteristics and their complexities, a potentiometric contour map was prepared for the ICPP-TRA-CFA region (Figure 74). The potentiometric surface over this relatively small area is complex and poorly defined, especially near and southwest of the ICPP area. It is not feasible, therefore, to draw an accurate flow net over this area. Although complex irregularities are present on a small scale, the overall flow direction is generally to the south-southwest as indicated on the larger area maps. Part of the irregularity in the contours could be due to erroneous elevations on the wells. This can only be checked by releveling the wells. A small amount of error can also be attributed to barometric pressure fluctuations over the period during which the water-level measurements were made. Much of the irregularity in the contours is likely due to the anisotropy and heterogeneity of the aquifer. Even if the potentiometric contours were very accurately defined, the groundwater flow would not necessarily be normal to them, and would therefore remain poorly defined. It would be particularly difficult to determine the flow pattern of groundwater in the area containing Wells 84, 85, and 38 because of the apparent flat gradient there. This zone is outlined by the large southward bulge in the 4,462.5-foot contour. The reason for the bulge is not known but it may very well be due to recharge from the nearby Big Lost River which had a high discharge during the preceding spring months.

In general, Figure 74 indicates the flow is to the south-southwest and is compatible with the observed movement patterns of waste products in the aquifer. The behavior of the

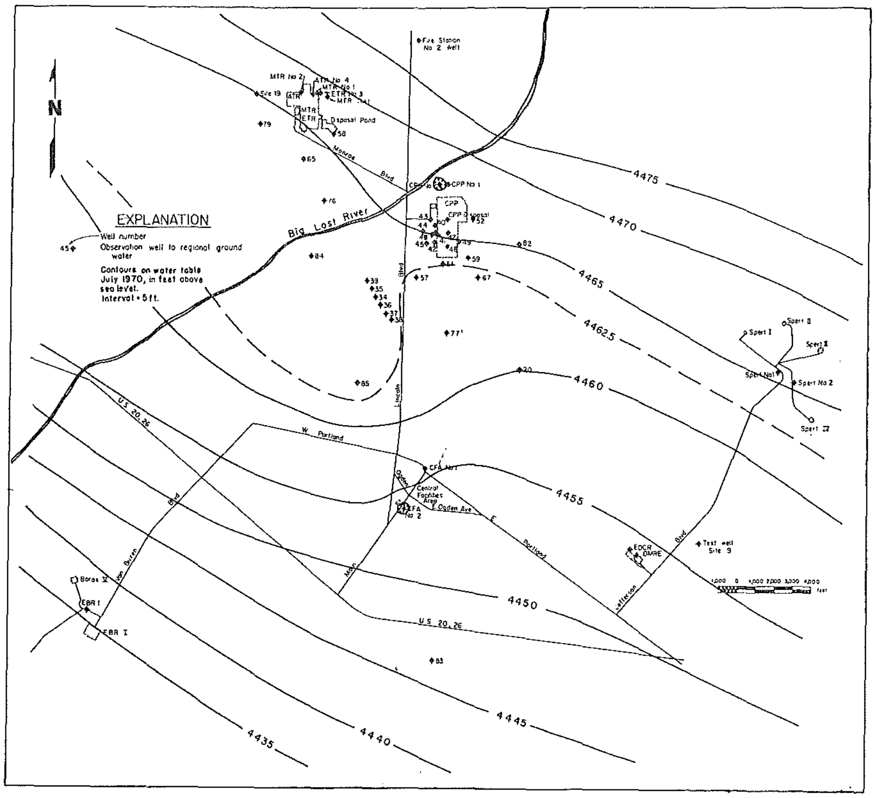


Fig. 74 Map showing potentiometric surface (water table elevation) in the ICPP-CFA vicinity.

waste plumes in the Snake River Plain aquifer indicates a groundwater flow more directly to the south than indicated by the regional water-level data which suggest a more southwesterly flow (Figures 1 and 6). The more detailed water-level data in Figure 74 support the local, more southerly flow in the ICPP-CFA region shown by the waste products. At least two factors may contribute to this. One is the influence of recharge from the Big Lost River. The recharge can cause a local head build-up in the aquifer beneath and near the river, which, in turn, could divert groundwater flow more to the south. There are not enough observation wells available to define this effect quantitatively. The other factor contributing to the southward flow from ICPP to CFA is the influence of pumping and injecting wells, which is discussed below.

7.32 Effects of Pumping and Injecting Wells. Discharging or recharging of wells can cause a significant change in the head distribution and flow pattern in the aquifer. A discharging well withdrawing water from the aquifer induces a cone of depression in the head surface and causes water from the surrounding portion of the aquifer to flow toward the well. A recharging or injecting well has exactly the opposite effect. Thus, the ICPP disposal and production wells and the CFA production wells would have such an influence on the flow from ICPP south. These effects are indicated schematically in Figure 74 by the closed contours around those wells and associated deviations in the regional contours. The magnitude of the well pumpages is small in comparison with the size and permeability of the aquifer, so that the resultant effects are rather small but, nevertheless, significant on the aquifer flow patterns. At the time for which Figure 74 was drawn, the ICPP disposal well was plugged, so that a cone of head-buildup is not shown around the well. However, the waste water was still recharging the aquifer from the perched water body, except over a much wider area beneath the ICPP. This recharge is apparently reflected in the 4,465-foot and possibly 4,462.5-foot contours which show a local deviation at the ICPP.

The ICPP production wells (CPP-1 and -2) are probably far enough upgradient so that they do not have much effect on the downstream migration of ICPP wastes. Therefore, once the wastes begin their southerly migration, the CFA production wells (CFA-1 and -2) have a tendency to draw some of the flow more directly south toward them. Well CFA-2 pumps about 90% of the supply whereas CFA-1 is used only for 10%. Therefore the influence of CFA-1 is assumed to be negligible and a cone of depression contour is shown only for CFA-2.

The CFA-2 well pumps at a rate of about 600 gpm. An aquifer test on the well in 1951 indicated an aquifer transmissivity of 1.6×10^5 gpd/ft and a specific capacity of 15 gpm/ft (W. C. Walton, written communication, 1958). This is an anomalously low transmissivity and is probably not representative of the surrounding aquifer. Generally, measured transmissivities have ranged from 10^6 to 10^7 gpd/ft at TRA, ICPP, Fire Station II, ARA, and EBR II.

If the aquifer water is assumed to flow uniformly southward, the pumping CFA-2 well will intercept a part of this flow within a band of a certain width. The width of this band can be estimated in different ways. One way is as follows. Although the well only penetrates about 200 feet into the aquifer, assume that the upper subaquifer from which it effectively draws water is 250 feet thick. Assume further that the natural groundwater velocity in the region averages seven feet per day and that the effective porosity of the aquifer is 7%, as indicated in the materials balances analyses. Under these conditions, the unit cross-sectional flow rate of the aquifer is given by (250 ft) x (7 ft/day) x (0.07 porosity) = 122 ft^3 per day per ft or about 0.63 gpm per ft aquifer width. A pumping rate of 600 gpm in CFA-2 would thus intercept water from a band $600/0.63=950$ feet wide. This means that the flow within two parallel flow lines 950 feet apart would be captured and withdrawn from the aquifer by well CFA-2 centered between them.

Another means of calculating the unit cross-sectional discharge of the aquifer is by the formula $q = T\partial h/\partial s$ (based on Darcy's law) where q is the unit cross-sectional flow of the aquifer, T the transmissivity of the aquifer, and $\partial h/\partial s$ the average head gradient in the aquifer. The average gradient from ICPP to CFA is about 4.5 ft per mile or 8.6×10^{-4} ft/ft. If the questionable transmissivity of 1.6×10^5 gpd/ft (measured at the well) is assumed, then q would be $(1.6 \times 10^5)(8.4 \times 10^{-4}) = 138$ gpd/ft = 0.1 gpm/ft. With CFA-2 pumping

600 gpm, a flow band 6,000 feet wide would be intercepted by the well. This obviously does not agree well with the 900-foot-wide band calculated above by the other method. If a more reasonable transmissivity of about 1 x 10^6 gpd/ft is assumed, then the intercept band width becomes 1,000 feet, about the same as the other method yielded.

Based on the above estimates, it appears that the band of aquifer water intercepted by CFA-2 is probably between 500 and 2,000 feet wide. However, the well pumps only intermittantly, about one-third of the time, to withdraw an average of about 1 x 10^8 gal/yr. This amounts to about 30% of the ICPP waste discharge rate.

From the qualitative and semi-quantitative information available, it is sufficient to say that the wells have a significant, but not predominant, influence on the migration patterns of the waste products.

7.33 River Recharge Effects. Intermittant recharge from the Big Lost River may divert the aquifer flow patterns more to the south in the region between the ICPP and CFA. The fresh river recharge water may also dilute wastes on the western fringe of the ICPP plume and, in effect, cause a reseparation of the coalescing TRA-ICPP waste plumes.

Flow in the river has been intermittant on the NRTS and many years have passed with no flow at all. From 1953 through 1963, the river showed a significant flow in the reach between the TRA and ICPP in only two years: 1953 and 1958. However, the years 1964 through 1970 each have had high or at least significant flows. In fact, the years 1969 and 1965 were the highest discharges on record, with 117,000 and 116,000 acre-ft, respectively, at the Lincoln Blvd. bridge (Figure 5). During those years the lowest discharge was 4,500 acre-ft in 1966. Even though the river has flowed each year during that period, the flow was not continuous and generally occurred during the spring and summer months continuing sometimes into fall. Flow ceases in the fall and winter for two reasons: first, this is the period of normal decline in flow due to decreased runoff and low releases from upstream Mackay Dam; second, when freezing weather begins, all the flow of the river is diverted into the NRTS diversion system in the southwest corner of the site in order to keep the main channel free of ice until spring. There has occasionally been periods when continuous flow did occur above the NRTS diversion for more than 12 months, but due to the regulation of the diversion gates, continuous flow was not allowed downstream on the NRTS.

The river loses water by seepage over its entire reach from Arco to the terminating playas at the north end of the NRTS. R. L. Nace, J. W. Stewart, and W. C. Walton (written communication, 1959) first measured and described the channel losses on the Big Lost River on the NRTS in 1951-53. Barraclough, Teasdale, and Jensen (1967) did additional work and reported that the reach with the highest seepage losses is that between the NRTS diversion and the Lincoln Blvd. bridge near the NRF. For instance, at a discharge of about 500 cfs, the average infiltration rate along that reach was about 16.1 gpd/sq ft of channel area (2.2

ft/day). This means that channel loss would be nearly 5 cfs (or 1%) per linear mile of channel at that discharge. Of course, the channel losses decline with declining discharge and stage. At a discharge of 250 cfs, the average infiltration rate over the same reach was 6.1 gpd/sq ft (0.82 ft/day). The infiltration rates in the channel change for several reasons. Colder water has a higher viscosity and therefore seeps more slowly into the ground. Consequently, as the temperature of the water increases, the infiltration rate tends to increase. As the river flows, the bottom may become more silted, reducing the infiltration rate. The converse also occurs. A high state has a two-fold increase on the total infiltration loss because it produces not only a higher unit area infiltration rate but also a higher wetted channel area and may scour fine-grained material off the bottom. It is beyond the scope of this report to analyze the infiltration variations in detail. However, some data on the overall recharge quantities are available and are discussed below in order to show these effects in reasonable perspective.

The reach of the river which has the most effect on TRA-ICPP wastes could be considered to extend from about one mile southwest of the U. S. Highway 20-26 bridge to about one mile northeast of Lincoln Blvd. bridge near TRA. The length of that reach is about seven miles. The average channel area over that reach is about 190,000 ft^2 per mile, or a total of 1.3×10^6 ft^2.

A good example of recharge effects from a high runoff year can be found in the data for 1965. During the 1965 runoff, a total of 116,000 acre-ft (5×10^9 ft^3) were discharged past the TRA bridge, over a period of about 170 days. This is an average flow of 340 cfs. The average infiltration rate for this flow should be approximately 1.3 ft/day based on previous data for that reach. The total infiltration loss for 1965 would be estimated at $(1.3) \times (170) \times (1.3 \times 10^6) = 2.9 \times 10^8$ ft^3 or 6,600 acre-ft. In other words, the seven-mile reach under consideration probably recharged about 6,600 acre-ft to the Snake River Plain aquifer during the 1965 runoff period. This amounts to roughly 6% of the total discharge through that reach. That quantity of recharge (6,600 acre-ft) is enough water to raise the water table level more than 10 ft over an area of 10 sq miles. If the 6,600 acre-ft were added to the aquifer over a one-mile-wide strip along the seven-mile reach (an area of 7 sq miles) the groundwater level in that reach would rise an average of more than 15 feet. In reality this does not occur so simply; as the water enters the aquifer, the induced head-rise spreads out laterally in an ever-widening mound. The 1965 recharge caused a water level rise of about 8.5 feet in Well 12, two miles west of the Big Lost River (Barraclough, Teasdale, Robertson, and Jensen, 1967). A rise of about six feet was recorded in Well 17, which is about 3.4 of a mile east of the river.

The data from Barraclough, Teasdale, Robertson, and Jensen (1967: Figure 10) indicate that the largest water level rises due to runoff recharge occur to the northwest of the subject river reach. This, in effect, superimposes a hydraulic gradient sloping to the southeast on the normal southwestward sloping aquifer gradient. This would tend to turn the aquifer flow direction from southwestward to southerly, which helps to explain some of the observed flow patterns of waste products in the aquifer. In addition, the recharging fresh water would tend to dilute any waste products present in the area of recharge. This effect has been observed in Wells 84, 34, 35, and 39, and was discussed previously in relation to the coalescence-separation phenomena between the TRA and ICPP waste plumes. It is clear, then, that river recharge has a significant effect on the behavior of NRTS waste products in the Snake River Plain aquifer.

7.4 Factors Related to Monitor Well Characteristics

Individual characteristics of each observation well can influence the data it yields and the subsequent interpretation of waste behavior based on those data. This is especially true in a highly heterogeneous system such as the Snake River Plain aquifer. In other words, data reflected by any one well are not necessarily representative of the aquifer in general. For example, one well might penetrate a very dense basalt zone of limited area of the aquifer with little permeability. The water in that well may be very stagnant in its responses to more dynamic waste concentration changes occurring in the surrounding portion of the aquifer. Several aspects can be included in this category: (a) the number and location or distribution of the wells; (b) construction aspects of each well such as diameter, casing, cement, packing, and perforations; (c) depth of each well; (d) pumping versus nonpumping status of wells; and (e) lithology and aquifer characteristics penetrated by the well.

The first aspect, well distribution, was adequately discussed in the previous section describing waste distribution in the Snake River Plain aquifer. It was emphasized previously that the waste distribution maps in this report are by no means considered absolutely accurate. They are merely interpretive approximations of the true patterns whose details will remain unknown. It would be desirable to have at least a few wells in areas with inadequate or questionable coverage at present such as the southern and western parts of the TRA waste plume, the area downgradient from NRF, and the leading edge of the ICPP plume. Although NRF releases less radioactive waste than the ICPP, it appears that it discharges considerably more chemical wastes. It is therefore assumed that a waste plume exists downgradient similar to that of the TRA or ICPP, but there are no wells to define it. The only observation well between NRF and TRA-ICPP is Fire Station No. 2 which has not shown evidence of NRF wastes as yet, except perhaps a small increase in specific conductance. It appears ICPP wastes have migrated closer to the NRTS southern boundary than wastes from other facilities. It is therefore important to define in more detail the distribution and future advancement of the southern fringe of the ICPP waste plume.

7.41 Depths of Wells. The depth a well penetrates below the water table is important in combination with lithologic and construction characteristics of the well. Most of the NRTS observation wells penetrate the aquifer from 125 to 250 feet with an average of about 185 feet (Table XIV). Most of the deeper-penetrating wells are nevertheless open or perforated to the upper part of the aquifer. It would be necessary to conduct detailed down-hole hydraulic tests to determine the relative contribution of different levels of the aquifer to a sample collected from the well.

Production well EBR-I is one in which its depth appears to be an influence on the sample data obtained from it. Water from well EBR-I occasionally contains small amounts of waste products. This well penetrates the aquifer about 500 feet and the lower 400 feet are open to the aquifer. It is questionable whether these waste concentrations are representative of all the water penetrated by the well or whether they represent a small portion of higher concentration water in the upper part of the well mixing with larger amounts of lower concentration water from the lower part of the well. In most cases, the waste concentrations in a water sample from a pumped well are assumed to represent the entire zone of the aquifer to which the well is open.

Although penetration depth alone is probably not a predominant influence on the waste concentration data for most of the wells, the unusual depth of a few wells may have a critical effect on the composition of samples collected from the well. The more likely wells for which this might be true are ATR-4, SPERT-2, OMRE, EOCR, EBR-I, Site 9, Site 14, and Site 19, Wells 7 and 15. Of those only EBR-I, Site 9, and either EOCR or OMRE could be considered critical in defining the waste dispersion plumes. The problems of Well 51 (discussed previously, page 155) may be related to depth but its anomalies are probably caused by construction characteristics.

7.42 Construction and Other Well Characteristics. The construction characteristics of observation wells are important because they determine, to some extent, the portion of the aquifer from which water is withdrawn and the internal hydraulics of the well. NRTS wells vary with regard to the types and amounts of casings used; the amount of uncased hole; the type, location, and quantity of perforations; where and how cement or grout was used in the hole; use of packers; and characteristics of the pump, if present.

One of the most important considerations regarding sampling is whether or not the well is pumped. A sample from a pumped well can be quite different from a grab or thief sample from a similar well that has never been pumped. In this respect, a thief sample can be considered a spot sample of the *bore-hole* water, whereas a pumped sample can be considered a composite sample of the *aquifer* water. The two may or may not yield the same results. Therefore, a pumped sample is generally more representative of aquifer water in the vicinity of the well than a thief sample from an unpumped well. A thief sample from an unpumped well, on the other hand, is much more subject to influence unrepresentative of the aquifer. For example, if a cased well became sealed from the aquifer by the intrusion of fine-grained sediments into the annular space between the casing and well wall, the water within the casing would then become essentially stagnant and unresponsive to changes in the aquifer water. It, instead, becomes influenced by other processes such as the inflow of fresh condensation water running down the inside casing wall, chemical reactions with the casing, and organisms in the well.

The anomalous waste concentration data from Well 51 are likely due to physical characteristics of the well, as explained in the previous section on waste sodium distribution in the aquifer. In addition to Well 51, Well 20 is an example of a well with constructional influence on samples. The well penetrates about 215 feet below the water table and is cased the entire length. The bottom 125 feet of casing is unperforated and is essentially a stagnant zone. The quality of water in that portion has been considerably different from that in the higher, perforated zone through which aquifer water flows (Barraclough, Teasdale, Robertson, and Jensen, 1967). The Well 20 situation exemplifies the problem of selecting the proper sampling point to collect routine thief samples.

Lithologic and natural hydraulic characteristics of the wells (particularly the unpumped wells) have an important influence on the data obtained from them. The heterogeneity of the aquifer is such that slight vertical head variations occur within most wells. This causes water to enter the well from a permeable zone with the higher head and flow up or down the well and out into the zone with lower head. This type of borehole flow has been measured numerous times in NRTS wells by down-hole tracejector logs or other flow meter logs.

It is important therefore to study the borehole hydraulics of each monitor well before selecting the most suitable sampling zone or interpreting sample results. Nearly all the NRTS observation wells have been investigated in this respect.

7.5 Physical-Chemical Reactions

7.51 Ion Exchange and Sorption. Sorption reactions, which are used herein to include ion exchange, have been shown to be a significant influence on the behavior of some waste products in the subsurface (namely Sr-90 and Cs-137). This influence is probably most pronounced on the pond wastes in the perched water system at TRA but is also significant in the Snake River Plain aquifer and the ICPP perched water system.

Nearly all the pertinent sorption studies of NRTS have been oriented toward the exchange capacities and distribution coefficient of the sediments with very little attention to the basalt phases (Hawkins and Short, 1965; Schmalz, 1972). Practically nothing quantitative is known about the in-place sorption capacity of the basalts in the Snake River Plain aquifer.

Hawkins and Short (1965) determined cation exchange capacities and distribution coefficients for a variety of conditions on the Big Lost River alluvium, through which the TRA pond wastes drain. A distribution coefficient of a particular solute is defined for a given solid-liquid chemical system as the ratio of the solute concentration on the adsorbant to the solute concentration in the solvent, expressed in ml/g.

Schmalz (1972) indicates that the distribution coefficients for Sr-90 and Cs-137 in TRA waste-water-alluvium system are on the order of 10 ml/g and 500 ml/g, respectively, for a typical waste water composition. In addition, his studies tentatively indicate that Big Lost River alluvial layer beneath the pond has reached its capacity to adsorb additional Sr-90 and perhaps Co-60. However, it appears that the alluvium still retains considerable capacity for the sorption of more Cs-137. These conclusions are fairly well substantiated by the observed distribution of dissolved waste products in the perched water beneath the TRA pond. The large perched waste water body in the basalt section (beneath the surface alluvial layer) contains no detectable Cs-137, but in recent years has shown small but increasing Sr-90 concentrations and relatively high and wide-spread Co-60 content (Figures 44 and 45). These data would support the idea that Sr-90 and Co-60 have "broken through" the ion-exchange column of the Big Lost River sediments beneath the ponds, but that Cs-137 has not.

In addition to the surface layer of Big Lost River alluvium, other interbedded layers of finer-grained sediments between the ground surface and the Snake River Plain aquifer provide ion-exchange opportunities for waste nucludes percolating downward toward the aquifer. One example of this is the sediment zone upon which the large TRA perched water body reposes. That bed and others through which the percolating waste water must pass have adsorbed essentially all of the Sr-90, Cs-137, and Co-60 so that no detectable concentrations of these isotopes have reached the Snake River Plain aquifer. However, other less sorbable waste products, such as tritium and NaCl, have reached the aquifer in low but significant concentrations. It is not known when Sr-90, Cs-137, and Co-60 will saturate the sorption capacity of the lithologic column between the ponds and aquifer and begin to contaminate the Snake River Plain aquifer. This will partly depend on future changes in the chemical characteristics of the water.

Even if these TRA wastes do reach the aquifer, sorption will continue to take place. However, the magnitude of the sorption process in the Snake River Plain aquifer would be considerably smaller than in the overlying sediment beds. This is because the aquifer is primarily basalt with a specific wetted surface area several orders of magnitude smaller than that of fine-grained sediments. Nevertheless, significant sorption apparently does occur in the aquifer, as evidenced by the data from ICPP, where Sr-90 and Cs-137 have been discharged directly to the aquifer for many years. Sr-90 contamination is apparent to a limited extent in the aquifer, but no Cs-137 has been observed.

In much the same way as the TRA pond wastes, the ICPP pit wastes have to pass through several sediment layers in their downward percolation toward the regional aquifer. The same is true for the waste products in the perched water body within the basalt beneath ICPP which has been recharged recently by the collapsed disposal well.

In conclusion, then, it is apparent that sorption processes (principally ion exchange) play a significant role in controlling the behavior of some waste products in the subsurface. The products most affected are the cationic isotopes Cs-137, Sr-90, and Co-60. Ordinary sodium also appears to have been retarded in its aquifer migration. Tritium and anionic products such as chloride and I-131 do not appear to be significantly influenced by ion-exchange processes. Because sorption delays the migration of some radionuclides, it provides the additional benefit of allowing more time for those nuclides to decay radioactively.

7.52 Chemical Equilibrium Reactions. Only limited conclusions can be made regarding this influence on subsurface waste behavior. The processes involved include solution-precipitation and oxidation-reduction reactions. There is no evidence to indicate any significant oxidation-reduction influences on subsurface waste products. Cr(VI), for instance, undergoes little reduction to Cr(III) underground.

The TRA pond situation is the only apparent instance where chemical precipitation reactions may have had an effect on the migration of liquid wastes underground. Chemical precipitation was previously pointed out as a factor which decreased the permeability of the TRA pond bottoms. A chemical equilibrium study of several TRA pond water analyses indicates that at a pH of 8 or less the water is generally not saturated with any mineral species. However, if the pH increases to 9 or 10 or higher, the waste water may become supersaturated in several mineral species such as calcium carbonate, magnesium carbonate, iron carbonate, ferric hydroxide, and several other species. Several measurements have shown pond water pH values in the range of 9 to 11, so without doubt there has been occasional supersaturation of some compounds in the water.

Although a full chemical analyses of the typical ICPP disposal well effluent has never been run, a computer analysis of the chemical equilibrium of an approximate but hypothetical composition of that water indicated it is generally not saturated in any significant mineral species. Therefore it is apparent that precipitation reactions are probably not a significant influence on this waste before or after it enters the aquifer. However, corrosion has certainly played an indirect but very significant role in the fate of ICPP disposal well wastes. The well effluent with its increased salt content, high dissolved oxygen, and occasional low pH, caused corrosion of the steel well casing which led to the well collapse. This in turn caused the wastes to enter a perched water zone instead of going directly into the aquifer which changed many of the factors affecting the waste products (such as ion exchange) and also increased contamination of the production wells. Additional discussion of chemical equilibria in the Snake River Plain aquifer was presented in Section IV, Geochemistry.

7.6 Other Factors

Radioactive decay certainly has a bearing on the distributions and concentrations of waste radionuclides in the groundwater. Given enough time, all radioactive wastes have the unique property of self-obliteration. For instance, if disposal of tritium were curtailed, the quantity of tritium in the groundwater would gradually decline so that after 86 years (7 half-lives) more than 99% of the originally present waste tritium would be gone.

The waste disposal summary indicates that about 70,000 Ci of liquid radioactive waste had been discharged at NRTS and of that amount, only about 13,000 Ci now remain. The loss is due almost entirely to radioactive decay. Radioactive decay, of course, has no influence on nonradioactive waste products such as NaCl and chromates. As long as these products are discharged, their inventory in the groundwater will continue to increase in an irreversible process.

Certain biological factors can, in some instances, have limited effects on the behavior and fate of liquid waste products discharged at the NRTS. These influences might include bacterial, algae, and higher plant and animal actions. The only instance where this is known to be a factor is at the TRA ponds, and has been described previously in this report. Other organisms at the pond, including water fowl, aquatic vegetation, and insects, may have some influences on the nuclides disposed there, but it is probably insignificant. Conversely, the effects of the waste products on the life system are also unknown.

8. SUMMARY OF SUBSURFACE CHANGES RESULTING FROM LIQUID WASTE DISPOSAL AT NRTS

This report has presented many data and interpretations regarding the influence of 18 years of waste disposal on the subsurface environment of the Snake River Plain. Perhaps the most significant conclusion from these data is that the NRTS effects underground are relatively small and localized and that no measurable change in the subsurface environment *outside* the NRTS boundaries can be attributed to site operations; the influence of NRTS waste disposal activities is detectable only in certain regions of the subsurface within the reservation. That is not to say, however, that effects will never be detected offsite. Eventually, perhaps within a few years, some waste products (such as chloride) will probably be detected in the Snake River Plain groundwater immediately south of the NRTS. Tritium will probably migrate beyond the boundary also, but it is possible that its dynamic equilibrium condition (see Section V-6) will prevent detectable migration to that extent. It is doubtful that significant amounts of the sorbable cationic isotopes Sr-90 and Cs-137 will be carried offsite, under present and anticipated disposal rates, and considering the long time available for decay. However, the last two statements are judgments based only on present observations.

The withdrawal, consumptive use, and recharge of water from the aquifer might be considered an adverse hydraulic effect on the groundwater supply. However the quantitative hydraulic influence of NRTS operations on the total aquifer is miniscule. Data in this report and those of Barraclough and others (1967) indicate that onsite activities consume 55% of the water withdrawn via supply wells while the other 45% is returned to the ground as waste water. In 1969, about 1.6 x 10^9 gallons (4.9 x 19^3 acre-ft) were consumed (evaporated) on the NRTS. As a comparison, it is not uncommon for 10 to 20 times that quantity of water to be recharged per year to the aquifer on the NRTS through the Big Lost River. For example, in the years 1965, 1967, and 1969, the river recharged well over 100,000 acre-feet per year to the aquifer on the NRTS. According to Mundorff and others (1964), over 1 million acre-feet per year pass under the NRTS in the Snake River Plain aquifer. At a consumption rate of 5,000 acre-feet per year, the NRTS consumes less than 1% of the underflow. Norvitch and others (1969) indicate that about 70% of the total natural discharge of the Snake River Plain aquifer occurs in the Thousand Springs area (from Milner to King Hill, Idaho) and amounts to about 4.7 x 10^6 acre-feet annually. Thus, the NRTS used only about 0.1% of that discharge. The hydraulic influence of the NRTS operations on the aquifer is therefore considered negligible for most practical purposes.

NRTS disposal practices have definitely had some minor adverse effects on the quality of groundwater locally. From a practical standpoint, perhaps the most significant result has been the contamination of the ICPP supply wells. This has apparently been caused by the perched waste water body extending northward to the wells as a result of the disposal well collapse. The chloride content of the CPP-1 water increased to a level in 1970 that was beyond the corrosive limits for submerged storage of spent reactor fuel elements. For that reason use of the well had to be discontinued, at least temporarily, so that all the production water is now taken from CPP-2 which is also slightly contaminated, but to a lesser degree than is CPP-1. The water is presently adequate for drinking and plant uses. Its future quality is uncertain, however. It is also known that radioactive and chemical waste contamination has been a continuing problem with NRF supply wells. Use of two of the wells (S5G and NRF-2) has had to be limited because of radioactive and chemical contaminations (E. I. Place and B. L. Schmalz, oral communications, 1971).

The two CFA production wells have become slightly contaminated by ICPP and TRA wastes. If current disposal rates are maintained, this minor CFA contamination will probably change little except for gradual increases in some parameters such as sodium and chloride.

Another minor result of waste disposal is the chromate contamination of the Snake River Plain aquifer by TRA effluents. Thus far, the only supply wells to be effected are those at CFA. However, some observation wells between TRA and CFA (Wells 65 and 84) have indicated chromate concentrations in slight excess of the U. S. Public Health Service drinking water limit of 0.05 mg/l. Attempts are being made to reduce or eliminate chromate as a waste product at TRA, so that it is not likely to pose a future threat to the water quality.

Another condition resulting from liquid waste disposal has been the loss of permeability in the TRA pond bottoms. If a pond is allowed to dry periodically in order to rejuvenate the permeability, the concentrated radioactive particulate matter on the bottom is more vulnerable to becoming airborne. Also, as the pond dries, radioactivity becomes more accessible to certain types of wildlife.

In conclusion, most water quality or other geohydrological changes attributable thus far to NRTS disposal activities have been minor. However, Sr-90 and Cr(VI) concentrations in the Snake River Plain aquifer have exceeded accepted drinking standards in a zone of small areal extent within the station boundaries. Generally, the natural capacity of the subsurface environment to accept low-level wastes has been conservatively utilized at the NRTS with relatively minor degradation. The increasing public concern for maintaining environmental quality may dictate continued efforts and increased expenditures toward reducing or eliminating waste releases to the Snake River Plain aquifer.

VI. SUMMARIZED CONCLUSIONS

Geology (including distribution and composition of rock units) exerts a strong control on the hydrology and geochemistry of the Snake River Plain aquifer. Direct comprehensive evidence of the geologic history of the region is lacking, however, so that any geologic analysis must be somewhat speculative. The analysis in this report indicates that the Snake River Plain was probably formed by tension that produced a huge graben.

From late Precambrian to Permian time, a thick sequence of geosynclinal sediments were deposited in the Snake River Plain region. Volcanism became active west of Challis in Permian time. The post-Pennsylvanian rock sequence indicates a long period of progressive tectonism, culminating in the Late Cretaceous Laramide orogeny. During this time the Idaho batholith was slowly emplaced and solidified. Much local tectonism, such as the western Wyoming thrusts, may have been controlled by the uplifting batholith.

Early Cenozoic history was dominated by erosion, with basin and range faulting beginning in the Miocene. Culmination of basin and range activity in late Miocene time was followed by a period of erosion. By the beginning of Pliocene time, 7 million years ago, southwestern Idaho consisted of a rugged batholithic mountain mass extending southward to the Nevada border; and in southeastern Idaho, horst-and-graben (basin-and-range type) features were dominant. Unknown and perhaps unrelated subcrustal processes then initiated the formation of the Snake River Plain. Silicic volcanism accompanied the beginning of collapse of the Plain in early to middle Pliocene. Following this, the vulcanism changed to entirely basaltic. Sediments collected in basins enclosed by basaltic lava flows as the graben continued to subside, yielding a thick sequence of basalt and interbedded sediments. Silicic volcanism recurred south of the NRTS with the intrusion and extrusion of rhyolitic rocks (forming Big Southern and Twin Buttes). Very recent basalt flows crop out near the bounding faults of the graben-plain and in a rift zone extending across the Plain from Craters of the Moon National Monument.

The graben hypothesis of origin for the Snake River Plain has certain implications of importance to the natural geochemistry, hydrology, and waste-disposal activities at the NRTS: rocks, other than sediment and basalt, beneath the NRTS will affect the composition of deep groundwater. Tuffaceous rocks and fractured Paleozoic carbonate rocks may provide deep reservoirs beneath the NRTS. Horsts and grabens beneath the NRTS may bound hydraulically isolated basins. Intrusions of relatively young silicic volcanics south of the NRTS undoubtedly affect hydraulic properties of the intruded rocks. Future volcanism and seismicity of the eastern Snake River Plain will probably be related to movements on bounding faults.

Groundwater in the Snake River Plain aquifer beneath the NRTS contains low levels of dissolved solids and is of good quality for most purposes. The compositions of this groundwater reflect the compositions of various sources of surface and groundwater recharge from mountains and valleys bordering the Plain. The compositions of the different sources of recharge can be explained by reaction of rain and snowmelt with the dominant reactive minerals believed to be present in the rocks of each recharge area. In addition, longer residence time of groundwater in rocks of the recharge areas, than in rocks of the Snake River Plain, allows reactions between minerals and groundwater to proceed and, in some cases, to equilibrate. Deep groundwater beneath the NRTS contains more sodium, fluoride, and silica than shallow groundwater, perhaps reflecting the presence of silicic volcanic rocks at depth and longer residence times to promote reactions between minerals and water.

Recharge water derived from areas of intensive irrigation can be recognized by its high content of dissolved solids, warm temperature, and high levels of fertilizer-based constituents such as nitrate. Irrigation recharge water quickly loses its identity in the Snake River Plain aquifer due to rapid dispersion.

Near-saturation of the groundwater beneath the NRTS with respect to calcite and dolomite requires that care be used in utilization of the water, where concentration or mixing may occur, to avoid precipitation of solids.

The quantitative record of liquid wastes released to the subsurface at NRTS is incomplete. Available information indicates that from 1952 (when disposal began) through 1970 about 1.9×10^{10} gallons of liquid waste containing 7.0×10^{4} curies of radioactivity and about 1×10^{8} pounds of chemical waste have been discharged to the ground at the NRTS. Most of this has been to the Idaho Chemical Processing Plant (ICPP) deep well, the Test Reactor Area (TRA) seepage ponds and deep well, and the NRF seepage ponds. Migration and distribution of wastes after release depends on a variety of complex influences. Wastes discharged above the Snake River Plain aquifer at the NRTS form temporary perched water bodies, but eventually percolate to the regional water table.

The subsurface influence of waste disposal has been analyzed for only two facilities at NRTS -- the TRA and ICPP. For other facilities, waste disposal is either insignificant or, as in the case of the Naval Reactor Facility (NRF), sufficient data has not been collected to prepare an analysis.

The principal waste products at TRA have been NaCl, chromate, tritium, Cs-137, Sr-90, and Co-60. Distribution of these products in the perched water system has been fairly well defined. The upper sedimentary layers at TRA have been very effective in removing most or all of the cationic waste products (Cs-137, Sr-90, and Co-60) except sodium and chromium. Significant quantities of the other wastes (tritium, NaCl, hexavalent chromium), however, have entered and been dispersed in the Snake River Plain aquifer beneath the NRTS. Their distribution in the aquifer is only partly defined because of the lack of observation wells to the south and southwest of TRA.

Because of better observation-well coverage, the behavior and distribution of ICPP wastes in the regional aquifer have been much more thoroughly studied. The principal ICPP waste products include NaCl, tritium, Sr-90, Cs-137, and heat. Analysis of the observed behavior of these products in the aquifer over the 18-year (1953-1970) discharge period indicates that dispersion is a very significant mechanism in spreading and diluting the waste plume, more so than classical dispersion theory would predict. This extraordinary dispersion process may be due largely to differential vertical anisotropy in the aquifer, although channel branching and turbulent mixing in the relatively fast-flowing groundwater may be involved. Basalt has relatively poor ion-exchange capacity (compared to fine sediments); nevertheless, exchange or sorption has a prominent influence on cationic waste products in the aquifer (namely Cs-137, Sr-90, and sodium). Cs-137, for instance, has been removed below detection limits from the aquifer water by sorption. Decay of radionuclides has also been a significant factor in reducing the extent of the waste plume. Additional factors, such as pumping-wells, have lesser, but significant, influences on the migration of NRTS wastes in the aquifer.

Tritium and NaCl, the most widespread wastes in groundwater at the NRTS, have been carried downgradient in detectable quantities about 4.5 miles and have contaminated an area of at least 12 to 15 square miles of the aquifer. Concentrations of these wastes are very small however, and no groundwater contamination has been detected close to the southern boundary of the NRTS. The use of water from three supply wells (Wells CPP-1, NRF-2, and S5G Production) has required restriction or prohibition because of contamination by waste products. (The CPP-1 well has recently been restored to unrestricted use.)

Materials-balance analyses and other data indicate that most of the wastes discharged at the NRTS remain in the upper 250 feet of the Snake River Plain aquifer, as they migrate downgradient. Waste tritium and heat in the groundwater appear to be maintaining an equilibrium inventory, dissipating by decay and conduction, respectively, at a rate equal to their recharge.

Data available at this time indicate that liquid waste discharged to groundwater in the Snake River Plain aquifer beneath the NRTS attenuates rapidly due to dispersion in the flowing groundwater, sorption of some cationic wastes, and decay of all radionuclides. However, there are many significant limitations in the data at this time.

VII. SELECTED REFERENCES

R. L. Armstrong, "K-Ar Chronology of Snake River Plain, Idaho [abs.]", *Geol. Soc. America, Abstracts with Programs,* 1971, p 366.

F. C. Armstrong and S. S. Oriel, "Tectonic Development of Idaho-Wyoming Thrust Belt", *Am. Assoc. Petroleum Geologists Bull.,* Vol 49, 1965, pp 1847-1866.

Ivan Barnes, "Geochemistry of Birch Creek, Inyo County, California, A Travertine Depositing Creek in an Arid Climate", *Geochim. et Cosmochim. Acta,* Vol 29, 1965, pp 85-112.

Ivan Barnes and F. E. Clarke, "Chemical Properties of Groundwater and Their Corrosion and Encrustation Effects on Wells", *U. S. Geol. Survey Prof. Paper* 489-D, 1969.

Ivan Barnes and J. R. O'Neil, "The Relationship Between Fluids in Some Fresh Alpine-Type Ultramafics and Possible Modern Serpentinization, Western United States", *Geol. Soc. America Bull.,* Vol 80, 1969, pp 1947-1960.

J. T. Barraclough, W. E. Teasdale, R. G. Jensen, *Hydrology of the National Reactor Testing Station, Idaho, 1965,* U. S. Geol. Survey Open-File Report, 1967 (106 pages, 46 figures, 3 tables).

J. T. Barraclough, W. E. Teasdale, J. B. Robertson, and R. G. Jensen, *Hydrology of the National Reactor Testing Station, Idaho, 1966,* U. S. Geol. Survey Open-File Report, 1967 (95 pages, 56 figures, 3 tables).

T. D. Brock, "Microbial Growth Under Extreme Conditions", Symposia of the Society for General Microbiology, XIX, 1969, pp 15-41.

J. C. Bruch and L. S. Street, "Two Dimensional Dispersion", *Am. Soc. Civil Engineers Proc., Sanitary Engineering Div. Jour.,* Vol 93, No. SA6, 1967, pp 17-39.

F. M. Bullard, "Volcanic History of the Great Rift, Craters of the Moon National Monument, South-Central Idaho [abs.]", *Geol. Soc. America, Abstracts with Programs 1971,* p 234.

F. M. Bullard and D. L. Rylander, "Holocene Volcanism in Craters of the Moon National Monument and Adjacent Areas, South-Central Idaho [abs.]", *Geol. Soc. America, Abstracts with Programs,* 1970, pp 273-274.

D. S. Carder, "Seismic Investigations of Large Explosions", *Coast and Geodetic Survey Jour.,* Vol 1, 1948, pp 71-73.

W. J. Carr and D. E. Trimble, "Geology of the American Falls Quadrangle, Idaho", *U. S. Geol. Survey Bull. 1121-G,* 1963.

P. H. Carrigan, *Probability of Exceeding Capacity of Flood Control System at the National Reactor Testing Station, Idaho,* U. S. Geol. Survey Open-File Report, 1971.

H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids,* Oxford University Press, London, 1959, p 59.

R. L. Christiansen and P. W. Lipman, "Cenozoic Volcanism and Tectonism in the Western United States and Adjacent Parts of the Spreading Ocean Floor: Part 2, Late Cenozoic [abs.]", *Geol. Soc. America, Abstracts with Programs,* 1970, pp 81-82.

R. R. Coats, "Geology of the Jarbidge Quadrangle, Nevada-Idaho", *U. S. Geol. Survey Bull.* 1141-M, 1964.

R. R. Coats, R. G. Marvin, T. W. Stern, "Reconnaissance of Mineral Ages of Plutons of Elko County, Nevada and Vicinity", *U. S. Geol. Survey Prof. Paper* 525-D, 1965, pp D11-D15.

M. D. Crittenden, Jr., F. E. Schaeffer, D. E. Trimble, and L. A. Woodward, "Nomenclature and Correlation of Some Upper Precambrian and Basal Cambrian Sequences in Western Utah and Southeastern Idaho", *Geol. Soc. America Bull.,* Vol 82, 1971, pp 581-602.

E. G. Crosthwaite, C. A. Thomas, K. L. Dyer, *Water Resources in the Big Lost River Basin, South-Central Idaho,* U. S. Geol. Survey Open-File Report, 1970.

John Echo and D. B. Hawkins, "Algae Influence on Radionuclides in Settling Ponds", *Nature,* Vol. 209, No. 5028, 1966, pp 1105-1107.

E. B. Ekren, C. L. Rogers, R. E. Anderson, P. P. Orkild, "Age of Basin and Range Normal Faults in Nevada Test Site and Nellis Air Force Range, Nevada", in E. B. Eckel, (ed.), "Nevada Test Site", *Geol. Soc. America Memoir 110,* 1968, pp 247-250.

P. J. Fox and Edward Schreiber, "Granodiorites from the Cayman Trench [abs.]", *Geol. Soc. America, Abstracts with Programs,* 1970, p 553.

R. M. Garrels and C. L. Christ, *Solutions, Minerals, and Equilibria,* New York, Harper and Row, 1965.

H. H. Ham, *Replacement Groundwater Supply First Phase -- Lower Teton Division, Teton Basin Project, Idaho,* U. S. Bur. Reclamation Report, 1968.

Warren Hamilton, "Overlapping of Late Mesozoic Orogens in Western Idaho", *Geol. Soc. America Bull.,* Vol 74, 1963, pp 779-788.

Warren Hamilton, *Geology and Petrogenesis of the Island Park Caldera of Rhyolite and Basalt, Eastern Idaho,* U. S. Geol. Survey Prof. Paper 504-C, 1965.

Warren Hamilton and W. B. Myers, "Cenozoic Tectonics of the Western United States", *Rev. Geophysics,* Vol 4, 1966, pp 509-549.

D. B. Hawkins and B. L. Schmalz, *Environmental Tritium Studies at the National Reactor Testing Station,* IDO-12043 issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1965 (39 pages, 17 figures).

D. B. Hawkins and H. L. Short, *Equations for the Sorption of Cesium and Strontium on Soil and Clinoptilolite*, IDO-12046 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1965 (33 pages, 25 figures, 14 tables).

Freidric Helfferich, *Ion Exchange,* New York, McGraw-Hill, 1962.

J. D. Hem, *Study and Interpretation of the Chemical Characteristics of Natural Water, Second Edition,* U. S. Geol. Survey Water-Supply Paper 1473, 1970.

D. P. Hill, "Gravity and Crustal Structure in the Western Snake River Plain, Idaho", *Jour. Geophys. Res.,* Vol 68, 1963, pp 5807-5819.

D. P. Hill, H. L. Baldwin, Jr., L. C. Pakiser, *Gravity, Volcanism, and Crustal Deformation in the Snake River Plain, Idaho,* U. S. Geol. Survey Prof. Paper 424-B, 1961, pp B248-B250.

D. P. Hill and L. C. Pakiser, "Seismic-Refraction Study of Crustal Structure Between the Nevada Test Site and Boise, Idaho", *Geol. Soc. America Bull.,* Vol 78, 1967, pp 685-704.

S. W. Hobbs, W. H. Hays, R. J. Ross, Jr., "The Kinnikinic Quartzite of Central Idaho -- Redefinition and Subdivision", *U. S. Geol. Survey Bull.* 1254-J, 1968.

J. R. Horan and Others, *Annual Report of Health and Safety Division, 1959,* IDO-12014 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1960, p 152.

J. R. Horan and Others, *Health and Safety Division Annual Report, 1961,* IDO-12021 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1962, pp 108-121.

J. R. Horan and Others, *Health and Safety Division Annual Progress Report, 1963,* IDO-12037 issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1963, pp 48-53.

D. G. Jacobs, *Sources of Tritium and Its Behavior Upon Release to the Environment,* U. S. Atomic Energy Commission, Oak Ridge, Tenn., AEC Critical Review Series, TID-24635, 1968.

E. A. Jenne, "Controls on Mn, Fe, Co, Ni, Cu, and Zn Concentrations in Soils and Water: The Significant Role of Hydrous Mn and Fe Oxides", *Am. Chem. Soc., Advances in Chemistry Series 73,* 1968, pp 337-387.

E. A. Jenne and J. S. Wahlberg, *Role of Certain Stream-Sediment Components in Radioion Sorption,* U. S. Geol. Survey Prof. Paper 433-F, 1968.

B. F. Jones, "Geochemical Evolution of Closed Basin Water in the Western Great Basin", in J. L. Rau (ed.), *Second Symposium on Salt: Northern Ohio Geological Society,* 1966, pp 181-200.

P. H. Jones, *Hydrology of Waste Disposal, National Reactor Testing Station, Idaho,* U. S. Geol. Survey Open-File Report, IDO-22042 issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1961 (82 pages, 70 figures).

V. C. Kennedy, "Silica Variation in Stream Water with Time and Discharge", *Am. Chem. Soc., Advances in Chemistry Series 106,* 1971, pp 93-130.

V. R. D. Kirkham, Snake River Downwarp: *Jour. Geology,* Vol 39, 1931, pp 456-482.

R. W. Kistler, J. F. Evernden, H. R. Shaw, "Sierra Nevada Plutonic Cycle: Part I, Origin of Composite Granitic Batholiths", *Geol. Soc. America Bull.,* Vol 82, 1971, pp 853-868.

K. B. Krauskopf, *Introduction to Geochemistry,* New York, McGraw-Hill, 1967.

T. R. La Fehr and L. C. Pakiser, *Gravity, Volcanism, and Crustal Deformation in the Eastern Snake River Plain, Idaho,* U. S. Geol. Survey Prof. Paper 450-D, 1962, pp D76-D78.

R. D. Lamke, *Stage Discharge Relations on Big Lost River within National Reactor Testing Station, Idaho,* U. S. Geol. Survey Open-File Report, IDO-22050 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1969.

Waldemar Lindgren, "Geologic Atlas of the United States, Boise Folio, Idaho", *U. S. Geol. Survey,* 1898.

D. R. Mabey, *Relation Between Bouguer Gravity Anomalies and Regional Topography in Nevada and the Eastern Snake River Plain, Idaho*, U. S. Geol. Survey Prof. Paper 550-B, 1966, pp B108-B110.

D. R. Mabey and F. C. Armstrong, *Gravity and Magnetic Anomalies in Gem Valley, Caribou County, Idaho,* U. S. Geol. Survey Prof. Paper 450-D, 1962, pp D73-D75.

E. H. McKee and M. L. Silberman, "Periods of Plutonism in North-Central Nevada [abs.]", *Geol. Soc. America, Abstracts with Programs,* 1970, pp 613-614.

H. E. Malde, "Fault Zone Along Northern Boundary of Western Snake River Plain, Idaho", *Science,* Vol 130, 1959, p 272.

H. E. Malde, *Geologic Investigations of Faulting Near the National Reactor Testing Station, Idaho,* U. S. Geol. Survey Open-File Report, 1971.

H. E. Malde and H. A. Powers, "Upper Cenozoic Stratigraphy of Western Snake River Plain, Idaho", *Geol. Soc. America Bull.,* Vol 73, 1962, pp 1197-1220.

E. C. J. Mohr and F. A. Van Baren, "Tropical Soils", *Interscience,* New York, 1954.

D. A. Morris, *Use of Chemical and Radioactive Tracers at the NRTS, Idaho,* Geophys. Monograph No. 11, Am. Geophys. Union, 1967, pp 130-142.

D. A. Morris and Others, *Hydrology of Waste Disposal, National Reactor Testing Station, Idaho,* U. S. Geol. Survey Open-File Report, IDO-22044 issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1963 (99 pages, 48 figures).

D. A. Morris and Others, *Hydrology of Subsurface Waste Disposal, National Reactor Testing Station, Idaho, Annual Progress Report 1964,* U. S. Geol. Survey Open-File Report, IDO-22047 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1965 (187 pages, 94 figures).

D. A. Morris, W. E. Teasdale, and Others, *Hydrology of Subsurface Waste Disposal, National Reactor Testing Station, Idaho,* U. S. Geol. Survey Open-File Report, IDO-22046 issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1964 (97 pages, 87 figures).

M. J. Mundorff, E. G. Crosthwaite, Chabot Kilburn, *Groundwater for Irrigation in the Snake River Basin in Idaho,* U. S. Geol. Survey Water-Supply Paper 1654 (224 pages, 6 plates, 54 figures, 14 tables).

R. L. Nace, Morris Deutsch, P. T. Voegeli, *Physical Environment of the National Reactor Testing Station -- A Summary,* U. S. Geol. Survey Professional Paper 725-A, 1973.

R. L. Nace, P. T. Voegeli, Morris Deutsch, *Geology, Hydrology, and Waste Management of the National Reactor Testing Station, Idaho,* U. S. Geol. Survey Professional Paper 725-B (in press).

W. H. Nelson and C. P. Ross, "Geology of Part of the Alder Creek Mining District, Custer County, Idaho", *U. S. Geol. Survey Bull.,* 1252A, 1968.

W. H. Nelson and C. P. Ross, "Geologic Map of the Mackay Quadrangle, South-Central Idaho", *U. S. Geol. Survey, Misc. Geol. Inv.,* 1969, Map I-580.

R. F. Norvitch, C. A. Thomas, R. J. Madison, *Artificial Recharge to the Snake Plain Aquifer; An Evaluation of Potential and Effect;* Water Information Bulletin No. 12, issued by Idaho Department of Reclamation, Boise, Idaho, 1969, p 20.

F. H. Olmsted, *Chemical and Physical Character of Groundwater in the National Reactor Testing Station, Idaho:* U. S. Geol. Survey Open-File Report, IDO-22043 issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1962 (81 pages, 19 figures).

J. H. Osloond, *Radioactive Waste Disposal Data for the National Reactor Testing Station,* IDO-12040 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1965 (29 pages, 3 figures, 20 tables).

J. H. Osloond, *Radioactive Waste Disposal Data for the National Reactor Testing Station, Idaho,* IDO-12040, Supplement No. 2, issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1967 (18 pages, 6 figures, 12 tables).

J. H. Osloond, *Waste Disposal Data for the National Reactor Testing Station, Idaho,* IDO-12074 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1970 (28 pages, 7 figures, 17 tables).

J. H. Osloond and D. L. Newcomb, *Radioactive Waste Disposal Data for the National Reactor Testing Station, Idaho,* IDO-12040, Supplement No. 3, issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1968 (13 pages, 6 figures, 11 tables).

J. H. Osloond and D. L. Newcomb, *Radioactive Waste Disposal Data for the National Reactor Testing Station, Idaho,* IDO-12040, Supplement No. 4, issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1969 (15 pages, 6 figures, 11 tables).

J. H. Osloond and B. L. Schmalz, *Radioactive Waste Disposal Data for the National Reactor Testing Station, Idaho,* IDO-12040, Supplement No. 1., issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1966 (12 pages, 6 figures, 9 tables).

L. C. Pakiser, "Structure of the Crust and Upper Mantle in the Western United States", *Jour. Geophys. Res.,* Vol 68, 1963, pp 5747-5756.

L. C. Pakiser and D. P. Hill, "Crustal Structure in Nevada and Southern Idaho from Nuclear Explosions", *Jour. Geophys. Res.,* Vol 68, 1963, pp 5757-5766.

R. A. Paull, M. A. Wolbrink, R. G. Volkman, R. L. Grover, "Upper Paleozoic Stratigraphic Section, Central Pioneer Mountains, South-Central Idaho[abs.]", *Geol. Soc. America, Abstracts with Programs,* 1971, pp 402-403.

A. E. Peckham, *Investigation of Underground Waste Disposal, Chemical Processing Plant Area, National Reactor Testing Station, Idaho,* U. S. Geol. Survey Open-File Report, IDO-22039 issued by the U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1959 (5 pages, 11 figures).

M. Prinz, "Idaho Rift System, Snake River Plain, Idaho", *Geol. Soc. America Bull.,* Vol 81, 1970, pp 941-948.

C. P. Ross, "Geology of the Southern Part of the Lemhi Range, Idaho", *U. S. Geol. Survey Bull.* 1081-F, 1961, pp 189-260.

S. H. Ross, *Geothermal Potential of Idaho,* Preprint of Paper for U. N. Symposium on Geothermal Resources, Pisa, Italy, (28 pages and appendices), Idaho Bur. of Mines and Geology Open-File Report, January 1970.

I. C. Russell, *Geology and Water Resources of the Snake River Plain of Idaho,* U. S. Geol. Survey Bull. 199, 1902.

B. L. Schmalz, *Liquid Waste at the National Reactor Testing Station, Idaho,* IDO-12066 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1968 (25 pages, 10 figures, 7 tables).

B. L. Schmalz, *Radionuclide Distribution in Soil Mantle of the Lithosphere as a Consequence of Waste Disposal at the National Reactor Testing Station,* IDO-10049 issued by U. S. Atomic Energy Commission, Idaho Falls, Idaho, 1972.

Robert Scholten "Paleozoic Evolution of the Geosynclinal Margin North of the Snake River Plain, Idaho-Montana", *Geol. Soc. America Bull.,* Vol. 68, 1957, pp 151-170.

Robert Scholten, "Model for Evolution of Rocky Mountains East of Idaho Batholith", *Tectonophysics,* Vol 6, 1968, pp 109-126.

E. S. Simpson, *Transverse Dispersion in Liquid Flow Through Porous Media,* U. S. Geol. Survey Prof. Paper 411-C, 1962, pp 23-25.

J. G. Smith, E. H. McKee, D. B. Tatlock, "Age and Chemistry of Plutons in Northwestern Nevada and their Relationship to the Sierra Nevada and Idaho Batholiths [abs.]", *Geol. Soc. America, Abstracts with Programs,* 1971, p 197.

R. B. Smith and M. L. Sbar, "Tectonics of the Intermountain Seismic Belt, Western United States, Part II: Focal Mechanisms of Major Earthquakes [abs.]", *Geol. Soc. America, Abstracts with Programs,* 1970, pp 687-688.

H. T. Stearns, *Geology of the Craters of the Moon National Monument, Idaho,* Caxton Printers, Caldwell, Idaho, 1963.

H. T. Stearns and L. L. Bryan, *Preliminary Report on the Geology and Water Resources of the Mud Lake Basin, Idaho,* U. S. Geol. Survey Water-Supply Paper 560-D, 1925, pp 87-134.

H. T. Stearns, L. L. Bryan, Lynn Crandall, *Geology and Water Resources of the Mud Lake Region, Idaho, Including the Island Park Area,* U. S. Geol. Survey Water-Supply Paper 818, 1939.

H. T. Stearns, L. Crandall, W. G. Steward, *Geology and Groundwater Resources of the Snake River Plain in Southeastern Idaho,* U. S. Geol. Survey Water-Supply Paper 774, 1938.

N. D. Stearns, H. T. Stearns, G. A. Waring, *Thermal Springs in the Unites States,* U. S. Geol. Survey Water-Supply Paper 679-B, 1937, pp 59-206.

Werner Stumm and J. J. Morgan, *Aquatic Chemistry,* New York, 1970.

W. H. Taubeneck, "Idaho Batholith and its Southern Extension", *Geol. Soc. America Bull.,* Vol 82, 1971 pp 1899-1928.

D. K. Todd, *Groundwater Hydrology* John Wiley and Sons, Inc., New York, 1959, p 59.

D. E. Trimble and W. J. Carr, *Paleozoic Rocks Measured Southwest of Pocatello, Idaho,* U. S. Geol. Survey Open File Report 651, 1962.

U. S. Atomic Energy Commission, 1968, Standards for Radiation Protection: U. S. Atomic Energy Comm., Manual, Chapter 0524, Appendix 0524, Paragraph B-1.

U. S. Atomic Energy Commission, 1970, Prevention, Control, and Abatement of Air and Water Pollution: AEC Manual, Chapter 0510.

U. S. Department of Health, Education, and Welfare, 1962, Public Health Service Drinking Water Standards -- 1962: Public Health Service Publication No. 956, pp 56-59.

G. A. Waring, *Thermal Springs of the United States and Other Countries of the World -- A Summary,* U. S. Geol. Survey Prof. Paper 492, 1965.

G. R. Yanskey, E. H. Markee, Jr., A. P. Richter, *Climatography of the National Reactor Testing Station,* U. S. Inst. for Atmospheric Sciences, IDO-12048 issued by U. S. Atomic Energy Comm, Idaho Falls, Idaho, 1966.

APPENDIX A

DISCUSSION OF GROUNDWATER HYDROGRAPHS IN NRTS VICINITY

APPENDIX A

DISCUSSION OF GROUNDWATER HYDROGRAPHS IN NRTS VICINITY

Hydrographs from the northern part of the station shown on Figure 3, reflect groundwater recharge from Birch Creek, other streams to the north, and underflow from the area to the notheast. The annual precipitation at TAN has ranged from 4.37 inches in 1956 to 15.60 inches in 1963 and averaged about 8.2 inches. The differences in precipitation at TAN appear to have little effect on the groundwater levels in nearby wells. The discharge of Birch Creek near Reno, Idaho is remarkably constant for the period of record. Average annual flow ranged from 75.2 to 84.2 cfs and the 15-year average is 78.8 cfs (57,000 acre-feet per year). Birch Creek is fed by uniform flowing springs which are annually recharged by snowmelt. Apparently little overland flow from snowmelt is carried across the long alluvial fans into Birch Creek. One exception is the high flow in the spring of 1962. Warm weather in February caused rapid snowmelt which increased the flow to 130 cfs. The water level in Well 25 fluctuated only about three feet from 1952 through 1968. The highest water level occurred in 1961 and the lowest in 1966. The water level in Well 25 represents the natural conditions in the area as the nearest groundwater pumping is about three miles south. Hydrographs of the water level in Well 26 are similar to those graphs of Well 25. The highest water level occurred in 1967 and the lowest in 1966. The water level fluctuates from one to two feet annually. Well 26 also represents the natural conditions because it is more than two miles from the nearest pumped well. The water level in Well ANP 9 fluctuated only three feet from 1956 through 1968 and followed the same trend as the water level in Wells 25 and 26.

The hydrographs indicate that the Snake River Plain aquifer water level in the northern part of NRTS remains rather constant over the period of record. The recharge effects from precipitation are generally dampened and represent a rather uniform volume of groundwater flow entering the station from the north and northeast.

Figure 8 shows hydrographs of four wells in the eastern part of the NRTS that respond to recharge from Mud Lake and from the northeastern part of the Snake River Plain. Water levels in the wells have a normal cyclic fluctuation of two to four feet annually. These annual changes probably represent the influence of the spring runoff due to snowmelt and recharge from irrigation. Water levels start to rise in late summer, peak in the winter, and then decline until the next rise in the summer. The highest water level for these wells was in 1952-54 and the lowest was in 1964. The Well 4 water level (near the Mud Lake irrigated area) has fluctuated almost seven feet. The average water level for the past few years in Well 4 is about two feet lower than it was in 1950-54. This decline may be due to increased withdrawal of groundwater for irrigation in the Mud Lake region. Water levels in Well 21 and the Highway 2 well fluctuated about six feet over the period of record. The average water level is now about two feet lower than in 1952-54. The water level in the Arbor Test well shows similar trends and changes as the other wells in Figure 8.

Hydrographs of Wells 18, 6, 5, and Site 14 in the central part of the Station show rising water levels during periods of flow in the nearby Big Lost River and declining water levels during years of no flow (Figure 9). The hydrograph of Well 5 is similar to that of Well 6. The maximum water level change over the period of record has been about six feet. The high occurred in 1953 and the low in 1964. The data from both wells show rises in 1952-53, 1958-59, and 1965-69. These period are associated with substantial flow in the Big Lost River near the wells (1951-53, 1958, 1965-68). Water levels in Well 18 and Site 14 show similar changes to those in Wells 5 and 6, except that recharge from the record Big Lost River flows of 1965 and 1967 produced bigger changes. Well 18 had a maximum water-level change of six feet and Site 14 changed about 7-1/2 feet. The highest water level was in 1965 and the lowest was in 1964. The water levels in these wells show rapid response to recharge from the Big Lost River as the water level has risen as much as five feet within a few months.

Hydrographs of Wells 20, 17, 23, and 12 in the western part of the NRTS show recharge effects from the Big and Little Lost Rivers (Figure 10). High water levels were measured in 1953, 1959, and 1966 and the lowest water levels occurred in 1964. Water levels in this part of the NRTS fluctuate more than those in any other part of the station, apparently because of hydraulic boundary conditions and recharge effects. Water levels in Well 12 fluctuated 11 feet during the period of record, the maximum change measured at the NRTS from 1950 to 1968. The maximum measured change of the water level in Wells 17 and 23 was about 10 feet and in Well 20, about 7 feet.

The hydrographs of the Cerro Grande Well, and Wells 1, 2, and 14, in the southeastern corner of the NRTS, reflect recharge from the Mud Lake area and from areas farther northeast on the Snake River Plain (Figure 11). In addition, the hydrographs were affected by recharge from the Big Lost River in 1965 and 1967. The highest water levels occurred during the period of 1950-53 and the lowest in 1964. The water levels show fluctuations of four to six feet over the period of record and usually show an annual cyclic change of one or two feet. Water levels have generally declined about two feet during the period of record.

Hydrographs of Wells 8, 9, 11, and 13, near the southwest corner of the NRTS, are strongly affected by major flows in the Big Lost River (Figure 12). The water levels declined from 1951 or 1952 until 1964. Recharge from the Big Lost River in 1965 and 1967 caused rapid changes in the water level. Water levels have fluctuated about five feet during the period of record. Long-term hydrographs of Wells 8, 9, and 11 show annual cyclic fluctuations with peaks occurring from November to January each year. Water levels in wells in this area have declined about two feet during the period of record.

Figure 39 shows that the water level of MTR Test well rises during period of high flows of the Big and Little Lost Rivers and declines during dry periods. The water level fluctuated almost 11 feet from 1950 to 1968 and was highest in 1953 and lowest in 1964. Pumping from nearby wells used for water supply at TRA has a minor drawdown effect on the water level in the MTR test well. The water level has generally declined during the period of record.

Hydrographs of the 24 wells (Figures 3, 8 through 12, and 42) show the general changes in the water level of the Snake River Plain aquifer beneath NRTS. Periods of record range from 10 to almost 20 years and average 16-1/2 years. The total fluctuation that was measured during the period of record ranged from 3 to 11 feet and averaged 6 feet. The highest water level was measured during the period of 1950-54 in 62% of the wells, while 25% had the highest water level in 1959-63. Thirteen percent of the wells had the highest water level in 1965. The lowest water level was measured in 75% of the wells in 1964. In the years 1961-62, about 8% of the wells had the lowest water level and in 1965-67, nearly 17% of the wells had the lowest water levels.

Long-term trends in the water level as NRTS are difficult to determine and evaluate. Recharge effects from different sources at considerable distances arrive at the wells at various times. Overall, the water levels appear to have declined slightly since 1950. The net change of the water level from the end of 1952 to the end of 1968 ranged from 0 to -5.3 feet for 20 of the 24 wells. The average change in the water level during this period was -2 feet. Some explanations for this slight decline would include decreased recharge from snow melt, additional groundwater pumping near Mud Lake and Hamer, pumping at the NRTS, and additional pumping elsewhere on the Snake River Plain.

APPENDIX B

BASIC HYDROCHEMICAL DATA

APPENDIX B

BASIC HYDROCHEMICAL DATA

COMMENTS ON TABLE B-1

The accuracy of most of these analyses is poor for several reasons. Most important is the uncontrolled conditions prevailing during the collection of groundwater samples. Some samples represent the output of a well after a long period of heavy pumping. These consist of a mixture of waters from the aquifers penetrated by the well, combined in an unknown ratio representing the differing productivities of each aquifer. Pumped samples, however, broadly represent the groundwater at and around each well. In Table B-1 the depth-interval listed for pumped samples extends from the water table to the bottom of the hole.

Bailer samples consist of water collected during cable-tool drilling; hence, they represent a more limited depth than do pumped samples. The high probability of impurities being introduced during drilling, however, compromises the quality of bailer samples. Samples collected with a Föerst thief sampler represent the water at specific levels in each well, but the large head differences commonly found between lava flows intercepted by a well negates the advantages of this sampling method. The apparent presence of a zone of fresher water of varying thickness at the top of the water table also limits the usefulness of some thief samples.

In addition to uncertainty regarding representation of well samples, all the analyses vary with regard to the number and kind of constituents analyzed. Because all constituents were determined in the laboratory after varied period of storage, the pH and alkalinity values are suspect. Values for dissolved iron cannot be relied upon because of lack of filtration and preservation of the samples at the time of collection.

In spite of these limitations on accuracy, the similarity of often redundant analyses of single well lends a degree of confidence to the entire group. Although newer and better techniques should be used in the future, the best analyses presented can be used with confidence to define certain broad trends in groundwater chemistry.

Because of the large number of analyses, the virtual duplication of analyses at many wells, and the existence of obviously bad analyses, a "best" analysis for each well was selected and arranged in Table 3. These 69 analyses form the basis for the isoconcentration contour maps, for the thermodynamic mineral solubility calculations, and, thus, for our conclusions.

TABLE B-I

CHEMICAL ANALYSES OF 207 GROUNDWATER SAMPLES FROM THE NATIONAL REACTOR TESTING STATION AND VICINITY

											mg/l (upper number) and equivalents per million (lower number) for indicated cations and anions ions												Hardness as $CaCO_3$		
Well No.	U.S.G.S. location number	Date Sampled	Method of sampling	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determined constituents	Residue on evaporation at 180°C	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)	Silica (SiO_2)	Dissolved iron (Fe)	Total	Noncarbonate	Type of Water
USGS 1	2N-31E-35 dcl	Dec. 1, 1949	Bailer	585-635	56	---	7.8	278	190	183	28 1.40	11 0.90	18 0.78	a a	150 2.46	0 0.00	14 0.29	10 0.28	1.8 0.03	0.7 0.04	32	0.27	115	0	B
Do	do	Oct. 15, 1952	Pump	582-635	54	3	7.9	284	186	181	28 1.40	11 0.90	14 0.61	2.7 0.07	148 2.43	0 0.00	14 0.29	9.0 0.25	1.2 0.02	0.6 0.03	33	0.04	115	0	B
Do	do	June 7, 1965	Thief	615	61	5	7.5	287	177	178	29 1.45	10 0.83	14 0.61	2.9 0.07	142 2.33	0 0.00	12 0.25	9.2 0.26	2.1 0.03	0.8 0.04	27	0.6	114	0	B
USGS 2	3N-32E-29 ddl	Jan. 4, 1950	Bailer	646-698	53.5	---	7.7	282	186	183	32 1.60	12 0.99	8.9 0.39	2.9 0.07	149 2.44	0 0.00	14 0.29	8.8 0.25	1.6 0.03	0.7 0.04	32	0.06	129	7	A
Do	do	Oct. 17, 1952	Pump	654-704	54	2	7.9	284	184	182	29 1.45	11 0.90	14 0.61	2.8 0.07	147 2.41	0 0.00	12 0.25	9.0 0.25	1.5 0.02	0.7 0.04	32	0.07	118	0	B
Do	do	June 7, 1965	Thief	690	56	0	7.7	280	169	169	27 1.35	9.9 0.81	15 0.65	3.1 0.08	139 2.28	0 0.00	11 0.23	10 0.28	2.1 0.3	0.8 0.04	22	0.38	108	0	B
USGS3A	3N-33E-3 abl	Apr. 19, 1950	Bailer	680-733	53	---	8.2	276	188	186	29 1.45	10 0.82	15 0.65	3.2 0.08	146 2.39	0 0.00	9.1 0.19	11 0.31	2.3 0.04	0.3 0.02	36	0.22	113	0	B
Do	do	Oct. 22, 1952	Pump	672-733	55	4	8.0	275	183	179	29 1.45	9.5 0.78	15 0.65	2.7 0.07	149 2.44	0 0.00	9.1 0.19	8.0 0.23	1.5 0.02	0.9 0.05	34	0.12	110	0	B
USGS 4	5N-34E-9 bdl	Feb. 3, 1950	---	254-321	54	---	7.8	1000	574	639	100 4.99	36 2.96	42 1.83	8.8 0.23	185 3.03	0 0.00	59 1.23	174 4.91	32 0.52	0.3 0.02	31	0.24	398	246	C
Do	do	Nov. 8, 1952	Pump	256-321	52	---	7.7	963	542	583	93 4.64	33 2.71	42 1.83	6.8 0.17	186 2.05	--- ---	57 1.19	160 4.51	29 0.47	0.3 0.02	29	0.12	368	215	C
USGS 5	3N-30E-12 cdl	Mar. 17, 1950	Bailer	450-500	55	---	8.5	242	159	161	24 1.20	8.0 0.66	10 0.44	4.5 0.12	74 1.21	12 0.40	23 0.48	10 0.28	1.2 0.02	0.3 0.02	30	0.03	93	12	C
Do	do	Sept. 22, 1952	Bailer	464-500	55	2	7.8	327	203	200	41 2.05	13 1.07	7.2 0.31	1.7 0.04	172 2.82	0 0.00	20 0.42	9.5 0.27	1.3 0.02	0.2 0.01	24	0.02	156	15	A
USGS 6	4N-31E-16 adl	Apr. 16, 1950	Bailer	415-475	53.5	---	7.5	692	369	---	76 3.79	21 1.73	21 0.91	3.7 0.09	102 1.67	0 0.00	37 0.77	138 3.89	5.3 0.09	0.2 0.01	17	0.05	276	192	C
Do	do	Sept. 12, 1952	Pump	414-620	57	7	7.6	304	185	183	30 1.50	12 0.99	14 0.61	2.7 0.07	150 2.46	0 0.00	20 0.42	9.5 0.27	1.4 0.02	0.4 0.02	21	0.21	124	2	B
Do	do	Feb. 27, 1962	Thief	460	53	5	7.9	250	125	119	18 0.9	9.1 0.75	15 0.65	2.7 0.07	64 1.05	0 0.00	7.8 0.16	38 1.07	0.2 0	0.3 0.02	2.2	0.03	82	30	C
Do	do	do	Thief	570	52	5	7.5	264	155	151	26 1.3	8.3 0.68	14 0.61	2.5 0.06	112 1.84	0 0.00	13 0.27	16 0.45	3.5 0.06	0.3 0.02	16	0.02	99	7	C
Do	do	Dec. 3, 1962	Thief	460	---	50	6.9	333	166	145	23 1.14	9.6 0.79	16 0.7	3.6 0.09	110 1.8	0 0.00	0.2 0	40 1.13	1.2 0.02	0.2 0.01	1.5	0.18	97	3	C
Do	do	Dec. 18, 1963	Thief	460	---	20	8.2	310	140	138	19 0.95	9.5 0.78	15 0.65	4.0 0.1	102 1.67	0 0.00	0.8 0.02	40 1.13	0.6 0.01	0.2 0.01	0.8	---	86	3	C
Do	do	June 21, 1965	Thief	435	---	20	8.0	354	164	163	24 1.2	11 0.88	16 0.7	4.1 0.1	132 2.16	0 0.00	0.2 0	41 1.16	0.1 0	0.3 0.02	2.2	3	104	0	C
USGS 7	6N-31E-27 bal	Mar. 31, 1950	Bailer	221-498	55	---	8.5	333	215	209	32 1.60	16 1.32	17 0.74	5.2 0.13	167 2.74	0 0.00	23 0.48	10 0.28	5.5 0.09	0.4 0.02	24	0.05	146	9	B
Do	do	Apr. 4, 1950	Bailer	223-600	53	---	8.2	338	214	209	34 1.70	15 1.23	15 0.65	4.8 0.12	173 2.84	0 0.00	20 0.42	10 0.28	5.0 0.08	0.3 0.02	25	0.05	147	5	B
Do	do	June 7, 1952	Pump	214-698	55	5	7.9	335	208	205	33 1.65	16 1.32	12 0.52	3.1 0.08	170 2.79	0 0.00	20 0.42	8.0 0.23	4.6 0.07	0.2 0.01	27	0.06	148	9	B
Do	do	Aug. 9, 1952	Pump	212-1200	66	2	7.7	311	218	214	26 1.30	11 0.90	24 1.04	4.0 0.10	148 2.43	0 0.00	21 0.44	9.5 0.27	0.5 0.01	1.6 0.08	47	0.11	110	0	B
Do	do	Aug. 13, 1952	Thief	825	66	---	---	317	197	---	23 1.15	7.7 0.63	31 1.34	a a	147 2.41	--- ---	20 0.42	10 0.28	0.6 0.01	--- ---	32	---	89	0	B
Do	do	May 18, 1961	Thief	380	---	---	8.6	231	---	---	11 0.55	8.2 0.67	27 1.17	4.7 0.12	118 1.93	4 0.13	1.4 0.03	10 0.28	0.1 0.00	1.5 0.08	---	---	61	0	B
Do	do	do	Thief	440	---	---	8.0	274	---	---	21 1.05	8.8 0.73	25 1.09	4.4 0.11	142 2.33	0 0.00	7.4 0.15	10 0.28	0.1 0.00	1.6 0.08	---	---	89	0	B
Do	do	do	Thief	720	---	---	7.9	276	---	---	22 1.10	8.4 0.69	25 1.09	4.4 0.11	144 2.36	0 0.00	8.2 0.17	10 0.28	0.1 0.00	1.6 0.08	---	---	90	0	B
Do	do	do	Thief	780	---	---	7.9	280	---	---	23 1.15	7.6 0.63	25 1.09	4.5 0.12	146 2.39	0 0.00	9.6 0.20	10 0.28	0.1 0.00	1.6 0.08	---	---	89	0	B
Do	do	Feb. 15, 1962	Thief	380	62	5	8.6	227	126	123	12 0.60	6.4 0.57	26 1.13	4.4 0.11	109 1.79	6 0.20	1.2 0.02	10 0.28	0.10 0	1.5 0.08	4	1.8	58	0	B
Do	do	do	Thief	440	62	0	8.1	249	142	138	17 0.85	7.2 0.59	24 1.04	4.4 0.11	132 2.16	0 0.00	5.6 0.12	9.8 0.28	0.1 0	1.6 0.08	7.7	2.4	72	0	B
Do	do	do	Thief	780	63	5	8.1	269	180	174	20 1.00	8.2 0.68	25 1.09	4.4 0.11	136 2.23	0 0.00	11 0.23	9.8 0.28	0.4 0.01	1.6 0.08	32	0.03	84	0	B
USGS 7	6N-31E-27 bal	Nov. 28, 1962	Thief	380	58	5	8.6	216	117	112	8.8 0.44	6.6 0.54	26 1.13	4.4 0.11	101 1.66	7 0.23	0.2 0	9.8 0.28	0.1 0	1.4 0.07	2.0	0 0	50	0	B
Do	do	Dec. 17, 1963	Thief	250	---	5	8.1	285	173	164	23 1.15	8.5 0.7	24 1.04	4.3 0.11	144 2.36	0 0.00	14 0.29	9.2 0.26	0.1 0	1.8 0.09	17	--- ---	92	0	B
Do	do	June 3, 1965	Thief	250	57	0	8.4	261	151	143	18 0.9	8.2 0.68	24 1.04	4.3 0.11	132 2.16	3 0.1	6.0 0.12	9.5 0.27	0.1 0	1.6 0.08	11	0.86	79	0	B
USGS 8	2N-27E-2 ddl	Sept. 9, 1950	Bailer	761-812	52	---	7.9	347	210	206	44 2.20	15 1.23	6.3 0.27	1.6 0.04	180 2.95	0 0.00	24 0.50	10 0.28	1.3 0.02	0.3 0.02	19	0.04	172	24	A

TABLE B-I (contd.)

											mg/l (upper number) and equivalents per million (lower number) for indicated cations and anions												Hardness as $CaCO_3$		
Well No.	U.S.G.S. location number	Date Sampled	Method of sampling	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determined constituents	Residue on evaporation at 180°C	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)	Silica (SiO_2)	Dissolved iron (Fe)	Total	Noncarbonate	Type of water
Do	do	June 8, 1965	Thief	785	52	0	7.8	351	208	207	45 2.25	14 1.19	6.4 0.28	1.7 0.04	180 2.95	0 0.00	22 0.46	9.0 0.25	2.1 0.03	0.3 0.02	19	0.05	172	24	A
USGS 9	2N-28E-35 ad1	Dec. 18, 1951	Bailer	604-654	52	3	8.0	310	204	196	37 1.85	14 1.15	7.9 0.34	5.0 0.13	162 2.66	0 0.00	22 0.46	10 0.28	0.7 0.01	0.3 0.02	27	0.03	150	17	A
Do	do	Dec. 6, 1962	Thief	500	52	5	7.0	186	100	102	12 0.60	5.7 0.47	13 0.57	4.5 0.12	59 0.97	0 0.00	22 0.46	12 0.34	0.2 0	0.3 0.02	0.8	0.0	54	5	C
USGS 11	1N-29E-30 bb1	Sept. 12, 1950	---	647-704	53	---	7.9	314	195	199	38 1.90	13 1.07	6.9 0.30	2.6 0.07	162 2.66	0 0.00	21 0.44	8.8 0.25	0.8 0.01	0.3 0.02	24	0.06	148	16	A
Do	do	May 12, 1952	Thief	676	57	5	7.6	301	193	185	38 1.90	14 1.15	6.5 0.28	2.0 0.05	158 2.59	0 0.00	24 0.50	7.4 0.21	0.8 0.01	0.1 0.01	22	0.14	152	23	A
USGS 12	4N-30E-7ad1	Aug. 30, 1950	Pump	325-509	53	---	8.0	540	324	354	70 3.49	22 1.81	10 0.43	1.6 0.04	221 3.62	0 0.00	40 0.83	44 1.24	4.4 0.07	0 0.00	23	0.02	265	84	C
Do	do	Sept. 30, 1952	Pump	325-634	52	2	7.7	536	313	327	67 3.34	22 1.81	11 0.48	2.0 0.05	218 3.57	0 0.00	38 0.79	40 1.13	4.1 0.07	0.2 0.01	21	0.02	258	79	C
Do	do	Feb. 27, 1962	Thief	400	51	0	7.8	420	225	232	43 2.15	19 1.58	11 0.48	2.1 0.05	169 2.77	0 0.00	26 0.54	31 0.87	0.8 0.01	0.2 0.01	8.7	0.15	186	48	C
Do	do	do	Thief	500	52	5	7.4	425	231	234	45 2.25	19 1.55	11 0.48	2.0 0.05	170 2.79	0 0.00	27 0.56	32 0.90	0.5 0.01	0.2 0.01	10	---	190	50	C
Do	do	Dec. 3, 1962	Thief	400	51	0	7.5	399	210	217	38 1.89	19 1.60	11 0.48	2.0 0.05	160 2.62	0 0.00	17 0.35	34 0.96	3.3 0.05	0.2 0.01	5.8	0.0	175	44	C
Do	do	Dec. 17, 1963	Thief	400	---	0	7.4	434	239	244	44 2.20	21 1.76	11 0.48	2.0 0.05	165 2. 0.00	0 0.00	31 0.65	39 1.1	0.3 0	0.2 0.01	9.2	---	198	63	C
Do	do	June 8, 1965	Thief	490	53	0	7.7	567	328	362	71 3.54	22 1.81	12 0.52	2.1 0.05	218 3.57	0 0.00	43 0.90	44 1.24	6.3 0.1	0.2 0.01	20	2.5	268	89	C
USGS 13	2N-27E-33ac2	May 7, 1952	---	983-1200	62	2	8.1	460	270	278	34 1.70	21 1.73	27 1.17	4.2 0.11	151 2.48	0 0.00	29 0.60	55 1.55	2.2 0.04	0.2 0.01	23	0.08	171	47	C
USGS 14	1S30E-15 bc1	Dec. 3, 1962	Thief	275	59	5	7.9	327	208	208	32 1.59	13 1.09	16 0.70	2.8 0.07	162 2.66	0	24 0.50	8.5 0.24	1.1 0.02	0.5 0.03	30	0.01	134	2	B
USGS 15	4N-30E-6 ab1	Apr. 1, 1952	Bailer	307-14°7	66	---	8.9	344	203	---	5.7 0.28	3.1 0.26	70 3.04	4.6 0.12	154 2.52	16 0.53	3.6 0.08	17 0.48	0.4 0.01	0.7 0.04	6.4	---	27	0	B
Do	do	Sept. 29, 1952	Pump	312-1497	53	---	7.8	303	186	178	32 1.60	16 1.32	8.3 0.36	1.5 0.04	163 2.67	0 0.00	19 0.40	7.0 0.20	1.2 0.02	0.1 0.01	21	0.02	146	12	A
USGS 17	4N-30E-22 bd1	Aug. 17, 1951	Pump	351-406	55.5	5	7.5	277	167	173	34 1.70	9.8 0.81	7.0 0.30	3.0 0.08	143 2.34	0 0.00	16 0.33	6.8 0.19	0.1 0.00	0.2 0.01	20	0.03	125	8	A
Do	do	Nov. 29, 1951	Bailer	351-497	52	5	7.6	220	143	147	27 1.35	6.6 0.54	7.5 0.33	3.2 0.08	100 1.64	0 0.00	21 0.44	7.0 0.20	0.5 0.01	0.2 0.01	21	0.01	94	13	B
Do	do	Nov. 30, 1951	Pump	351-497	52	---	8.3	225	144	153	28 1.40	5.9 0.49	7.0 0.30	4.2 0.11	81 1.33	9.8 0.33	21 0.44	6.6 0.19	0.5 0.01	0.2 0.01	21	0.03	94	11	B
Do	do	Feb. 7, 1962	Thief	360	52	5	8.5	165	95	97	18 0.9	5.0 0.41	6.4 0.28	2.1 0.05	70 1.15	2 0.07	9.6 0.2	7.5 0.21	0.3 0	0.3 0.02	9.6	---	66	4	B
Do	do	do	Thief	455	53	5	8.0	237	144	147	29 1.45	8.5 0.70	6.2 0.27	2.3 0.06	115 1.88	0 0.00	16 0.33	7.0 0.20	0.5 0.01	0.3 0.02	17	---	108	14	A
Do	do	Dec. 3, 1962	Thief	390	52	5	7.9	212	127	126	24 1.19	8.0 0.66	6.5 0.28	2.3 0.06	102 1.67	0 0.00	15 0.30	6.8 0.19	0.1 0.0	0.2 0.01	14	0.06	93	10	B
Do	do	Dec. 18, 1963	Thief	420	---	5	7.8	250	156	153	30 1.50	10 0.83	6 0.26	2.3 0.06	125 2.05	0 0.00	19 0.40	6.5 0.18	0.4 0.01	0.3 0.02	19	---	116	12	A
Do	do	June 8, 1965	Thief	390	54	0	7.9	248	147	153	29 1.45	8.7 0.72	8.1 0.35	2.5 0.06	124 2.03	0 0.00	16 0.33	5.8 0.16	0.2 0	0.40 0.02	15	0.26	108	7	B
USGS 18	5N-31E-14 bc1	Sept. 13, 1951	Pump	267-329	59	5	8.1	332	215	205	33 1.65	16 1.32	13 0.56	4.3 0.11	166 2.72	0 0.00	27 0.56	9.2 0.26	1.4 0.02	0.3 0.02	29	0.34	148	12	B
USGS 19	5N-29E-23 cd1	May 9, 1952	Thief	304	62	5	8.0	376	223	227	47 2.34	17 1.40	7.0 0.30	2.3 0.06	186 3.05	0 0.00	26 0.54	14 0.40	3.1 0.05	0.1 0.01	15	0.03	187	35	A
Do	do	Feb. 21, 1962	Thief	305	60	5	7.5	418	236	243	49 2.44	18 1.45	8.3 0.36	1.5 0.04	180 2.95	0 0.00	30 0.62	20 0.56	5.5 0.09	0.2 0.01	14	---	194	47	A
Do	do	Feb. 21, 1962	Thief	375	62	0	7.5	423	242	239	50 2.50	18 1.48	8.5 0.37	1.5 0.04	185 3.03	0 0.00	30 0.62	20 0.56	6.6 0.11	0.2 0.01	16	---	199	48	A
Do	do	Dec. 11, 1962	Thief	310	60	5	7.7	421	241	250	50 2.49	18 1.44	8.5 0.37	1.4 0.04	190 3.11	0 0.00	30 0.62	20 0.56	4.3 0.07	0.20 0.01	14	0.0	199	42	A
Do	do	Dec. 18, 1963	Thief	310	---	0	7.6	417	241	246	50 2.50	19 1.54	8.5 0.37	1.4 0.04	181 2.97	0 0.00	32 0.67	23 0.65	4.0 0.06	0.20 0.01	14	---	202	54	C
Do	do	June 3, 1965	Thief	401	60	0	7.8	454	258	247	54 2.69	20 1.66	8.9 0.39	1.4 0.04	190 3.11	0 0.00	34 0.71	28 0.79	6.0 0.10	0.1 0.01	13	0.13	218	62	C
USGS 20	3N-30E-31 aa1	Nov. 17, 1951	Bailer	464-678	54	7	7.5	430	260	258	27 1.35	10 0.82	46 2.00	5.1 0.13	140 2.29	0 0.00	25 0.52	53 1.50	1.2 0.02	0.3 0.02	23	0.21	108	0	C
Do	do	Oct. 3, 1952	Pump	455-678	53	2	8.0	292	180	179	35 1.75	11 0.90	7.9 0.34	2.3 0.06	144 2.36	0 0.00	17 0.35	12 0.34	0.8 0.01	0.1 0.01	23	0.07	133	15	A
Do	do	Feb. 6, 1962	Thief	500	52	5	7.9	288	170	170	34 1.70	10 0.86	8.1 0.35	2.5 0.06	132 2.16	0 0.00	16 0.33	14 0.39	0.5 0.01	0.3 0.02	10	---	128	20	A
Do	do	Feb. 6, 1962	Thief	620	52	5	7.7	375	212	222	39 1.95	13 1.04	16 0.70	3.0 0.08	142 2.33	0 0.00	19 0.40	32 0.90	1.5 0.02	0.3 0.02	18	---	150	33	A
Do	do	Dec. 4, 1963	Thief	520	---	5	7.7	303	186	193	37 1.85	11 0.91	7.8 0.34	2.4 0.06	140 2.29	0 0.00	19 0.40	15 0.42	1.1 0.02	0.3 0.02	23	---	138	24	A
Do	do	June 8, 1965	Thief	600	54	0	8.0	503	275	304	46 2.3	15 1.22	28 1.22	3.6 0.09	152 2.49	0 0.00	24 0.5	63 1.78	3.6 0.06	0.2 0.01	17	0.79	176	52	A
USGS 21	5N-32E-36 ad1	June 3, 1952	Pump	330-405	55	5	7.7	315	194	195	33 1.65	11 0.90	15 0.65	3.6 0.09	140 2.29	0 0.00	25 0.52	14 0.40	2.8 0.04	0.3 0.02	20	0.03	128	13	A

TABLE B-I (contd.)

											mg/1 (upper number) and equivalents per million (lower number) for indicated cations and anions												Hardness as $CaCO_3$		
Well No.	U.S.G.S. location number	Date Sampled	Method of samples	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determined constituents	Residue on evaporation at 180°C	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)	Silica (SiO_2)	Dissolved iron (Fe)	Total	Noncarbonate	Type of water
USGS 22	3N-29E- 19 cb1	June 9, 1952	Pump	604-658	62	5	8.1	350	206	228	31 1.55	10 0.82	20 0.87	3.8 0.10	88 1.44	0 0.00	22 0.46	47 1.33	4.1 0.07	0.2 0.01	25	0.05	118	46	A
Do	do	Feb. 28, 1962	Thief	630	54	0	7.5	442	231	254	40 2.00	9.5 0.78	25 1.09	5.1 0.13	90 1.48	0 0.00	24 0.50	72 2.03	1.7 0.03	0.3 0.02	9.1	0.01	139	65	A
Do	do	Nov. 26 1962	Thief	630	54	5	7.5	420	238	245	38 1.88	11 0.87	23 1.00	6.7 0.17	91 1.49	0 0.00	26 0.54	65 1.83	4.8 0.08	0.1 0.01	18	0.04	138	64	A
Do	do	Dec. 5, 1963	Thief	640	---	5	7.6	370	202	210	32 1.60	9.5 0.78	21 0.91	6.3 0.16	70 1.15	0 0.00	25 0.52	63 1.78	0.6 0.01	0.2 0.01	10	---	119	62	A
Do	do	June 2, 1965	Thief	640	---	5	7.5	550	313	318	46 2.30	14 1.16	39 1.70	7.8 0.20	133 2.18	0 0.00	32 0.67	82 2.31	5.4 0.09	0.2 0.01	22	---	173	64	A
USGS 23	4N-29E- 9 dc1	June 7, 1952	Pump	395-463	60	5	7.9	349	203	203	39 1.95	18 1.48	7.5 0.33	1.4 0.04	176 2.88	0 0.00	20 0.42	11 0.31	2.3 0.04	0.3 0.02	17	0.11	171	27	A
USGS 24	6N-31E- 13 db1	Aug. 26, 1952	Pump	214-326	50	2	7.7	365	224	222	51 2.54	13 1.07	6.6 0.29	2.3 0.06	189 3.10	0 0.00	27 0.56	7.4 0.21	2.2 0.04	0.2 0.01	21	0.04	181	26	A
Do	do	Feb. 21, 1962	Thief	235	50	0	8.0	232	115	110	18 0.90	9.4 0.78	8.3 0.36	2.4 0.06	44 0.72	0 0.00	19 0.40	34 0.96	0.2 0	0.2 0.01	1.1	4.6	84	48	A
Do	do	Feb. 21, 1962	Thief	300	50	5	7.7	553	308	309	71 3.54	18 1.45	10 0.44	2.6 0.07	187 3.06	0 0.00	35 0.73	58 1.64	4.2 0.07	0.2 0.01	17	---	250	96	A
Do	do	Dec. 3, 1962	Thief	235	49	0	8.0	224	111	115	17 0.84	8.7 0.72	8.6 0.37	2.4 0.06	39 0.64	0 0.00	17 0.35	36 1.02	1.2 0.02	0.2 0.01	1.2	0.00	78	46	A
Do	do	Dec. 17, 1963	Thief	230	---	0	8.8	213	105	107	16 0.80	8.6 0.70	8.4 0.37	2.5 0.06	29 0.48	4 0.13	14 0.29	36 1.02	0.2 0	0.3 0.02	1.2	---	75	44	A
Do	do	June 3, 1965	Thief	300	49	0	7.9	609	347	342	76 3.79	20 1.64	17 0.74	2.9 0.07	216 3.54	0 0.00	40 0.83	63 1.78	2.4 0.04	0.2 0.01	19	0.48	272	94	A
USGS 25	7N-31E- 34 bd1	Oct. 11, 1952	Pump	269-320	50	2	8.0	359	215	213	45 2.25	17 1.40	6.3 0.27	1.5 0.04	187 3.06	0 0.00	29 0.60	6.5 0.18	1.6 0.03	0.1 0.01	16	0.03	182	29	A
USGS 26	6N-32E- 11 ab1	Oct. 31, 1952	Bailer	208-267	60	2	7.7	366	237	236	39 1.95	15 1.23	15 0.65	3.5 0.09	179 2.93	--- ---	30 0.62	11 0.31	1.7 0.03	0.5 0.03	33	0.06	159	12	B
USGS 28	5N-33E- 17 ad1	Feb. 21, 1953	Bailer	232-334	58	2	7.8	331	217	212	33 1.65	14 1.15	15 0.65	3.6 0.09	164 2.69	0 0.00	25 0.52	9.0 0.25	1.3 0.02	0.5 0.03	35	0.01	140	6	B
USGS 29	5N-34E- 29 da1	Apr. 25, 1953	Bailer	348-398	52	7	8.4	310	205	204	26 1.30	13 1.07	15 0.65	3.3 0.08	100 1.64	6 0.20	49 0.40	32 0.90	2.0 0.03	0.5 0.03	39	0.03	118	26	C
USGS 30	5N-33E- 13 bd1	Apr. 22, 1953	Bailer	264-359	58	7	8.4	312	210	211	26 1.30	13 1.07	17 0.74	3.6 0.09	128 2.10	5 0.17	28 0.58	14 0.40	0.9 0.02	0.7 0.04	39	0.02	118	5	C
Do	do	Apr. 27, 1953	Pump	265-359	57	5	7.9	358	233	226	36 1.80	13 1.07	18 0.78	4.1 0.10	172 2.82	0 0.00	27 0.40	14 0.40	1.0 0.02	0.6 0.03	35	0.03	143	2	B
USGS 31	5N-32E- 10 cd1	July 11, 1953	Pump	253-429	60	2	7.9	344	223	220	36 1.80	13 1.07	14 0.61	3.3 0.08	169 2.77	0 0.00	24 0.50	10 0.28	1.3 0.02	0.5 0.03	37	0.05	143	5	B
USGS 32	5N-33E- 23 dd1	July 8, 1953	Bailer	288-392	59	2	7.9	375	233	230	35 1.75	14 1.15	21 0.91	4.4 0.11	164 2.69	0 0.00	27 0.56	18 0.51	2.6 0.04	0.6 0.03	29	0.12	145	10	B
USGS 33	5N-33E- 35 da1	Sept. 3, 1953	Bailer	365-516	56	2	7.8	567	335	348	51 2.54	19 1.56	33 1.43	5.1 0.13	164 2.69	0 0.00	32 0.67	69 1.95	9.9 0.16	0.6 0.03	34	0.11	205	70	C
USGS 34	3N-29E- 25 bd1	Oct. 22, 1952	---	---	55	---	---	275	179	---	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---	---	---	---	---	B
USGS 38	3N-30E- 25 bd1	Dec. 20, 1963	Thief	540	---	5	8.1	340	180	171	20 1.00	10 0.85	30 1.30	3.2 0.08	100 1.64	0 0.00	12 0.25	48 1.35	0.4 0.01	1.9 0.10	5.6	---	92	10	C
USGS 40	3N-29E- 24 da1	Aug. 27, 1956	Bailer	378-452	54	21	8.0	549	304	303	56 2.79	15 1.23	25 1.09	3.9 0.10	144 2.36	--- ---	24 0.50	81 2.28	5.1 0.08	0.3 0.02	23	0.00	201	83	C
Do	do	Mar. 13, 1957	Thief	525	55	0	8.1	792	447	452	55 2.74	13 1.07	84 3.65	3.9 0.10	188 3.08	--- ---	34 0.71	126 3.55	14 0.23	0.3 0.02	24	0.01	190	36	C
USGS 41	3N-29E- 24 dd1	do	Thief	500	56	0	8.1	782	442	447	56 2.79	13 1.07	80 3.48	4.0 0.10	189 3.10	--- ---	34 0.71	126 3.55	12 0.19	0.3 0.02	24	0.01	193	38	C
USGS 42	3N-29E- 24 dd2	Mar. 8, 1957	Bailer	455-675	54	0	8.2	530	307	314	54 2.69	14 1.15	33 1.44	3.1 0.08	190 3.11	--- ---	25 0.52	54 1.52	5.2 0.08	0.2 0.01	24	0.02	192	36	C
Do	do	Aug. 19, 1960	Pump	460-517	55	5	8.4	465	279	283	52 2.59	12 1.00	28 1.22	2.8 0.07	186 3.05	3 0.10	25 0.52	40 1.13	4.2 0.07	0.3 0.02	20	0.00	180	22	C
Do	do	do	Pump	517-565	55	5	8.0	555	318	318	54 2.69	11 0.90	42 1.83	3.4 0.09	196 3.21	0 0.00	27 0.56	56 1.58	5.9 0.10	0.3 0.02	21	0.04	182	21	C
Do	do	do	do	565-678	55	5	8.4	511	300	298	52 2.59	12 0.99	36 1.57	3.1 0.08	187 3.06	3 0.10	27 0.56	48 1.35	5.1 0.08	0.3 0.02	21	0.13	180	22	C
USGS 43	3N-29E- 24 ad2	Mar. 26, 1957	Bailer	360-390	49	0	8.2	273	168	163	27 1.35	8.6 0.71	17 0.74	3.0 0.08	129 2.11	--- ---	21 0.44	8.0 0.23	1.1 0.02	0.5 0.03	18	0.00	103	0	B
Do	do	July 21, 1960	Pump	528-560	---	5	8.5	615	355	354	54 2.69	11 0.90	56 2.44	3.3 0.08	186 3.05	4 0.13	29 0.60	77 2.17	7.7 0.12	0.3 0.02	21	0.01	180	20	C
Do	do	do	Pump	560-675	54	5	7.8	645	365	367	54 2.69	11 0.90	60 2.61	3.4 0.09	194 3.18	0 0.00	28 0.58	84 2.37	7.9 0.13	0.3 0.02	20	0.01	182	22	C
USGS 44	3N-29E- 24 dd3	Aug. 29, 1957	Bailer	370-385	---	0	8.0	307	187	184	33 1.65	9.7 0.80	15 0.65	3.8 0.10	161 2.64	--- ---	20 0.42	6.5 0.18	0.5 0.01	0.4 0.02	19	0.00	122	0	B
Do	do	Oct. 10, 1957	Thief	456-650	53	5	8.2	377	216	223	49 2.44	14 1.15	8.6 0.37	2.0 0.05	188 3.08	0 0.00	22 0.46	11 0.31	1.6 0.03	0.2 0.01	15	1.00	180	26	A
Do	do	Aug. 15, 1960	Pump	600-650	54	5	8.2	347	208	206	43 2.14	13 1.07	9.3 0.40	2.2 0.06	174 2.85	0 0.00	21 0.44	10 0.28	1.9 0.03	0.3 0.02	21	0.06	106	18	A

TABLE B-I (contd.)

											mg/l (upper number) and equivalents per million (lower number) for indicated cations and anions												Hardness as $CaCO_3$		
Well No.	U.S.G.S. location number	Date Sampled	Method of samples	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determined constituents	Residue on evaporation at 180°C	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)	Silica (SiO_2)	Dissolved iron (Fe)	Total	Noncarbonate	Type of water
USGS 45	3N-29E-24 dd4	Dec. 19, 1957	Thief	500	53	0	8.1	410	241	242	52 2.59	12 0.99	14 0.61	2.5 0.06	187 3.06	0 0.00	24 0.50	22 0.60	2.4 0.04	0.1 0.01	20	0.27	179	26	B
USGS 46	3N-29E-24 dd5	Feb. 12, 1958	Thief	500	54	5	7.8	505	287	292	55 2.74	13 1.07	29 1.26	2.8 0.07	190 3.11	0 0.00	26 0.54	46 1.30	4.1 0.07	0.2 0.01	17	0.13	190	34	C
Do	do	Oct. 25, 1960	Pump	450-537	55	5	8.0	394	240	244	50 2.49	12 0.99	17 0.74	2.4 0.06	192 3.15	0 0.00	21 0.44	21 0.59	2.2 0.04	0.3 0.02	19	0.15	176	18	B
Do	do	do	do	537-564	55	5	8.0	503	294	298	52 2.59	12 0.99	35 1.52	3.0 0.08	194 3.18	0 0.00	23 0.48	48 1.35	4.3 0.07	0.3 0.02	20	0.25	178	20	C
Do	do	do	do	564-650	55	5	8.1	484	281	280	51 2.53	12 0.99	30 1.30	2.8 0.07	194 3.18	0 0.00	25 0.52	40 1.13	3.8 0.06	0.3 0.02	20	0.11	178	18	C
USGS 47	3N-30E-19 cd1	May 13, 1958	Thief	458-651?	61	0	7.8	882	488	508	60 2.99	12 0.99	98 4.26	4.0 0.10	193 3.16	0 0.00	39 0.81	154 4.34	9.0 0.15	0.1 0.01	17	0.06	200	42	C
USGS 48	3N-30E-19 cd2	July 14, 1958	Thief	600	55.5	0	7.9	746	422	440	61 3.04	17 1.40	64 2.78	3.8 0.10	189 3.10	0 0.00	32 0.67	120 3.38	8.6 0.14	0.2 0.01	22	0.16	222	67	C
USGS 49	3N-30E-19 cc3	Nov. 11, 1959	Thief	500	56	0	7.9	630	352	345	50 2.50	12 0.99	56 2.44	3.6 0.09	200 3.28	0 0.00	30 0.62	68 1.92	8.5 0.14	0.3 0.02	23	1.1	173	9	C
Do	do	Oct. 17, 1960	Pump	450-516	59	5	8.0	595	342	342	54 2.69	12 0.99	48 2.09	3.8 0.10	190 3.11	0 0.00	29 0.60	73 2.06	5.6 0.09	0.3 0.02	22	0.13	184	28	C
Do	do	do	do	516-556	59	5	8.0	592	353	357	54 2.69	11 0.90	54 2.35	3.8 0.10	192 3.15	0 0.00	29 0.60	78 2.20	6.4 0.10	0.3 0.02	21	0.25	182	24	C
Do	do	do	do	556-656	59	5	7.9	593	346	350	54 2.69	11 0.90	51 2.22	3.8 0.10	192 3.15	0 0.00	27 0.56	76 2.14	6.4 0.10	0.3 0.02	21	0.23	182	24	C
USGS 51	3N-29E-30 bb1	Feb. 12, 1960	Thief	575	54	5	7.8	446	261	272	55 2.74	14 1.15	12 0.52	3.0 0.08	169 2.77	0 0.00	23 0.48	40 1.13	2.6 0.04	0.2 0.01	24	---	194	55	C
USGS 55	3N-29E-13 cc1	Oct. 21, 1960	Thief	58	58	---	7.6	1280	928	99	160 7.97	31 2.57	82 3.57	3.7 0.09	175 2.87	0 0.00	464 9.66	46 1.30	11 0.18	0 0.00	35	---	528	384	D
USGS 58	3N-29E-13 cc3	do	Thief	88	57	---	7.6	1170	891	951	150 7.47	30 2.50	76 3.31	3.2 0.08	96 1.57	0 0.00	498 10.37	42 1.18	7.6 0.12	5.0 0.04	27	0.10	499	420	D
USGS 60	3N-29E-14 bb1	Oct. 21, 1960	Thief	95	53	---	7.7	1020	756	792	135 6.72	24 1.97	62 2.70	2.7 0.07	104 1.70	0 0.00	410 8.54	37 1.04	6.2 0.10	0.7 0.04	20	0.00	434	350	D
USGS 61	3N-29E-14 bb2	do	Thief	106-117	50	15	7.6	725	481	508	112 5.57	21 1.73	8.6 0.37	2.5 0.06	144 2.36	0 0.00	218 4.54	23 0.65	3.9 0.06	0.2 0.01	18	0.09	366	248	D
USGS 62	3N-29E-14 ba1	do	Thief	145	51	---	7.6	980	718	765	138 6.87	25 2.06	48 2.09	3.0 0.08	102 1.67	0 0.00	390 8.12	38 1.07	4.8 0.08	0.8 0.04	15	---	446	363	D
USGS 65	3N-29E-23 aa1	Dec. 12, 1960	Bailer	456-472	---	5	7.8	413	251	256	55 2.74	14 1.15	7.3 0.32	2.1 0.05	149 2.44	0 0.00	60 1.25	16 0.45	3.1 0.05	0.2 0.01	20	---	196	74	C
USGS 66	3N-29E-24 bd1	---	---	458-475	---	0	8.3	440	263	257	35 1.75	21 1.73	24 1.04	4.2 0.11	194 3.02	2 0.07	44 0.92	16 0.45	3.8 0.06	0.8 0.04	21	---	174	20	C
USGS 83	2N-29E-13 ac1	June 7, 1965	Thief	560	53	0	7.8	269	169	172	26 1.30	12 0.96	10 0.44	2.7 0.07	124 2.03	0 0.00	19 0.40	9.5 0.27	1.5 0.02	0.4 0.02	27	0.52	114	12	B
ANP 1	6N-31E-13 ac1	Apr. 18, 1953	Pump	209-365	---	5	8.1	404	243	248	54 2.69	15 1.23	6.8 0.30	2.1 0.05	204 3.34	0 0.00	32 0.67	9.5 0.27	2.3 0.04	0 0.00	21	0.03	196	29	A
Do	do	June 28, 1956	Pump	214-365	51	0	8.0	405	248	252	56 2.80	15 1.23	7.2 0.31	2.4 0.06	200 3.28	0 0.00	32 0.67	10 0.28	3.0 0.05	0.2 0.01	23	0.00	201	37	A
ANP 2	6N-31E-13 ac2	Aug. 18, 1953	Bailer	215-346	53	7	8.2	443	273	272	56 2.79	17 1.40	13 0.57	3.4 0.09	210 3.44	0 0.00	41 0.85	14 0.39	5.0 0.08	0.3 0.02	20	0.01	210	38	A
Do	do	Nov. 15, 1953	Pump	---	50	0	8.2	391	247	252	51 2.54	16 1.32	8.1 0.35	2.4 0.06	200 3.28	--- ---	33 0.69	12 0.34	3.2 0.05	0.2 0.01	22	0.01	193	29	A
Do	do	June 28, 1956	Pump	211-346	51	0	8.1	405	247	248	56 2.79	15 1.23	7.3 0.32	2.4 0.06	199 3.26	0 0.00	32 0.67	10 0.28	2.9 0.05	0.2 0.01	23	0.00	201	38	A
Do	do	Aug. 20, 1968	Pump	215-346	50	0	7.7	401	243	244	53	15 1.23	7.2 0.31	2.3 0.06	192 3.15	0 0.00	32 0.67	12 0.34	3.7 0.06	0.3 0.02	23	0.01	194	36	A
ANP 3	6N-31E-13 ca1	June 25, 1953	Bailer	199-310	52	---	9.5	197	145	156	23 1.15	2.8 0.23	9.0 0.39	3.2 0.08	--- ---	18 0.60	42 0.87	8.2 0.23	1.2 0.02	0.5 0.03	37	0.02	69	---	D
ANP 5	7N-31E-33 dc1	June 16, 1956	Pump	294-395	50	0	8.1	356	212	209	43 2.15	17 1.40	6.3 0.27	1.2 0.03	184 3.02	0 0.00	27 0.56	7.0 0.20	1.9 0.03	0.2 0.01	17	0.00	177	26	A
ANP 6	6N-31E-10 ac1	Sept. 6, 1956	Pump	213-305	55	0	8.0	392	236	239	44 2.20	17 1.40	10 0.44	2.4 0.06	176 2.88	--- ---	35 0.73	14 0.40	2.5 0.04	0.3 0.02	23	0.00	180	43	A
ANP 7	7N-31E-22 bd1	July 10, 1956	Pump	352-436	49.75	0	8.0	356	211	204	46 2.30	16 1.32	6.0 0.26	1.2 0.03	184 3.02	0 0.00	28 0.58	6.8 0.19	1.6 0.03	0.2 0.01	14	0.00	181	30	A
ANP 8	6N-32E-22 ca1	July 20, 1956	Pump	209-309	52	0	---	366	228	232	46 2.30	15 1.23	7.0 0.30	2.9 0.07	184 3.02	--- ---	29 0.60	7.2 0.20	2.6 0.04	0.2 0.01	27	0.02	176	25	A
ANP 9	6N-32E-26 cd1	July 18, 1956	Pump	222-322	58	0	8.2	359	227	223	37 1.85	15 1.23	14 0.61	3.1 0.08	168 2.75	--- ---	30 0.62	11 0.31	1.7 0.03	0.4 0.02	32	0.00	154	16	B
ANP 10	6N-32E-26	July 22, 1959	Pump	220-681	---	0	7.6	356	216	207	34 1.70	15 1.23	13 0.57	3.2 0.08	164 2.69	0 0.00	28 0.58	9.5 0.27	1.3 0.02	0.4 0.02	31	---	145	10	B
Do	do	Dec. 19, 1961	Thief	460	58	5	7.8	293	159	154	22 1.10	15 1.24	14 0.61	3.5 0.09	131 2.15	0 0.00	27 0.56	10 0.28	0.0 0.00	0.5 0.03	2.2	0.00	117	10	B
Do	do	Dec. 19, 1961	Thief	620	57	5	7.9	304	174	169	25 1.25	15 1.21	14 0.61	3.3 0.08	137 2.25	0 0.00	28 0.58	10 0.28	0.5 0.01	0.5 0.03	11	0.11	123	10	B

TABLE B-I (contd.)

											mg/l (upper number) and equivalents per million (lower number) for indicated cations and anions												Hardness as $CaCO_3$		
Well No.	U.S.G.S location number	Date Sampled	Method of samples	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determined constituents	Residue on evaporation at 180°C	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)	Silica (SiO_2)	Dissolved iron (Fe)	Total	Noncarbonate	Type of water
ARBOR 1	3N-32E- 13 dcl	Dec. 28, 1957	Pump	675-790	55	0	8.1	277	178	178	30 1.50	9.1 0.75	14 0.61	2.6 0.07	144 2.36	0 0.00	10 0.21	8.8 0.25	2.4 0.04	0.8 0.04	29	0.00	112	0	B
AREA II	3N-31E- 34 adl	Apr. 23, 1960	Pump	666-881	57	0	7.8	309	197	193	31 1.55	12 0.99	14 0.61	3.0 0.08	148 2.43	0 0.00	15 0.31	13 0.37	2.3 0.04	0.5 0.03	33	0.05	126	4	B
ATR 4	3N-29E- 14 cb	July 31, 1963	Pump	460-970	58	0	7.8	384	234	230	49 2.45	17 1.37	7.5 0.33	1.6 0.04	203 3.33	0 0.00	22 0.46	11 0.31	3.4 0.05	0.2 0.01	22	—	191	24	B
CFA 2	2N-29E- 1dbl	Jan. 16, 1949	Pump	—	53.5	—	7.3	348	217	216	39 1.95	15 1.23	7.9 0.34	3.5 0.09	150 2.46	— —	21 0.44	24 0.68	1.9 0.03	0.2 0.01	30	0.04	159	36	B
Do	do	Feb. 27, 1956	Tap	472-681	44	0	8.0	348	210	214	42 2.10	15 1.23	8.3 0.36	2.5 0.06	162 2.67	0 0.00	21 0.44	16 0.45	1.6 0.03	0.1 0.01	24	0.00	166	33	B
Do	do	June 27, 1956	Tap	474-681	61	0	7.5	352	209	216	42 2.10	13 1.07	8.4 0.36	2.6 0.07	149 2.44	— —	21 0.44	23 0.65	1.4 0.02	0.2 0.01	24	0.00	158	36	B
Do	do	Aug. 20, 1968	Pump	474-681	53	0	7.6	480	273	274	48 2.40	19 1.56	14 0.61	3.0 0.08	143 2.43	0 0.00	29 0.60	58 1.64	4.7 0.08	0.2 0.01	27	0.01	198	81	B
CPP 1	3N-30E- 19 bcl	Dec. 7, 1950	Pump	450-586	54	—	7.8	334	210	208	43 2.14	13 1.07	7.9 0.34	3.5 0.09	174 2.85	0 0.00	20 0.41	10 0.28	0.9 0.01	0.2 0.01	25	0.03	161	18	A
Do	do	Sept. 14, 1955	Tap	450-586	54	0	7.8	369	216	219	48 2.40	12 0.99	8.3 0.36	2.5 0.06	187 3.06	0 0.00	22 0.46	9.0 0.25	1.4 0.02	0.1 0.01	21	0.00	169	16	A
CPP 2	3N-29E- 24 adl	Sept. 1, 1951	Pump	453-605	54	5	7.9	337	208	208	44 2.19	13 1.07	7.8 0.34	1.2 0.03	176 2.88	0 0.00	21 0.44	10 0.28	1.0 0.02	0.2 0.01	22	0.02	163	19	A
Do	do	Aug. 20, 1968	Pump	450-605	53	0	7.9	469	275	270	52 2.59	15 1.23	20 0.87	2.7 0.07	180 2.95	0 0.00	24 0.50	42 0.18	7.2 0.12	0.2 0.01	23	0.03	191	44	C
CPP 3	3N-30E- 19 cbl	Sept. 7, 1951	Bailer	453-598	55	5	8.0	315	191	188	39 1.95	12 0.99	8.0 0.35	4.5 0.12	160 2.62	0 0.00	21 0.44	9.8 0.28	1.2 0.02	0.2 0.01	16	0.21	147	16	A
EBR 1	2N-29E- 9 cal	Aug. 12, 1949	Pump	597-1075	65.5	—	8.0	267	181	166	22 1.10	16 1.32	9.1 0.40	4.0 0.10	140 2.29	— —	18 0.38	6.0 0.17	1.0 0.02	0.2 0.01	36	0.10	121	6	B
Do	do	Aug. 15, 1949	Pump	603-1075	65	—	8.0	267	180	169	22 1.10	15 1.23	9.3 0.40	3.2 0.08	140 2.29	— —	18 0.38	6.2 0.17	0.9 0.01	0.2 0.01	36	0.05	117	2	B
Do	do	Apr. 17, 1950	Pump	588-1075	—	—	7.9	269	179	173	22 1.10	16 1.32	8.7 0.38	2.6 0.07	140 2.29	0 0.00	17 0.35	6.3 0.18	0.8 0.01	0.3 0.02	36	0.13	121	6	B
Do	do	Aug. 10, 1951	Pump	586-1075	66	10	8.2	268	184	174	22 1.10	16 1.32	9.0 0.39	5.0 0.13	144 2.36	0 0.00	18 0.38	6.2 0.18	1.3 0.02	0.4 0.02	35	0.02	121	3	B
Do	do	Apr. 4, 1955	—	—	—	0	8.2	273	178	172	23 1.15	15 1.23	8.8 0.38	3.3 0.08	142 2.33	— —	16 0.33	6.0 0.17	0.8 0.01	0.1 0.01	35	0.00	119	3	B
Do	do	June 27, 1956	Pump	586-1075	61	0	8.1	266	177	169	23 1.15	16 1.32	8.4 0.36	3.0 0.08	140 2.30	0 0.00	17 0.35	6.2 0.18	1.1 0.02	0.3 0.02	33	0.00	123	8	A
EBR II-1	3N-32E- 13 bb2	Oct. 3, 1958	Pump	635-745	54	0	7.7	293	192	191	32 1.60	9.7 0.80	14 0.61	3.0 0.08	149 2.44	0 0.00	13 0.27	12 0.34	1.9 0.03	0.7 0.04	33	0.25	120	0	B
Do	do	June 2, 1965	Pump	635-758	—	—	8.0	306	193	168	33 1.65	10 0.85	14 0.61	3.0 0.08	154 2.52	0 0.00	12 0.25	11 0.31	2.1 0.03	0.8 0.04	31	0.14	125	0	B
Do	do	Aug. 20, 1968	Pump	635-758	55	0	7.6	309	202	194	31 1.55	11 0.90	17 0.74	2.9 0.07	154 2.52	0 0.00	13 0.27	14 0.39	2.7 0.04	0.7 0.04	34	0.01	122	0	B
EOCR 1	2N-30E- 5 ddl	June 28, 1960	Pump	484-1237	55	0	7.9	384	231	234	45 2.25	18 1.48	8.5 0.37	1.9 0.05	188 3.08	0 0.00	22 0.46	15 0.42	3.0 0.05	0.4 0.02	24	0.04	187	33	A
ETR	3N-29E- 14 ad2	June 7, 1957	Pump	458-596	54.5	0	8.2	416	245	246	52 2.60	18 1.48	9.1 0.40	1.5 0.04	214 3.51	0 0.00	25 0.52	13 0.37	4.3 0.07	0.2 0.01	17	0.00	204	29	A
FET 1	6N-31E- 14 abl	Apr. 17, 1958	Pump	199-340	50	5	8.1	386	237	242	51 2.54	15 1.23	7.4 0.32	4.2 0.11	182 2.98	0 0.00	33 0.69	11 0.31	3.1 0.05	0.1 0.01	22	0.10	190	41	A
FET 2	6N-31E- 14 ab2	May 3, 1958	Pump	200-462	52	0	8.1	371	225	227	46 2.30	15 1.23	7.9 0.34	3.8 0.10	178 2.92	0 0.00	31 0.65	9.0 0.25	2.4 0.04	0.1 0.01	22	0.12	178	32	A
FET Disp.	6N-31E- 11 cdl	Nov. 24, 1957	Pump	201-300	50	5	8.1	391	229	236	52 2.59	14 1.15	7.8 0.34	2.2 0.06	176 2.88	— —	34 0.71	12 0.34	3.7 0.06	0.2 0.01	16	0.02	187	43	A
Fire Sta. 2	3N-29E- 12 ddl	Nov. 5, 1957	Pump	420-516	51.5	5	8.1	385	222	230	51 2.54	15 1.23	7.1 0.31	2.1 0.05	188 3.08	0 0.00	22 0.46	14 0.40	2.7 0.04	0.1 0.01	15	0.06	189	45	A
GCRE 1	2N-30E- 1 bdl	Mar. 2, 1959	Pump	592-1340	59.5	5	7.6	358	224	223	35 1.75	15 1.23	16 0.70	3.2 0.08	158 2.59	0 0.00	24 0.50	18 0.51	2.9 0.05	0.5 0.03	31	0.08	150	21	B
IET 1	6N-31E- 12 acl	Aug. 18, 1953	Bailer	250	55	8	8.1	365	227	221	41 2.05	14 1.15	15 0.65	3.4 0.09	156 2.56	0 0.00	39 0.81	16 0.45	2.6 0.04	0.3 0.02	19	0.02	160	32	C
LPTF Disp.	6N-32E- 22 ccl	June 21, 1957	Pump	210-315	50	5	8.1	354	216	217	43 2.15	15 1.23	7.1 0.31	3.1 0.08	178 2.92	0 0.00	29 0.60	6.5 0.18	2.9 0.05	0.3 0.02	21	0.00	169	23	A
MTR Test	3N-29E- 14 adl	Nov. 30, 1949	Pump	454-588	55	—	7.2	398	238	240	52 2.60	19 1.56	2.7 0.12	2.2 0.06	216 3.54	0 0.00	20 0.42	12 0.34	4.1 0.07	0.2 0.01	19	0.06	208	31	A
Do	do	Dec. 2, 1949	Pump	453-588	55.5	—	7.7	397	236	241	52 2.60	19 1.56	2.6 0.11	2.1 0.05	216 3.54	0 0.00	20 0.42	11 0.31	4.1 0.07	0.2 0.01	19	0.02	208	31	A
MTR 1	3N-29E- 14 acl	Mar. 31, 1950	Bailer?	453-600	53	—	8.0	398	244	—	48 2.40	19 1.56	8.4 0.37	5.4 0.14	212 3.47	0 0.00	21 0.44	13 0.37	0.0 0.00	0.2 0.01	25	0.05	198	24	A
Do	do	July 24, 1957	Pump	458-600	—	0	8.0	411	242	239	55 2.74	16 1.32	8.3 0.36	1.4 0.04	211 3.46	0 0.00	23 0.48	12 0.34	4.3 0.07	0.2 0.01	18	0.01	203	30	A
Do	do	Aug. 20 1968	Pump	457-600	—	0	7.8	418	249	254	51 2.54	18 1.48	8.4 0.37	1.6 0.04	213 3.49	0	25 0.52	14 0.39	5.2 0.06	0.2 0.01	21	0.01	201	26	A
MTR 2	3N-29E- 14 ac2	Mar. 19, 1951	Pump	459-601	56	3	8.0	320	205	198	36 1.80	16 1.32	8.0 0.35	3.4 0.09	176 2.88	0 0.00	18 0.37	8.8 0.25	1.7 0.03	0 0.00	26	0.03	156	11	A

TABLE B-I (contd.)

											mg/l (upper number) and equivalents per million (lower number) for indicated cations and anions												Hardness as $CaCO_3$		
Well No.	U.S.G.S. location number	Date Sampled	Method of samples	Depth of sample (feet)	Temperature when collected (°F)	Color	pH	Specific conductance (micromhos at 25°C)	Sum of determines constituents	Residue on evaporation at 180°C	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Fluoride (F)	Silica (SiO_2)	Dissolved iron (Fe)	Total	Noncarbonate	Type of water
Do	do	Mar. 26, 1951	Pump	457-772	—	3	8.0	324	205	199	36 1.80	16 1.32	7.9 0.34	4.2 0.11	176 2.88	0 0.00	18 0.37	7.5 0.21	1.7 0.03	0.2 0.01	26	0.01	156	11	A
MTR 2	3N-29E-14 ac2	Nov. 1, 1952	Pump	457-746	56	2	7.9	346	213	209	39 1.95	18 1.48	7.5 0.33	2.1 0.05	183 3.00	0 0.00	19 0.40	10 0.28	1.7 0.03	0.1 0.01	25	0.04	171	21	A
Do	do	Sept. 14, 1955	Pump	456-772	59	0	8.0	366	217	217	40 2.00	17 1.40	8.6 0.37	2.3 0.06	183 3.00	— —	22 0.46	10 0.28	2.3 0.04	0.1 0.01	25	0.00	170	20	A
NRF 1	4N-30E-30 aa1	Aug. 4, 1950	Pump	364-485	52	—	7.8	527	312	319	69 3.44	21 1.73	9.0 0.39	5.1 0.13	224 3.67	0 0.00	35 0.73	35 1.00	4.4 0.07	0.1 0.01	23	0.03	258	75	C
Do	do	June 12, 1951	Pump	357-535	54	9	7.8	531	306	349	67 3.34	21 1.73	9.6 0.42	1.1 0.03	224 3.67	0 0.00	35 0.73	35 0.99	3.8 0.06	0.2 0.01	23	0.04	254	70	C
Do	do	Sept. 14, 1955	Tap	363-535	54	0	8.1	531	308	322	66 3.29	22 1.81	10 0.43	2.1 0.05	223 3.65	0 0.00	36 0.75	36 1.02	3.7 0.06	0.1 0.01	22	0.00	255	72	C
NRF 2	4N-30E-30 ad1	Aug. 5, 1951	Pump	366-528	54	5	7.8	529	315	342	68 3.39	21 1.73	9.4 0.41	2.4 0.06	226 3.70	0 0.00	36 0.75	38 1.07	4.8 0.08	0.2 0.01	24	0.03	256	71	C
Do	do	May 11, 1955	—	—	—	7	7.0	527	304	329	67 3.34	20 1.64	10 0.44	2.0 0.05	225 3.69	0 0.00	38 0.79	33 0.93	4.2 0.07	0.2 0.01	19	0.04	250	65	C
NRF 3	4N-30E-30 aa2	Sept. 26, 1956	Pump	365-549	52.5	0	8.1	537	308	315	69 3.44	21 1.73	10 0.44	2.0 0.05	223 3.65	— —	37 0.77	36 1.02	1.9 0.03	0.2 0.01	21	0.00	258	75	C
Do	do	Aug. 20, 1968	Pump	368-546	55	0	7.7	554	327	334	66 3.29	21 1.73	16 0.70	2.0 0.05	226 3.70	0 0.00	37 0.77	42 1.18	6.3 0.10	0.2 0.01	25	0.01	251	66	C
OMRE	2N-30E 8 aa1	Mar. 23, 1957	Pump	480-940	55	0	8.0	364	220	221	44 2.20	15 1.23	7.9 0.34	2.1 0.05	182 2.98	— —	20 0.42	12 0.34	2.1 0.03	0.2 0.01	27	0.00	172	23	A
P&W 1	7N-31E-28 ca1	Aug. 10, 1957	Pump	317-432	49.5	0	8.0	360	207	201	45 2.25	16 1.32	6.3 0.27	1.2 0.03	182 2.98	0 0.00	28 0.58	6.5 0.18	2.0 0.03	0.3 0.02	12	0.02	178	29	A
P&W 2	7N-31E-28 da1	Sept. 7, 1957	Pump	311-386	50	5	8.0	361	211	212	43 2.15	16 1.32	7.2 0.31	1.5 0.04	178 2.92	— —	30 0.62	7.5 0.21	2.3 0.04	0.3 0.02	15	0.00	173	17	A
P&W 3	7N-31E-26 bb1	Nov. 13, 1957	Pump	304-406	49	5	8.1	357	209	206	47 2.34	16 1.32	6.1 0.26	1.3 0.03	183 3.00	0 0.00	28 0.58	7.5 0.21	1.7 0.03	0.1 0.01	11	0.02	183	33	A
PSTF Test	6N-31E-21 dc1	Dec. 21, 1957	Pump	208-320	55	0	8.1	301	186	189	33 1.65	15 1.23	7.4 0.32	2.5 0.06	160 2.62	0 0.00	16 0.33	7.0 0.20	2.3 0.04	0.1 0.01	24	0.07	144	13	A
Do	do	Dec. 19, 1961	Thief	280	55.5	5	7.8	301	185	181	32 1.60	15 1.23	7.6 0.33	2.5 0.06	159 2.61	0 0.00	15 0.31	6.8 0.19	2.3 0.04	0.3 0.02	25	0.12	142	11	A
Site 4	3N-30E 8 ab1	Jan. 3, 1957	Pump	395-496	53	0	8.0	348	214	210	47 2.34	13 1.07	6.7 0.29	1.6 0.04	181 2.97	— —	21 0.44	8.5 0.24	1.6 0.03	0.2 0.01	25	0.01	171	23	A
Site 6-1	4N-30E-26 cc1	Nov. 5, 1959	Pump	352-523	57	0	8.0	327	203	208	41 2.05	14 1.11	6.9 0.30	2.0 0.05	168 2.75	0 0.00	19 0.40	9.0 0.25	1.5 0.02	0.2 0.01	26	0.43	158	20	A
Site 14	5N-31E-28 cb1	Feb. 20, 1962	Thief	275	62	5	7.8	322	208	211	34 1.70	12 0.99	16 0.70	3.0 0.08	159 2.61	0 0.00	23 0.48	8.5 0.24	1.5 0.02	0.5 0.03	31	0.12	134	4	B
Do	do	June 3, 1965	Thief	350	60	0	7.9	332	208	198	34 1.70	13 1.04	15 0.65	2.08 0.05	162 2.66	0 0.00	24 0.50	8.0 0.23	1.4 0.02	0.5 0.03	29	0.14	137	4	B
Site 16	3N-32E-13 bb1	Jan. 16, 1957	Thief	670	—	0	7.8	292	187	186	31 1.55	10 0.82	15 0.65	2.8 0.07	152 2.49	— —	12 0.25	11 0.31	2.1 0.03	0.7 0.04	27	0.03	118	0	B
Do	do	Oct. 28, 1957	Thief	634-758	54	5	8.1	299	182	190	33 1.65	9.7 0.80	15 0.65	3.4 0.09	149 2.44	0 0.00	12 0.25	10 0.28	2.2 0.04	0.7 0.04	23	1.1	122	0	B
Site 19	3N-29E-14 bd1	June 9, 1960	Pump	466-575	57	0	8.1	353	217	215	40 2.00	18 1.48	7.7 0.33	2.0 0.05	176 2.88	0 0.00	22 0.46	12 0.34	3.4 0.05	0.3 0.02	24	0.27	173	29	A
Do	do	Sept. 27, 1960	Pump	466-865	58	5	8.0	364	221	221	42 2.10	18 1.48	7.6 0.33	2.0 0.05	186 3.05	0 0.00	21 0.44	12 0.34	3.6 0.06	0.2 0.01	22	0.03	178	26	A
SL-1 1	2N-30E-12 ab1	Sept. 10, 1957	Pump	606-787	57	5	8.0	328	202	202	33 1.65	13 1.07	14 0.61	3.0 0.08	151 2.48	— —	18 0.38	16 0.45	3.0 0.05	0.5 0.03	27	0.00	136	12	B
SPERT 1	3N-30E-34 ba1	Feb. 27, 1956	Pump	466-653	—	0	8.2	332	205	208	39 1.95	14 1.15	8.8 0.38	2.7 0.07	158 2.59	0 0.00	19 0.40	16 0.45	1.2 0.02	0.1 0.01	26	0.04	155	25	A
SPERT IV	3N-31E-34 dd1	Apr. 14, 1960	Pump	465-1217	57	0	7.8	328	207	203	35 1.75	13 1.07	13 0.57	2.6 0.07	160 2.62	0 0.00	23 0.48	10 0.28	2.0 0.03	0.4 0.02	29	0.19	140	9	B
USBR	5S23E-17 ca1	Mar. 11, 1967	Bailer	308-333	55	0	7.7	281	183	188	24 1.20	14 1.15	15 0.65	4.3 0.11	143 2.34	0 0.00	20 0.92	9.0 0.25	0.5 0.01	0.60 0.03	26	0.49	118	0	B
USBR	4S24E-6 bb2	Mar. 12, 1967	Bailer	416-445	53	5	7.7	257	164	160	26 1.30	9.6 0.79	13 0.57	2.0 0.05	127 2.08	0 0.00	16 0.33	7.5 0.21	1.0 0.02	0.50 0.03	26	0.44	104	0	B

In selecting analyses for Table 3, we looked first for pumped samples, and if the well was subject to contamination by site activities, we chose an early sample taken prior to extensive operations. Where only thief or bailer samples were available, we rejected the analysis if nearby wells offered pumped samples. If thief or bailer samples had to be used, we first made a decision as to the validity of the analysis in representing the composition of water in the upper 100 feet of the groundwater body. We based this decision on the presence or absence of gross differences in the suspect analyses relative to the general levels of analyses of pumped samples. Only 16 of the analyses in Table 3 required this final selection process for inclusion.

Among the wells in Table B-1 that are not included in Table 3 are those drilled specifically in close-spaced arrays to intercept and monitor the movement of discharged waste. The composition of the groundwater in these wells is irrelevant to the study of natural geochemistry of the Snake River Plain aquifer, and is properly omitted from Table 3.

APPENDIX C

ICPP WATER BUDGET

APPENDIX C

ICPP WATER BUDGET

In addition to the intentional waste discharges to the well and pit, significant quantities of waste waters have also entered the ground unintentionally through leaks in the ICPP waste handling and piping systems. The presence of a perched body of groundwater which contains radioactive and chemical waste products has been the principal long-term evidence of these leakages. Although some of the perched water may be attributed to discharges to the disposal pit, most of it appears to be from other sources. Although leaks are periodically discovered and repaired, it appears that they are nearly a continuous problem at the ICPP. A common type of leak is a corroded or broken underground pipeline. A good example of this is the pipeline which extends from the service waste monitoring building 350 feet to the disposal well. The previous underground line was recently replaced by a stainless steel line because of substantial leaks in the old line.

It is not possible to determine an accurate volume of waste leakage that has occurred at ICPP. However, a crude water budget was calculated for the ICPP in hopes of gaining a better understanding of leakage magnitude. Such a budget involves balancing all known inflows to the area against all known discharges or losses. The only sources of inflow to the ICPP are the two production wells (CPP-1 and -2 in Figure 48). Pumpage rates from these wells are metered and complete records are available from July 1959 to the present, although the accuracy of these data is not known. The meters of these wells are reportedly calibrated every six months. The outflow side of the balance would include all waste water discharges, construction and fire-water uses, leaks, and consumptive (evaporative) losses. Evaporative losses at the ICPP are considered negligible (less than 2% of pumpage) because there are no major consumptive processes, such as reactor cooling towers or extensive lawn sprinkling. Construction and fire-water uses are also considered a negligible portion of the total.

The waste discharges include those to the disposal well, the shallow pit, sewage effluent, and a few minor disposal operations (such as the hydrofluoric acid waste discharges to a shallow well). In a volume basis, the first three waste sources (well, pit, and sewage) are the most significant; the others are probably negligible. Metered waste discharge records are available for the well and pit wastes from 1953 to the present. The total sewage discharge has been estimated at about 27,000 gal/day or 10×10^6 gal/year.

Table C-1 shows the tabulated water budget data for the ICPP on a yearly basis -- 1959 through 1970. Except for 1969, all years show more water coming in than going out. The 1969 data are undoubtedly in error; it is most probable that inaccurate discharge measurements at the deep disposal well are responsible for most of the error.

TABLE C-I

WATER BUDGET FOR THE ICPP AREA

			Difference (production-discharge)	
Yearly	Production well pumpage (million gallons)	Waste discharges (well, pit, sewage) (million gallons)	million gallons	percent
1970	346	289	+ 57	+16.5
1969	310	338	- 28	- 9.0
1968	292	281	+ 11	+ 3.9
1967	344	311	33	9.6
1966	380	374	6	1.5
1965	479	427	52	10.9
1964	360	359	1	0.3
1963	327	269	58	17.7
1962	388	273	115	29.6
1961	307	198	109	35.5
1960	283	202	81	28.6
1959[a]	162	128	34	21.0
Totals[b] (excluding 1969)	3,668	3,111	557	
Average[b]				15.1[b]

---

[a] July through December

[b] 1969 data are excluded because they are known to be in error. (The waste discharge data are probably erroneously high.)

Because of the known error, the 1969 data were not used in the average and total figures at the bottom of the table. If the figures are correct, an average of 15% of the production well intake is unaccounted for, during the period 1959 through 1970. This amounts to a total deficit of 557 million gallons. This figure is a residual from data of questionable accuracy. There is no assurance, therefore, that the 557 million gallons is an accurate representation of the amount of leakage that has occurred over the 10-year period. It is probably within the right order of magnitude and it is certainly adequate to account for the amounts of leakage that are known or suspected to have occurred in the plant. One of the known but unmeasured water releases occurs on the east side of building CPP-606 (Service Building, Figure 48). Water from the capillary air washer in the air conditioning system is released to the ground surface. This water is known to cause a small body of near-surface perched groundwater. The amount of flow is probably less than 5 x 10^6 gal/year and carries no significant waste products. Because neither the quantities nor sources of the leakages are accurately known, it is impossible to determine products that may have been carried to the subsurface by leakage. The perched groundwater body beneath the ICPP, which is assumed to originate at least in part from the leakage, contains both radioactive and chemical waste products. Results of studies on this perched water are described in previous sections of this report.

From all indications, therefore, leakage or other unaccountable losses at the ICPP have contributed significant quantities of water and waste products to the subsurface. Unfortunately the quantity, character, and history of these discharges are not well known; consequently, it is difficult to make any quantitative assessment of their effects on the environment.