Hydrology and Surface Morphology of the Bonneville Salt Flats and Pilot Valley Playa, Utah

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2057

Prepared in cooperation with the U.S. Bureau of Land Management

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By GREGORY C. LINES

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CONVERSION FACTORS

[Most numbers are given in this report in English units. For those readers who may prefer to use metric units rather than English units, the conversion factors for the terms used in this report are listed below: Multiply English unit by factor to obtain metric]

English			*Metric*	
Units	*Abbreviation*	*Conversion factor*	*Units*	*Abbreviation*
Acres		0.4047	Square hectometers	hm^2
Acre-feet	acre-ft	.001233	Cubic hectometers	hm^3
Degrees Celsius per mile	°C/mi	.6214	Degrees Celsius per kilometer	°C/km
Feet	ft	.3048	Meters	m
Feet per mile	ft/mi	.1894	Meters per kilometer	m/km
Gallons per minute	gal/min	.06309	Liters per second	L/s
Inches	in.	25.40	Millimeters	mm
		2.540	Centimeters	cm
Miles	mi	1.609	Kilometers	km
Miles per hour	mi/h	1.609	Kilometers per hour	km/h
Square feet	ft^2	.0929	Square meters	m^2
Square miles	mi^2	2.590	Square kilometers	km^2
Tons (short, 2,000 pounds)		.9072	Megagram	Mg

Chemical concentration and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L). For concentrations less than 7,000 mg/L, the numerical value is about the same as for concentrations in the English unit, parts per million (ppm). For more highly mineralized water, the concentrations in milligrams per liter must be adjusted for water density to get the equivalent concentrations in parts per million. For example, a brine with a density of 1.185 g/mL (grams per milliliter) and a dissolved-solids concentration of 294,000 mg/L would have an equivalent dissolved-solids concentration of 248,000 ppm.

Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation: °F 1.8(°C) + 32.

HYDROLOGY AND SURFACE MORPHOLOGY OF THE BONNEVILLE SALT FLATS AND PILOT VALLEY PLAYA, UTAH

By Gregory C. Lines

ABSTRACT

The Bonneville Salt Flats and Pilot Valley are in the western part of the Great Salt Lake Desert in northwest Utah. The areas are separate, though similar, hydrologic basins, and both contain a salt crust. The Bonneville salt crust covered about 40 square miles in the fall of 1976, and the salt crust in Pilot Valley covered 7 square miles. Both areas lack any noticeable surface relief (in 1976, 1.3 feet on the Bonneville salt crust and 0.3 foot on the Pilot Valley salt crust).

The salt crust on the Salt Flats has been used for many years for automobile racing, and brines from shallow lacustrine deposits have been used for the production of potash. In recent years, there has been an apparent conflict between these two major uses of the area as the salt crust has diminished in both thickness and extent. Much of the Bonneville Racetrack has become rougher, and there has also been an increase in the amount of sediment on the south end of the racetrack. The Pilot Valley salt crust and surrounding playa have been largely unused.

Evaporite minerals on the Salt Flats and the Pilot Valley playa are concentrated in three zones: (1) a carbonate zone composed mainly of authigenic clay-size carbonate minerals, (2) a sulfate zone composed mainly of authigenic gypsum, and (3) a chloride zone composed of crystalline halite (the salt crust). Five major types of salt crust were recognized on the Salt Flats, but only one type was observed in Pilot Valley. Geomorphic differences in the salt crust are caused by differences in their hydrologic environments. The salt crusts are dynamic features that are subject to change because of climatic factors and man's activities.

Ground water occurs in three distinct aquifers in much of the western Great Salt Lake Desert: (1) the basin-fill aquifer, which yields water from conglomerate in the lower part of the basin fill, (2) the alluvial-fan aquifer, which yields water from sand and gravel along the western margins of both playas, and (3) the shallow-brine aquifer, which yields water from near-surface carbonate muds and crystalline halite and gypsum. The shallow-brine aquifer is the main source of brine used for the production of potash on the Salt Flats.

Recharge to that part of the shallow-brine aquifer north of Interstate Highway 80 on the Salt Flats is mainly by infiltration of precipitation and wind-driven floods of surface brine. Discharge was mainly by evaporation at the playa surface and withdrawals from brine-collection ditches. Some water was transpired by phreatophytes, and some leaked into the alluvial fan along the western edge of the playa.

Salt-scraping studies indicate that the amount of halite on the Salt Flats is directly related to the amount of recharge through the surface (which causes re-solution of halite) and the amount of evaporation at the surface (which causes crystallization of halite).

Evaporation rates through sediment-covered salt crust and the gypsum surface were estimated at between $3x10^{-3}$ and $4x10^{-3}$ inches per day during the summer and fall of 1976. Evaporation rates through the surface of thick perennial salt crust were much higher.

The concentration of dissolved solids in brine in the shallow-brine aquifer varies, but it generally increases from the edges of the playas toward areas of salt crust. Dissolved-solids concentration in the shallow brine ranges from less than 100,000 to more than 300,000 milligrams per liter on both playas. The increase in salinity toward areas of salt crust reflects the natural direction of brine movement through the aquifer toward the natural discharge area.

On the Salt Flats, the percentages of dissolved potassium chloride and magnesium chloride in the shallow-brine aquifer generally increase from the edge of the playa toward the salt crust. The relative enrichment in potassium and magnesium reflects the many years of subsurface drainage toward the main discharge area (the salt crust) prior to man's withdrawal of brine. By artificially extracting brines from the carbonate muds, the percentages of potassium and magnesium have decreased while brine salinity has been maintained by re-solution of the salt crust.

The configuration of the density-corrected potentiometric surface in the fall of 1976 indicates that brine in the shallow-brine aquifer under the Bonneville Racetrack was draining toward brine-collection ditches or a well field to the west. Ground-water divides have no effect on the movement of dissolved salt across the surface in wind-driven floods, and salt in surface brine was carried from the racetrack into the area of influence of the ditches by such surface movement. During 1976 on the Salt Flats, some brine was moving through the shallow-brine aquifer across lease and property boundaries.

An evaluation of suggested remedial measures indicates that none will completely eliminate the conflict between uses or transform the Bonneville Salt Flats to its original state prior to man's activities in the area.

INTRODUCTION

The Bonneville Salt Flats and Pilot Valley are in the western part of the Great Salt Lake Desert in northwest Utah. (See fig. 1.) The salt crust in the Pilot Valley is about 20 miles northwest of the salt crust of the Bonneville Salt Flats and the two areas are separated by the Silver Island Mountains. The Bonneville salt crust covered about 40 mi^2 in the fall of 1976, and the Pilot Valley salt crust covered 7 mi^2. The two salt crusts and surrounding playas are in separate, though similar, hydrologic basins.

The Bonneville salt crust and surrounding playa have been used for many years for both mineral production and automobile racing; the salt crust and surrounding playa of Pilot Valley have been largely unused. The Salt Flats are internationally famous as the site where most land speed records for various types of vehicles have been set. The first organized racing on the Salt Flats took place in 1914, and a land speed record of 141.7 mi/h was set (Houlgate and others, 1971, p. 25). The current land speed record, set on the Salt Flats in 1970, is 622.4 mi/h. During 1976, approximately 300 racers from 20 States used the Salt Flats.

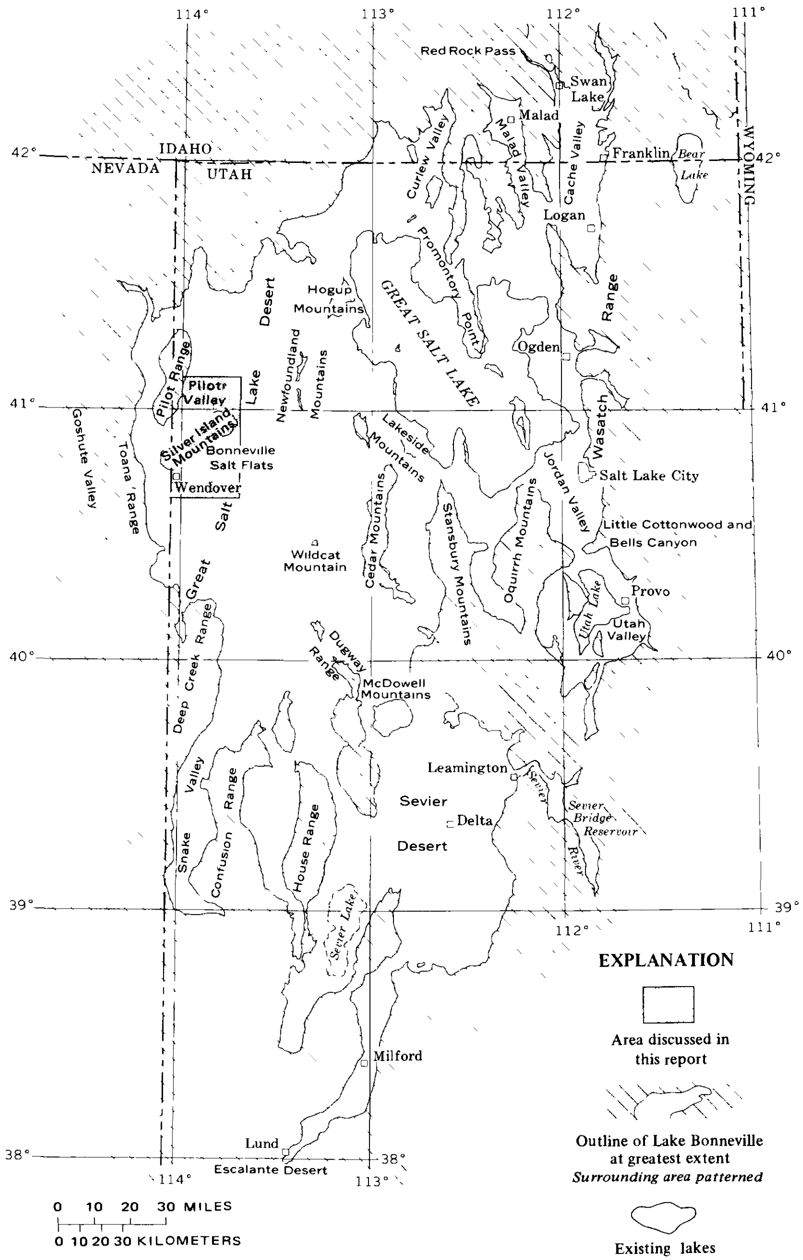

FIGURE 1.—Map of northern Utah and adjacent areas showing the study area, the physiography, and the extent of ancient Lake Bonneville (modified from Crittenden, 1963, fig. 1).

Mineral production on the Bonneville Salt Flats started in the early 1900's when the Montello Salt Co. built a plant and for a few years gathered and processed common salt or halite (sodium chloride) from the salt crust. After German supplies of potassium salts to this country were halted by World War I, the Solvay Process Co. began production of potassium in 1917. By 1920, the Solvay Process Co. was this country's largest producer of potassium salts (Nolan, 1928, p. 27). Prior to the Mineral Leasing Law of 1920, much of the Salt Flats, mainly south of the present Interstate Highway 80 (fig. 2), was patented and came under private ownership. The Solvay Process Co. ceased production in 1921 when German supplies of potash again became available, and the plant lay idle until 1938 when the Bonneville Limited Co. began production. Bonneville Limited extracted brines from ditches on their property until 1963 when the operation was sold to Kaiser Aluminum and Chemical Corp. In 1963, mineral leases on the 25,000 acres of Federal land were issued. Kaiser's present potash operation is on about 73 percent private land, 22 percent leased Federal land, and 5 percent leased State land. Mineral production includes muriate of potash (potassium chloride), halite, and a small amount of magnesium chloride.

Racing enthusiasts and others claim that brine withdrawals for the mineral production have caused the salt crust to deteriorate. Most complaints state that the crust underlying the racetrack area has become rougher and that there has been a loss of salt and an increase in silt on both the north and south ends of the racetrack.

SCOPE AND OBJECTIVES

This investigation was carried out by the Water Resources Division of the U.S. Geological Survey in cooperation with the U.S. Bureau of Land Management and the Conservation Division of the Geological Survey. The study was started in July 1975 and ended in September 1977.

The objectives of the study were to (1) determine if and how brine withdrawals for mineral production affect the salt crust of the Bonneville Salt Flats, (2) determine the location and extent of the area from which brine is withdrawn, (3) determine the effects of natural climatic changes on the geomorphic features of the salt crust, (4) evaluate possible remedial measures that might be implemented to resolve the conflict between uses, if a conflict exists, and (5) recommend a monitoring program or future study that would provide additional information relevant to the management of the public lands and minerals of the area.

The salt crust in Pilot Valley was studied because of its proximity to the Bonneville salt crust and because no manmade withdrawals of brine have taken place in the valley. Thus, the Pilot Valley salt crust and the hydrology of the valley serve as controls for distinguishing natural and man-caused changes that have taken place on the Bonneville Salt Flats.

FIELDWORK

Fieldwork covered the period from July 1975 to June 1977. A total of 133 wells were installed. On the Bonneville Salt Flats, 72 wells were hand augered, and where the surface would support a drilling rig, an additional 47 wells were drilled with a truck-mounted auger. Fourteen observation wells were hand augered in Pilot Valley. The wells range in depth from 1 to 19 feet because some wells were designed to penetrate only the salt crust, and others were designed to tap only the carbonate muds that underlie the salt crust. All the wells were cased with $2^1/_2$-inch plastic pipe, which was perforated with either a hacksaw or drill. The location of the wells and other sites where data were collected are shown in figures 2 and 3, and the data are given in a report by Lines (1978).

Level lines were run to each of the wells to determine altitudes of land surface and tops of casings. Level lines were run from Geological Survey bench marks located off the playa surfaces along the east flanks of the Silver Island Mountains and the Pilot Range. Closure of a level line was considered acceptable if it was within 0.02 ft/mi.

Two sets of water-level measurements were made on the Bonneville Salt Flats during this study to determine the configuration of the potentiometric surface and directions of brine movement. The first set was made in the spring of 1976, prior to the seasonal production of brine from the ditches; the other set was made in the fall of 1976, shortly after the brine-collection season. One set of water-level measurements was made in Pilot Valley in the fall of 1976.

After the water-level measurements in both areas, the wells were pumped or bailed to obtain samples to determine brine densities. Water samples were also collected at 48 wells for chemical analyses.

Aquifer tests were made in four gravel-packed wells on the Salt Flats to determine hydraulic characteristics of the carbonate muds. Three of the tests were also designed to determine the hydraulic connection between the muds and the overlying salt crust.

Two climatological stations were installed. One was on the Bonneville salt crust near the racetrack, and the other was in Pilot Valley near the edge of the playa, south of the salt crust.

During 1976, salt was scraped periodically from the surface at two sites on the Bonneville Salt Flats. The data obtained were used to

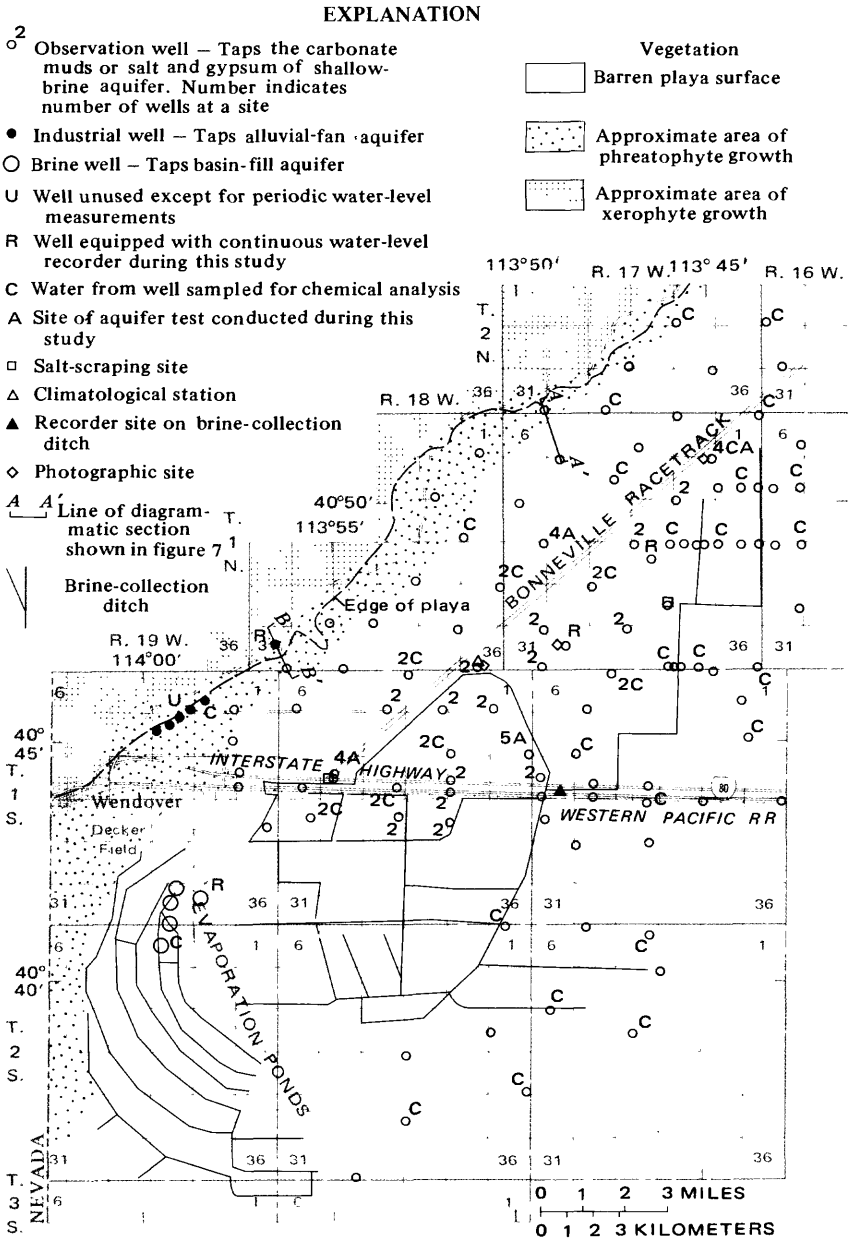

FIGURE 2.—The data-collection network and extent of different types of vegetation on the Bonneville Salt Flats

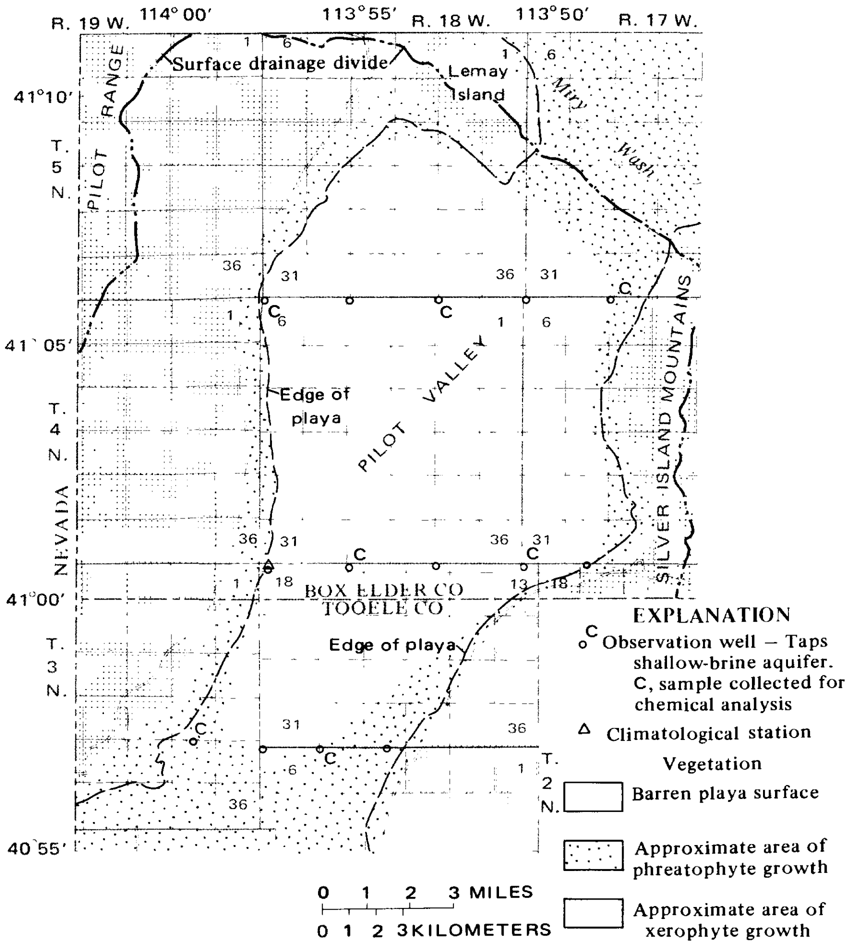

FIGURE 3.—The data-collection network and extent of different types of vegetation in Pilot Valley

determine rates of salt accumulation on the surface during the summer and to estimate rates of ground-water evaporation from the barren surface.

The extent of the Bonneville and Pilot Valley salt crusts and their different geomorphic features were mapped in the fall of 1975 and the fall of 1976. Throughout the study, photographs were taken to document geomorphic features of the salt crusts and changes that took place. Where possible, photographs were taken to document environmental factors that were acting to change the surface.

Fieldwork was hindered by transportation problems, particularly when working in Pilot Valley and off the firm salt crust on the Bonneville Salt Flats. Many days were lost in digging and pulling out trucks, drilling rigs, and even trailbikes that had become mired in the soft playa mud. From October 1975 through May 1976 most of the Salt Flats was flooded with brine as much as 6 inches deep, and driving through the highly corrosive brine had its toll on vehicles.

PREVIOUS INVESTIGATIONS

The first known reference to a salt crust in northwest Utah was by Stansbury (1852, p. 110 and 111) in his description of crossing the northern part of Pilot Valley in October 1849. Most of his description would apply to conditions that existed in the fall of 1976, 127 years later. Stansbury wrote:

> The first part of the plain consisted simply of dried mud, with small crystals of salt scattered thickly over the surface. Crossing this, we came upon another portion of it, three miles in width, where the ground was entirely covered with a thin layer of salt in a state of deliquescence, and so soft a consistence that the feet of our mules sank at every step into the mud beneath. But we soon came upon a portion of the plain where the salt lay in a solid state, in one unbroken sheet, extending apparently to its western border. So firm and strong was this unique and snowy floor, that it sustained the weight of our entire train, without at the least giving way or cracking beneath the pressure. Our mules walked upon it as upon a sheet of solid ice. The whole field was crossed by a network of little ridges, projecting about half an inch, as if the salt had expanded in the process of crystallization. I estimated this field to be at least seven miles wide and ten miles in length. How much farther it extended northward I could not tell; but if it covered the plain in that direction as it did where we crossed, its extent must have been very much greater. The salt, which was very pure and white, averaged from one-half to three-fourths of an inch in thickness, and was equal in all respects to our finest specimens for table use. Assuming these data, the quantity that here lay upon the ground in one body, exclusive of that in a deliquescent state, amounted to over four and a-half millions of cubic yards, or about one hundred millions of bushels.

Stansbury and his men camped at a spring on the west side of Pilot Valley for 3 days, and he wrote:

> During our stay here, it rained almost every day and night. The salt plain, which before had glistened in the sunlight like a sheet of molten silver, now became black and sombre; the salt, over which we had passed with so much ease dissolved, and the flat, in places, became almost impassable.

Stansbury's description points out the dynamic nature of salt crusts and their sensitivity to even daily climatic changes. Indeed, if Stansbury had crossed Pilot Valley only 3 days later than he did, he would not have seen the Pilot Valley salt crust, and his description of the crossing would have been much different.

Gilbert (1890) studied the area covered by ancient Lake Bonneville, and he showed that the flats of the Great Salt Lake Desert are underlain by fine-grained calcareous sediments that were deposited in the lake. Gilbert believed that much of the basin fill was deposited in lakes that predated Lake Bonneville. He noted that ancient shorelines of Lake Bonneville are at higher altitudes near the lake's geographic center than they are farther away. To explain this phenomenon, Gilbert postulated that the lake bottom had differentially rebounded in response to weight loss when the lake water evaporated. Later investigation has substantiated Gilbert's theory of isostatic rebound (Crittenden, 1963).

The first comprehensive study of the shallow brines in the Great Salt Lake Desert was by Nolan (1928). Nolan hand bored 405 shallow test holes in the desert and mapped the extent of the Bonneville and Pilot Valley salt crusts. On the basis of analyses of brine samples, he presented a map that shows the concentrations of chloride, potassium, and magnesium in the shallow brines in 1925. Nolan concluded that differences in concentrations of potassium and magnesium in the brine were related to the quantity and chemical differences of surface-water runoff to different parts of the desert. He postulated that rebound of the bottom of Lake Bonneville near its geographic center (where the lake was deepest) and little or no rebound near its western border resulted in a westward tilting of the lake bottom. He suggested that the Bonneville and Pilot Valley salt crusts were the concentrated products of lake desiccation.

On the basis of carbon-14 dating of carbonate muds, Eardley (1962) worked out an evaporite history for the Great Salt Lake Desert. He believed that the Bonneville salt crust migrated westward 20–25 miles across the desert floor from its original site of crystallization in the center of the Bonneville basin. He concluded that rebound in the central part of the basin and wind ablation along the western edge created a westward tilt of the desert floor and that the Bonneville salt crust slowly migrated to its present location, aided by dissolving precipitation.

Kaliser (1967) conducted a series of short-term aquifer tests in a small area near the racetrack on the Bonneville Salt Flats. He concluded that two aquifers (the salt crust and the underlying carbonate mud) exist and that there is little hydraulic connection between them.

Turk (1969) studied the hydrology of the Bonneville Salt Flats to evaluate the immediate and long-term potential of Kaiser's potash production. He presented a transmissivity map of the shallow-brine aquifer (the salt crust and carbonate muds) that was based on 82 aquifer tests conducted by personnel of Kaiser Aluminum and Chemical Corp., engineers from Utah State University, and by himself. He also presented maps of the Salt Flats that show the distribution of potassium and magnesium in the near-surface brines during 1965–67. Turk concluded that the collection of near-surface brines for potash production had selectively removed potassium and magnesium ions from the shallow brine while the salinity of the brine had been maintained by re-solution of the salt crust.

Stephens and Hood (1973) conducted a hydrologic reconnaissance in Pilot Valley, and Stephens (1974) conducted a hydrologic reconnaissance of the northern Great Salt Lake Desert. They concluded that three aquifers exist in much of the area: (1) an aquifer containing brine and composed of salt crust and the uppermost 25 feet of underlying carbonate muds, (2) alluvial fans that flank the mountains and contain fresh to moderately saline water, and (3) unexposed unconsolidated to consolidated valley fill that contains brine and is tapped by wells at depths of 1,000–1,600 feet in the Bonneville Salt Flats area.

The Utah Geological and Mineral Survey (1974) compared measurements of the thickness of the Bonneville salt crust made in 1960 and 1974. Both sets of measurements were made by personnel from the Utah Department of Transportation in a series of holes that were drilled at 1-mile intervals perpendicular to the racetrack. Comparison of the measurements indicated that north of Interstate Highway 80 the volume of the salt crust had decreased about 15 percent, and the area of the crust where the salt was thicker than 0.1 foot had decreased by about 9 percent.

ACKNOWLEDGMENTS

The writer expresses his gratitude to Kaiser Aluminum and Chemical Corp. for allowing access to its property for drilling and other studies and for supplying unpublished reports and data. Thanks are given to Lois A. Arnow, curator of the Garret Herbarium, University of Utah, for identifying plant specimens. Richard Glanzman, U.S. Geological Survey, supplied X-ray diffraction data for clay-size minerals from the Bonneville Salt Flats and in Pilot Valley.

WELL- AND SITE-NUMBERING SYSTEM

The system of numbering wells and data-collection sites in Utah is based on the cadastral land-survey system of the U.S. Government. The number, in addition to designating the well or site, describes its position in the land net. By the land-survey system, the State is divided into four quadrants by the Salt Lake base line and meridian, and these quadrants are designated by the upper-case letters A, B, C, and D, indicating the northeast, northwest, southwest, and southeast quadrants, respectively. Numbers designating the township and range (in that order) follow the quadrant letter, and all three are enclosed in parentheses. The number after the parentheses indicates the section and is followed by three letters indicating the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section—generally 10 acres;[1] the letters a, b, c, and d indicate, respectively, the northeast, northwest, southwest, and southeast quarters of each subdivision. The number after the letters is the serial number of the well within the 10-acre tract. If a well cannot be located within a 10-acre tract, one or two location letters are used and the serial number is omitted. Thus (C-1-17) 19bdc-1 designates the first well constructed or visited in the SW¼SE¼NW¼ sec. 19, T. 1 S., R. 17 W. Sites where hydrologic data were collected are numbered in the same manner, but three letters are used after the section number and no serial number is used. The numbering system is illustrated in figure 4.

THE PLAYA ENVIRONMENT

TOPOGRAPHY AND SURFACE DRAINAGE

The Great Salt Lake Desert is in the Great Basin section of the Basin and Range physiographic province (Fenneman, 1931, pl. 1). The Basin and Range province is characterized by a series of nearly parallel north-trending mountain ranges that are separated by desert basins. In the western part of the Great Salt Lake Desert, the mountain ranges abruptly rise from the surrounding flat surface of the basin, and in the summer, when viewed from a distance of several miles from a point on the desert floor, the mountains appear to be islands surrounded by water. The illusion is a mirage.

The Pilot Range has about 6,500 feet of relief, and the summit of Pilot Peak, the highest point in the range, is at an altitude of 10,716 feet above mean sea level. Graham Peak, the highest point in the Silver Island Mountains, attains an altitude of 7,563 feet.

To the casual observer, the floor of the Great Salt Lake Desert appears to be a single drainage basin. Instrument leveling is needed in most of the area to detect slight changes in altitude of the land surface. Small changes in altitude of the land surface have formed several closed basins, the two largest of which contain the Bonneville and Pilot Valley salt crusts. As Nolan (1928, p. 30) pointed out, the existence of many different closed basins is suggested by shallow drainage channels, by ponds of water on calm winter days, by the salinity of brine in the shallow lacustrine deposits that underlie the playas, and by areas of salt crust. Many of the smaller closed basins have little hydrologic significance because sheets of water are often driven across the desert floor by strong winds, and minor drainage divides are often breached.

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[1]Although the basic land unit, the section, is theoretically 1 mi^2, many sections are irregular. Such sections are subdivided into 10-acre tracts, generally beginning at the southeast corner, and the surplus or shortage is taken up in the tracts along the north and west sides of the section.

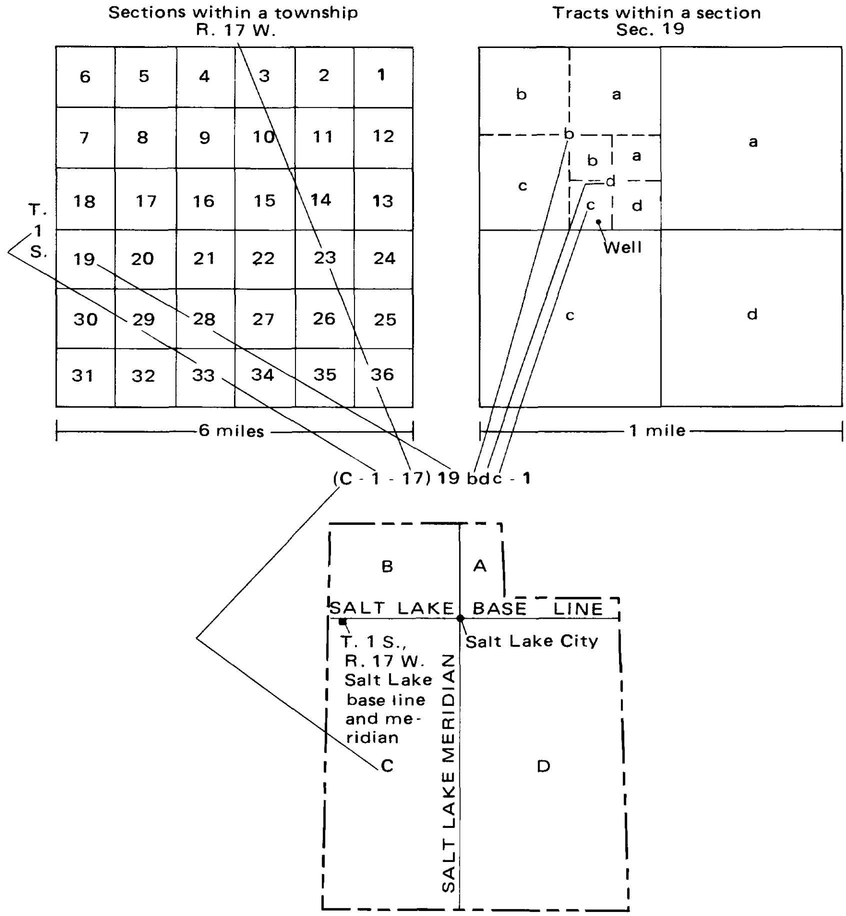

FIGURE 4.—Well- and site-numbering system used in Utah

The surface of the Bonneville salt crust north of Interstate Highway 80 had 1.3 feet of relief in 1976. The mean altitude of the salt crust was 4,214 feet, and it is the lowest area in the western Great Salt Lake Desert. The surface of the Bonneville playa generally slopes upward in all directions from the edge of the salt crust, and it attains a maximum altitude of about 4,230 feet along its western edge. East of the Bonneville salt crust and north of Interstate Highway 80, the playa surface slopes upward to an altitude of 4,217 feet in a distance of about 10 miles and then gradually drops off to the east. The eastward slope is part of the Great Salt Lake drainage basin.

Manmade structures have altered the natural surface drainage on the Bonneville Salt Flats. Roadfills for Interstate Highway 80 that dissect the Salt Flats in an east-west direction act as a drainage divide. Tailings piles along brine-collection ditches and around evaporation ponds have also changed natural drainage patterns.

The playa surface in Pilot Valley ranges in altitude from 4,241 to about 4,260 feet. The salt crust in Pilot Valley is in the lowest part of the playa, along the northwest edge, and surface relief on the salt crust was 0.3 foot during 1976.

Pilot Valley is a closed topographic basin with all surface drainage toward the northwest edge of the playa. The lowest part of the drainage divide is in the gap between Lemay Island and the Silver Island Mountains, at an altitude of 4,245 feet.

Ephemeral streams in the Silver Island Mountains and the lower reaches of streams in the Pilot Range flow only in response to thunderstorms or rapid snowmelt. The main channels of the streams and the tributaries are relatively straight where they descend from the mountains and cross the alluvial fans. Braided streams also cross the fans, but they are not as common as the straight channels.

Upon reaching the playas, the main channels of the mountain streams divide into shallow distributaries that fan out over the flat surface. No discharge from mountain streams onto the playas was witnessed during the course of this investigation. However, during the spring and winter of 1976, such discharge did occur, as indicated by washed-out roads at channel crossings on the alluvial fans and ponds of surface water downstream on the playas.

CLIMATE

The Bonneville Salt Flats and Pilot Valley are areas of low precipitation, high summer and low winter temperatures, moderately high wind speeds during spring months, and high summer evaporation. Weather records at a U.S. National Weather Service station at Wendover extend back through 1912.

Climatological stations were installed for this study on the Bonneville Salt Flats near the racetrack and on the Pilot Valley playa. (See figs. 2 and 3.) The stations were equipped with a standard evaporation pan, an anemometer, a nonrecording rain gage, a hygrothermograph, and maximum and minimum thermometers. The station on the Bonneville Salt Flats became operational on September 23, 1975, and measurements were made at least once a week. The Pilot Valley station was started on November 11, 1975, and daily measurements were made by an observer.

PRECIPITATION

Precipitation at Wendover averaged 4.81 inches per year during the period from 1912 through 1976 (U.S. Weather Bureau, 1937, 1957, 1961-66, and 1965; U.S. Environmental Science Services Administration, 1966-71; U.S. National Oceanic and Atmospheric Administration, 1971-77). Annual precipitation varied from a low of 1.77 inches in 1926 to a high of 10.13 inches in 1941 (fig. 5). Precipitation is fairly well distributed throughout the year, but spring months are usually the wettest. Mean monthly precipitation ranged from a low of 0.27 inch in January to a high of 0.66 inch in May. From November through March, precipitation in the area usually occurs as snow, but snow has been recorded as early as October and as late as June. Afternoon thunderstorms are common during the summer months.

Precipitation at Wendover has varied considerably, not only from year to year but over periods of several years. The 65 years of record at Wendover can be divided into alternating wet and dry periods of about equal length (fig. 5). The 14-year period of 1948-61 was the driest, with an average of 3.80 inches. The wettest period was from 1936 to 1947, when precipitation averaged 5.87 inches. Precipitation was above average for 12 of the last 15 years (1962-76).

In most of the western part of the Great Salt Lake Desert, precipitation averages less than 6 inches per year. But because of orographic effects, precipitation probably exceeds 10 inches per year in the higher altitudes of the Pilot Range and Silver Island Mountains (Stephens, 1974, fig. 1).

Only 15 months of concurrent records are available to compare precipitation at the Wendover station with precipitation at the two climatological stations established for this study. During this 15-month period (December 1975-February 1977), 4.94 inches of precipitation was recorded at Wendover, 3.42 inches was recorded at the station on the Bonneville Salt Flats, and 4.36 inches was recorded at the Pilot Valley station. Monthly precipitation at the three stations during the period October 1975-February 1977 is shown in figure 6. Although the period of concurrent record is too short to estimate precipitation during previous years on the Bonneville Salt Flats and in Pilot Valley, wet and dry months during the concurrent period agree fairly well. It is probably safe to assume that the long-term wet and dry periods that have been recorded at Wendover have also occurred on the Bonneville Salt Flats and in Pilot Valley.

TEMPERATURE

Temperature records obtained at the climatological stations on the Bonneville Salt Flats and in Pilot Valley during 1976 are summarized in table 1. During 1976, mean monthly air temperatures on the Salt Flats were 0.5°-1.5°C higher than in Pilot Valley. During most days the maximum temperature in Pilot Valley exceeded that on the

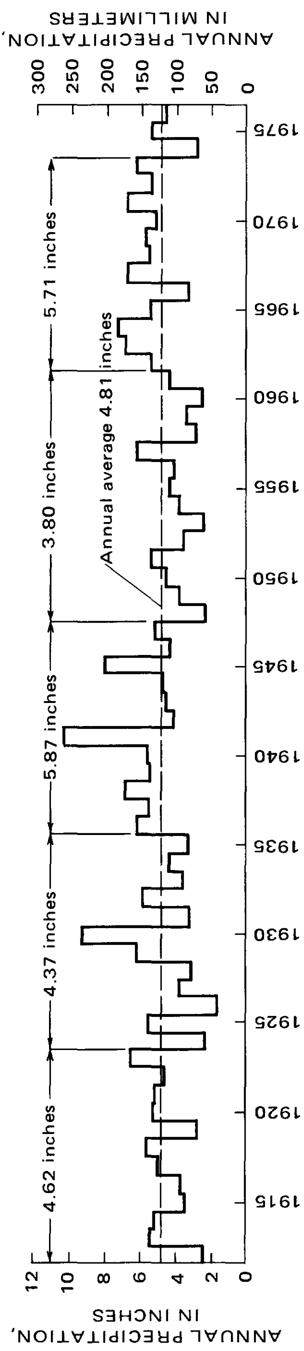

FIGURE 5.—Annual precipitation and relatively wet and dry periods at U.S. National Weather Service station at Wendover, Utah (1912–76).

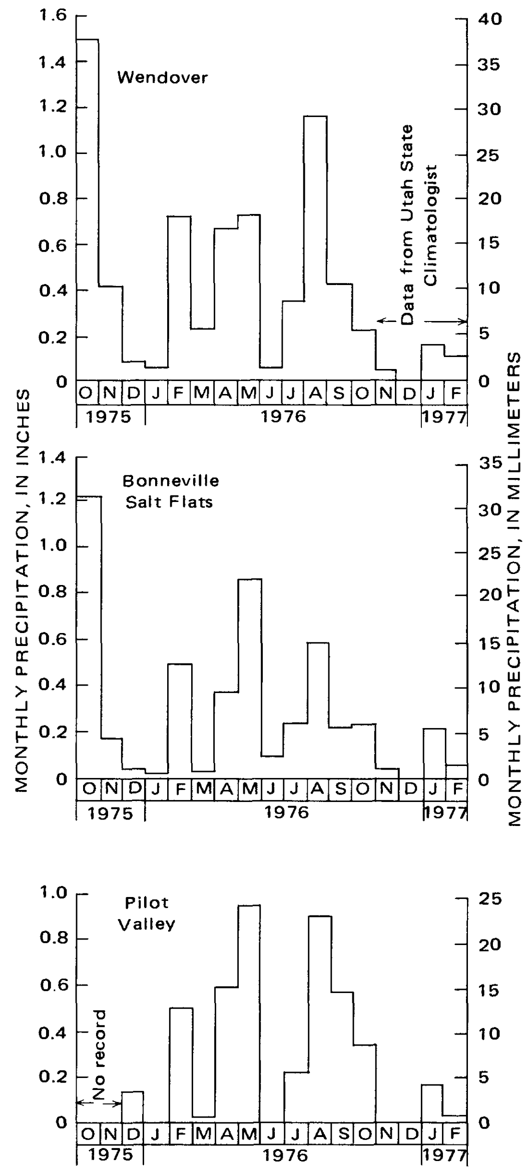

FIGURE 6.—Monthly precipitation at U.S. National Weather Service station at Wendover, Utah, and at climatological stations on the Bonneville Salt Flats and in Pilot Valley, October 1975–February 1977.

Salt Flats, but greater cooling in Pilot Valley consistently lowered temperatures a few degrees below nighttime temperatures on the Salt Flats. The temperatures listed in table 1 were recorded in the shade of a wooden instrument shelter. Air temperatures in the sun commonly exceeded 43.5°C (110°F) during mid to late afternoons in July and August in both areas.

WIND

The mean annual wind velocity at the climatological station on the Bonneville Salt Flats in 1976 was 4.1 mi/h, and it was 4.3 mi/h at the Pilot Valley station. Wind velocities were greatest during spring and summer months in both areas. Mean monthly wind velocities on the Salt Flats ranged from a low of 1.5 mi/h in December to a high of 6.7 mi/h in April. At the Pilot Valley station, mean monthly wind velocities ranged from a low of 2.1 mi/h in December to a high of 6.3 mi/h in June.

No records are available for wind velocities for periods of less than 24 hours. The highest 24-hour velocity recorded in 1976 was in Pilot Valley in March when the velocity averaged 15 mi/h. Gusts associated with summer afternoon cloudiness and thunderstorms probably exceeded 50 mi/h. High mean monthly wind velocities during the summer of 1976 resulted from a few hours of strong winds in mid to late afternoon, the remainder of the day usually being calm.

RELATIVE HUMIDITY

The relative humidity on the Bonneville Salt Flats and in Pilot Valley was fairly high during 1976 in comparison with the other desert areas in the Western United States. Relative humidities at the climatological stations averaged 40-50 percent during spring and summer months and 60-70 percent during fall and winter months.

High humidity in the area can be attributed to a number of factors, the more important of which are (1) rain and snowmelt are ponded on the playa and salt-crust surfaces during periods of low evaporation, (2) the saturated zone, or the capillary fringe, is at or near the land surface in much of the area, (3) the Bonneville Salt Flats contain large areas of water in evaporation ponds, and (4) the Pilot Valley station was near phreatophytes and irrigated land along the edge of the playa.

PAN EVAPORATION

Pan evaporation during 1976 at the station on the Bonneville Salt Flats was 80.5 inches, and it was 95.1 inches at the station in Pilot Valley (table 2). Pan evaporation in Pilot Valley exceeded evapora-

TABLE 1.—*Monthly temperatures during 1976 at U.S. Geological Survey climatological stations on the Bonneville Salt Flats and in Pilot Valley*

[Values are in degrees Celsius (values in parentheses are degrees Fahrenheit)]

	Bonneville Salt Falts			Pilot Valley		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
Jan	−2.5 (28)	10.5 (51)	−13.0 (9)	−3.0 (27)	14.5 (58)	−12.0 (10)
Feb	.5 (33)	16.5 (62)	−9.5 (15)	.0 (32)	18.0 (64)	−11.5 (11)
Mar	3.5 (38)	17.5 (64)	−8.5 (17)	3.0 (37)	19.0 (66)	−13.5 (8)
Apr	9.5 (49)	20.5 (69)	−2.5 (28)	8.5 (47)	22.0 (72)	−5.5 (22)
May	18.0 (64)	29.5 (85)	6.5 (44)	16.5 (62)	31.0 (88)	.5 (33)
June	20.5 (69)	37.0 (99)	6.5 (44)	20.0 (68)	37.0 (99)	5.5 (42)
July	26.5 (80)	38.0 (100)	15.0 (59)	26.0 (79)	39.5 (103)	9.5 (49)
Aug	22.5 (72)	35.0 (95)	11.0 (52)	21.0 (70)	34.5 (94)	6.0 (43)
Sept	20.0 (68)	34.5 (94)	10.0 (50)	18.5 (65)	34.5 (94)	4.0 (39)
Oct	10.5 (51)	24.5 (76)	−2.0 (28)	9.0 (48)	22.5 (72)	−6.5 (20)
Nov	3.0 (37)	16.5 (62)	−12..0 (10)	2.5 (36)	18.0 (64)	−15.5 (4)
Dec	−5.0 (23)	5.0 (41)	−15.5 (4)	−5.5 (22)	11.0 (52)	−20.5 (−5)
Annual	10.5 (51)	38.0 (100)	−15.5 (4)	9.5 (49)	39.5 (103)	−20.5 (−5)

TABLE 2.—*Monthly and annual freshwater pan evaporation, in inches, during 1976 at U.S. Geological Survey climatological stations on the Bonneville Salt Flats and in Pilot Valley*

	Bonneville Salt Flats	Pilot Valley
Jan	1 10	1.29
Feb	1 64	2.17
Mar	5.23	8.41
Apr	4 99	7.59
May	10.2	11.2
June	14.2	15.4
July	15.3	16.7
Aug	11.9	14.0
Sept	7.72	9.72
Oct	4.09	4.86
Nov	2.89	2.39
Dec	1.26	1.33
Annual (rounded)	80.5	95.1

tion at the Salt Flats station during every month of 1976 except November. In both areas, about 60 percent of the yearly pan evaporation was in the period May-August, and about 90 percent was during the period March-October.

Fresh water was used in the pans from May through October. To prevent the water from freezing, brine with a density of 1.2 g/mL (about 320,000 mg/L of dissolved solids) was used in the pans during the period November-April. Turk (1970, fig. 4) found that pan evaporation of brine with a density 1.2 g/mL was about 70 percent of the rate of evaporation of fresh water. The value of 70 percent also agrees with curves by Harbeck (1955, fig. 2) that show effects of salinity on evaporation. Thus, evaporation rates for November-April were adjusted by 70 percent to obtain the equivalent rates of evaporation for fresh water that are shown in table 2.

VEGETATION

Plants grow along the edges of the Bonneville and Pilot Valley playas, on the slopes of adjoining alluvial fans, and in the mountains where soil has developed. Except for green algae that grows just below the salt-crust surface, no plants grow on the salt-crust areas or on most of the playa surfaces because the salinity of shallow ground water exceeds plant tolerances. The areal extent of different types of plants along the margins of the Bonneville Salt Flats is shown in figure 2; vegetation in Pilot Valley is shown in figure 3. An orderly zoning of vegetation exists in the two areas, and this zoning and its relation to salinity and depth of ground water is illustrated in figure 7.

PHREATOPHYTES

Phreatophytes, plants that habitually use ground water from either the saturated zone or the capillary fringe, are the dominant

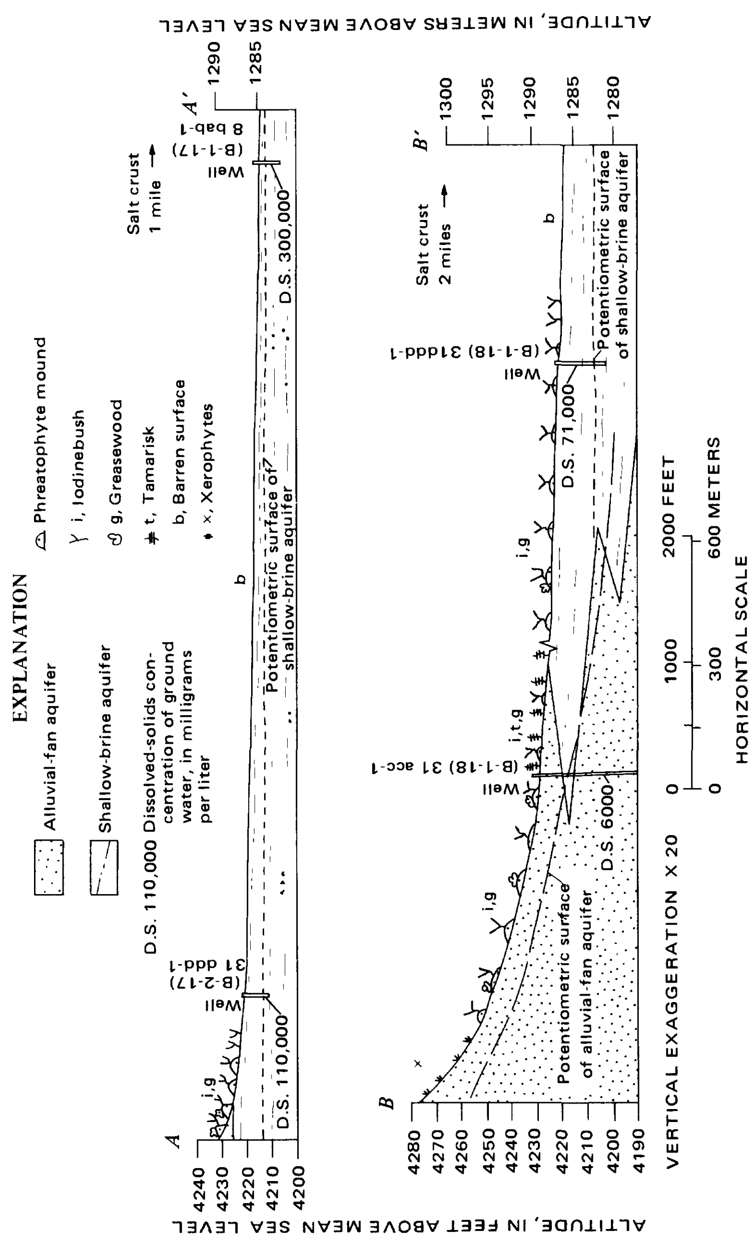

FIGURE 7.—Diagrammatic sections along the west side of the Bonneville Salt Flats showing the increase in salinity of ground water toward the center of the playa and the orderly zoning of phreatophytes reflecting the increase in salinity.

plants along the margins of the playas and extreme lower slopes of alluvial fans. In these areas the saturated zone, or the capillary fringe, is usually within 20 feet of the land surface; during the spring and winter, the capillary fringe may be at the land surface on the playas a short distance from the edge. The most common phreatophytes that grow in the area, their occurrence, and apparent salt tolerance are discussed below.

Iodinebush (*Allenrolfea occidentalis*), a perennial, is the most abundant phreatophyte, and it has the highest salt tolerance. Iodinebush grows along the margins of the playas, and its area of growth onto the playa corresponds fairly well with those areas that contain brine with less than 100,000 mg/L chloride in the shallow lacustrine deposits. Rows of iodinebush commonly grow in the shallow distributary channels as much as 1 mile onto the playas beyond their normal limit. During thunderstorms the shallow distributaries carry relatively fresh water onto the playas, and apparently the brine directly under the channels is diluted below the salt-tolerance levels of the plant. Iodinebush, as shown in figure 8, commonly grows on phreatophyte mounds near the edges of the playas.

FIGURE 8.—View of soft, puffy ground along the western margin of the Bonneville playa; iodinebush growing on phreatophyte mounds and shorelines of ancient Lake Bonneville on the Silver Island Mountains (P, Provo stage; S, Stansbury stage).

Saltgrass (*Distichlis spicata,* var. *stricta*) appears to be the second-most salt-tolerant phreatophyte in the area. Saltgrass commonly grows in association with iodinebush, but it does not grow as far onto the playa. Saltgrass is abundant along the western edge of the Pilot Valley playa, but it is not common along the eastern edge of the Pilot Valley playa or the western edge of the Bonneville playa. It is a relatively shallow-rooted plant, and depth to water seems to be a major factor in determining those areas where it will grow. Robinson (1958, p. 56) reports that saltgrass usually grows in areas where the saturated zone is less than 8 feet below land surface. Observations on its growth in the western part of the Great Salt Lake Desert support Robinson's observations.

Greasewood (*Sarcobatus vermiculatus*) is the second most abundant phreatophyte in the area. Greasewood commonly grows in association with iodinebush and to a lesser extent with saltgrass. Like iodinebush, it grows on phreatophyte mounds near the extreme edges of the playas, but it also grows on the lower slopes of alluvial fans. It is capable of growing a deep root system and commonly grows in areas where the saturated zone is as much as 20 feet below the land surface.

Rabbitbrush (*Chrysothamnus nauseosus*) is widespread in the area. It most commonly grows in association with xerophytes on the upper slopes of alluvial fans where the saturated zone is several tens of feet below the land surface. In these areas where the saturated zone is out of reach, rabbitbrush must rely on soil moisture for its water supply. Rabbitbrush also grows in association with greasewood on the lower slopes of alluvial fans, where it is probably a phreatophyte. According to Robinson (1958, p. 53), it is common throughout the Great Basin to have rabbitbrush growing both as a phreatophyte and a xerophyte. Rabbitbrush appears to have one of the lowest salt-tolerance levels of phreatophytes that grow in the area.

Saltcedar or tamarisk (*Tamarix* sp.) grows only in isolated areas west of the Bonneville Salt Flats; it was not found in Pilot Valley. Saltcedar grows along ditches that carry moderately saline water (about 6,000 mg/L of dissolved solids) to the potash plant from wells that tap the alluvial fan along the western edge of the playa. It also grows along abandoned sections of this ditch system. The saturated zone varies from less than 5 feet below the land surface along ditches in use to as much as 15 feet along abandoned sections. Along the ditches in use, saltcedar grows in association with iodinebush and greasewood. The ditch system crosses highly saline areas where shallow ground water contains more than 200,000 mg/L of dissolved solids and where not even iodinebush normally grows. The saltcedar in these areas is apparently receiving its water supply directly from the ditches.

XEROPHYTES

On the upper slopes of alluvial fans and on soil-covered surfaces in the mountains, xerophytes, which use soil moisture as their water supply, are the dominant plant types. Xerophytes in the area are usually less than 1-foot tall, but they are quite abundant. By far the most common xerophyte is shadscale (*Atriplex confertifolia*). Halogeton (*Halogeton glomeratus*) is abundant, particularly in disturbed areas such as borrow ditches along roads and in heavily grazed areas on the alluvial fans. In addition to the rabbitbrush previously referred to, other common xerotypes include horsebrush (*Tetradymia glabrata*), snakeweed (*Xanthocephalum sarothal*), mormon tea (*Ephedra nevadensis*), green molly (*Kochia americana*), and pricklypear (*Opuntia polyacantha*). The amount of water transpired by xerophytes is unknown; however, they probably do not use much more water than would evaporate from the soil if it were bare.

GEOLOGIC SETTING

The Great Salt Lake Desert and the Basin and Range province as a whole is characterized by a series of isolated nearly parallel north-trending mountain ranges separated by basins. This alternating sequence of basins and mountains is the surface expression of intense block faulting that started in Miocene time and that has continued to the present in some areas (Schaeffer and Anderson, 1960, p. 131). The mountain ranges are bordered on one or more sides by block faults that can have several thousand feet of displacement. The basins, in downthrown blocks or grabens, are filled with detrital material eroded from the adjacent mountains and a large amount of evaporite material. Much of the basin fill in the Great Salt Lake Desert was deposited in ancient Lake Bonneville and in lake basins that predate Lake Bonneville. The Basin and Range block faulting has been superimposed on earlier folding and faulting that occurred on a regional scale during the Nevadan orogeny (Late Jurassic and Early Cretaceous) and (or) the Laramide orogeny (Late Cretaceous through Eocene time) (Schaeffer and Anderson, 1960, p. 131).

PALEOZOIC ROCKS

The mountain ranges in the western part of the Great Salt Lake Desert are composed mainly of limestone, dolomite, shale, and quartzite of Paleozoic age (fig. 9). Because of block faulting and basin fill, the Paleozoic rocks are several thousand feet below land surface in the centers of the basins. This was demonstrated in a petroleum-test well by Alpha Minerals, Inc., about 8 miles southeast of the Bonneville Racetrack (fig. 9). The test penetrated Paleozoic rocks at

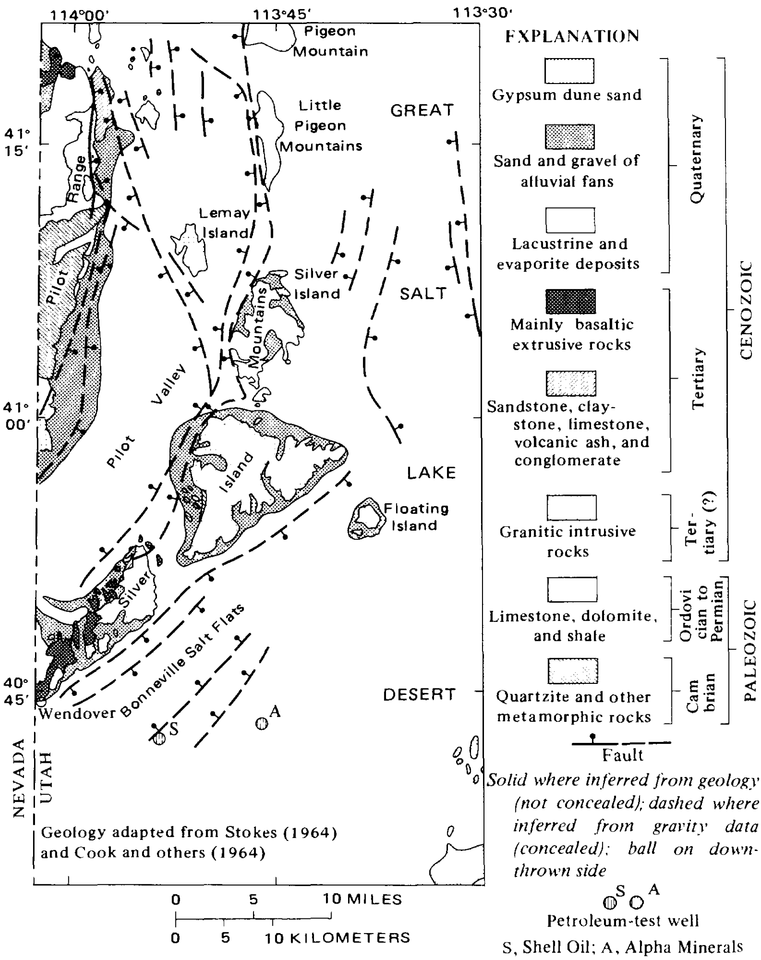

FIGURE 9.—Sketch map showing the geology of the Bonneville Salt Flats and Pilot Valley region of the Great Salt Lake Desert.

a depth of 2,980 feet below land surface and bottomed in Paleozoic rocks at a depth of 4,260 feet (table 3). Another test well by Shell Oil Co. about 2 miles southeast of the racetrack was drilled to a depth of 2,950 feet below land surface and did not penetrate Paleozoic rocks.

BASIN FILL

Regional gravity surveys (Cook and others, 1964, pl. 1) indicate that the Bonneville Salt Flats and Pilot Valley are in grabens formed

TABLE 3.—*Lithologic logs of two petroleum-test wells on the Bonneville Salt Flats*

Description	Thickness (ft)	Depth below land surface (ft)
Alpha Minerals, Inc. (C-1-17)34ba-1. Altitude of land surface 4,222 ft above mean sea level. Log condensed from log by T.R. Blazzard on file with the U.S Geological Survey, Salt Lake City, Utah.		
No description logged	150	150
Mudstone, white to light-gray, soft; contains gypsum crystals	10	160
Limestone, light-buff, very fine, pelletal, dense	5	165
No description logged	45	210
Mudstone; as above	10	220
Limestone, light-gray, very fine, pelletal	5	225
Mudstone; as above	35	260
Limestone; as above	5	265
Mudstone; as above	65	330
No description logged	90	420
Mudstone; as above	30	450
Conglomerate, yellowish-brown, gray, and green; contains volcanic pebbles, few limestone pebbles; has mudstone matrix	30	480
No description logged	20	500
Volcanics, brownish-orange, gray, and black, aphanitic, dense, hard	165	665
Siltstone, light-gray, calcareous, sandy, soft	5	670
Limestone, white to buff, microcrystalline, chalky, soft	20	690
No description logged	10	700
Conglomerate; contains volcanic and limestone pebbles; has sandstone matrix	45	745
Volcanics, gray to green, aphanitic, glassy	345	1,090
No description logged	60	1,150
Mudstone, light-gray, slightly calcareous, soft	10	1,160
Limestone and dolomite, buff, gray, microcrystalline, chalky, slightly sandy	20	1,180
Volcanics, gray to green, aphanitic, glassy; has quartz porphyries	10	1,190
Sandstone, light-green to gray, conglomeratic, limy	65	1,255
Claystone, light-green to buff, firm	5	1,260
Conglomerate; contains volcanic and chert fragments; has mudstone and sandstone matrix	30	1,290
Claystone, buff, slightly micaceous, sandy, hard	75	1,365
Conglomerate; contains volcanic and chert pebbles; has sandstone matrix	95	1,460
Mudstone, white to light-green, slightly sandy, soft to firm	80	1,540
Conglomerate; contains quartzite and chert pebbles; has sandstone matrix; very hard	40	1,580
Shale, tan, green, gray, slightly sandy and carbonaceous, blocky, waxy; contains some pyrite	705	2,285
Limestone, white to light-green, microcrystalline, very sandy; grades to limy sandstone; contains some dolomite	35	2,320
Shale, light-green, some reddish-brown, slightly sandy; contains thin beds of buff limestone	660	2,980
Dolomite, white to tan, microcrystalline, sandy, dense; contains some limestone	105	3,085
Shale, light-green to reddish-brown, soft, blocky	10	3,095
Limestone and dolomite, buff and tan, slightly sandy, dense, hard	35	3,130
Sandstone, light-gray to light-green, fine- to medium-grained, friable, very micaceous; contains some pyrite	15	3,145
Dolomite and limestone, white, gray, and tan, microgranular, slightly argillaceous and sandy, somewhat mottled, dense	355	3,500

TABLE 3.—*Lithologic logs of two petroleum-test wells on the Bonneville Salt Flats*—*Continued*

Description	Thickness (ft)	Depth below land surface (ft)
Limestone, light-tan to gray, microcrystalline, hard, slightly argillaceous and fossiliferous	100	3,600
Dolomite and limestone, light-tan to dark-gray, slightly argillaceous, dense, hard	210	3,810
Limestone, gray, sucrosic, slightly argillaceous, hard	70	3,880
Gypsum, clear, crystalline	15	3,895
Dolomite, light- to medium-gray, sucrosic, hard; contains some chalky limestone	195	4,090
Limestone, tan to gray, microcrystalline; many calcite-filled fractures; slightly argillaceous and fossiliferous; dense	170	4,260
Shell Oil Co., (C-2-18)4bd-1. Altitude of land surface 4,216 ft above mean sea level. Log condensed from log by R. W. Olsen and W. Roberts on file with the U.S. Geological Survey, Salt Lake City, Utah.		
No description logged	40	40
Clay, light-grayish-green, calcareous, very soft, gummy	300	340
Clay (70 percent), as above, and gypsum (30 percent), transparent, fractured	230	570
Gypsum (90 percent), and clay (10 percent); both as above	40	610
Gypsum (50 percent), as above, and limestone (50 percent), light-gray, oolitic, fossiliferous	20	630
Gypsum (80 percent), clay (10 percent), and limestone (10 percent); all as above	80	710
Gypsum (60 percent), as above, clay (10 percent), as above, and limestone (30 percent), light-brownish-gray, very fossiliferous	20	730
Limestone (90 percent), light-brownish-gray, very fossililiferous, and gypsum (10 percent)	60	790
Siltstone, gray, calcareous, argillaceous	100	890
Limestone, siltstone, and gypsum, interbedded	80	970
Shale, medium-gray, silty, gummy, and shale, interbedded	350	1,320
Limestone, medium-gray, very argillaceous	30	1,350
Volcanic fragments (conglomerate?), basaltic, andesitic, and tuffaceous	139	1,489
Conglomerate, reddish-brown and dark-green; contains andesitic and tuffaceous fragments; has clay to fine sand matrix	121	1,610
Volcanics (andesite?), variegated, green, red, black, fine-grained to aphanitic; calcite veinlets common	130	1,740
Limestone, light-gray, sandy, tuffaceous; contains biotite, chert, and some pyrite	60	1,800
Tuff(?), bright-yellow, altered	40	1,840
Sandstone, light-gray, calcareous, tuffaceous; contains some chert	20	1,860
Volcanic breccia; mainly light-brown to black andesite; contains few tuffaceous clasts; fractures filled with calcite	400	2,260
Bentonite or tuff, reddish-brown, calcareous	20	2,280
Volcanic breccia, as above	20	2,300
Bentonite or tuff, light-gray, calcareous	40	2,340
Volcanic breccia, as above	220	2,560
Limestone, white to light-brown, sandy, tuffaceous; contains some interbedded calcareous sandstone and tuff	80	2,640

TABLE 3.—*Lithologic logs of two petroleum-test wells on the Bonneville Salt Flats—Continued*

Description	Thickness (ft)	Depth below land surface (ft)
Andesite, black and dark-green, fine-grained, calcite veins	80	2,720
Limestone, brown-mottled	20	2,740
Basalt, black-, brown-, green-mottled, hard, massive; contains feldspar laths and probably some olivine	90	2,830
Microgabbro, black, dark-gray, brown, green-mottled, fine- to medium-grained, partially altered	111	2,941
Diabase, black to dark-gray (greenish cast), massive; in part altered to greenstone; commonly fractured (fractures filled with serpentine, chlorite, and pyrite)	9	2,950

by Basin and Range faulting. The basin fill is about 5,000 feet thick in the deepest part of the graben that underlies the Bonneville Salt Flats and is about 5,300 feet thick in the deepest part of the Pilot Valley graben, according to Cook and others (1964, p. 732 and 733). They included all strata that overlie pre-Tertiary rocks as part of the basin fill.

The lower part of the fill underlying the Bonneville Salt Flats is composed mainly of extrusive volcanic rocks and associated sandstone, claystone, ash, and conglomerate of Tertiary age. The upper part of the fill is composed mainly of claystone, limestone, and gypsum of Quaternary age. Most of the sedimentary rocks and evaporite deposits that fill the basins are of fluvial or lacustrine origin, and much of the deposition took place in basins that predate Lake Bonneville (Gilbert, 1890, p. 98-101).

All deposits that are exposed at the surface of the Bonneville and Pilot Valley playas were deposited in Lake Bonneville or are of younger age. The upper 20 feet of Lake Bonneville deposits underlying the two playas is composed mainly of dark-gray to dark-brown carbonate muds made up of clay-size calcite, aragonite, and dolomites. Interbedded with the carbonate muds are thin stringers of fine-grained quartz oolitic sand. Overlying the carbonate muds are gypsum evaporite deposits and the crystalline salt crust.

Shorelines of Lake Bonneville are well marked in the Silver Island Mountains by calcareous tufa deposits and beach bars. Schaeffer and Anderson (1960, p. 112) report eight prominent shorelines or terrace levels of Lake Bonneville in the Silver Island Mountains; two of the shorelines are shown in figure 8.

ALLUVIAL FANS

Sand and gravel in alluvial fans of Quanternary age blanket most slopes of the Silver Island Mountains and the Pilot Range. The fans are derived from weathering of outcrops of Paleozoic and volcanic rocks. Driller's logs of several water wells near the edge of the Bonneville playa (Stephens, 1974, p. 46 and 47) indicate that sand and gravel of the alluvial fans are interbedded with the carbonate muds of the basin fill. "Bedrock" (Paleozoic rock?) was logged in one of the wells at a depth of 219 feet.

PLAYA-SURFACE MORPHOLOGY

DEVELOPMENT OF THE SALT CRUSTS

The extent of the Bonneville salt crust and the different geomorphic features in the fall of 1975 and in the fall of 1976 are shown in figures 10 and 11, and the extent of the Pilot Valley salt crust in the fall of 1976 is shown in figure 12. Salt crust was mapped in both areas where the crystalline halite at the surface had a thickness of at least one-eighth inch.

Both playas can be divided into three zones: (1) a carbonate zone composed mainly of authigenic clay-size carbonate minerals, (2) a sulfate zone composed mainly of authigenic gypsum ($CaSO_4 \cdot 2H_2O$), and (3) a chloride zone composed of crystalline halite (NaCl) (the salt crust). All three zones are interbedded or covered to some extent with reworked muds from the underlying carbonate zone and detrital material weathered from the adjacent mountains.

As postulated by Nolan (1928, p. 40), the Bonneville and Pilot Valley salt crusts are largely the end products of the desiccation of Lake Bonneville. The zoning of evaporite minerals, as occurs on the surface of the Bonneville Salt Flats and in Pilot Valley, is a common phenomenon in other salt-encrusted areas associated with lake desiccation. Hunt and others (1966, p. B46-B48) divided the Death Valley salt pan, also largely a product of lake desiccation, into carbonate, sulfate, and chloride zones.

Lake desiccation and the resulting zoning of evaporite minerals can be compared to the crystallization of salts that occurs when water is evaporated in a dish in the laboratory. As water in a dish or lake evaporates, the concentrations of dissolved salts increase. When concentrations reach saturation levels, the salts crystallize in an orderly way with respect to their solubilities. The least soluble common salts, the carbonates, are the first to crystallize. The carbonates crystallize along the edges and across the bottom of the dish or lake. The sulfate salts are the next to start to crystallize, and they form on top of the carbonate salts. The most soluble of the common salts, the chlorides,

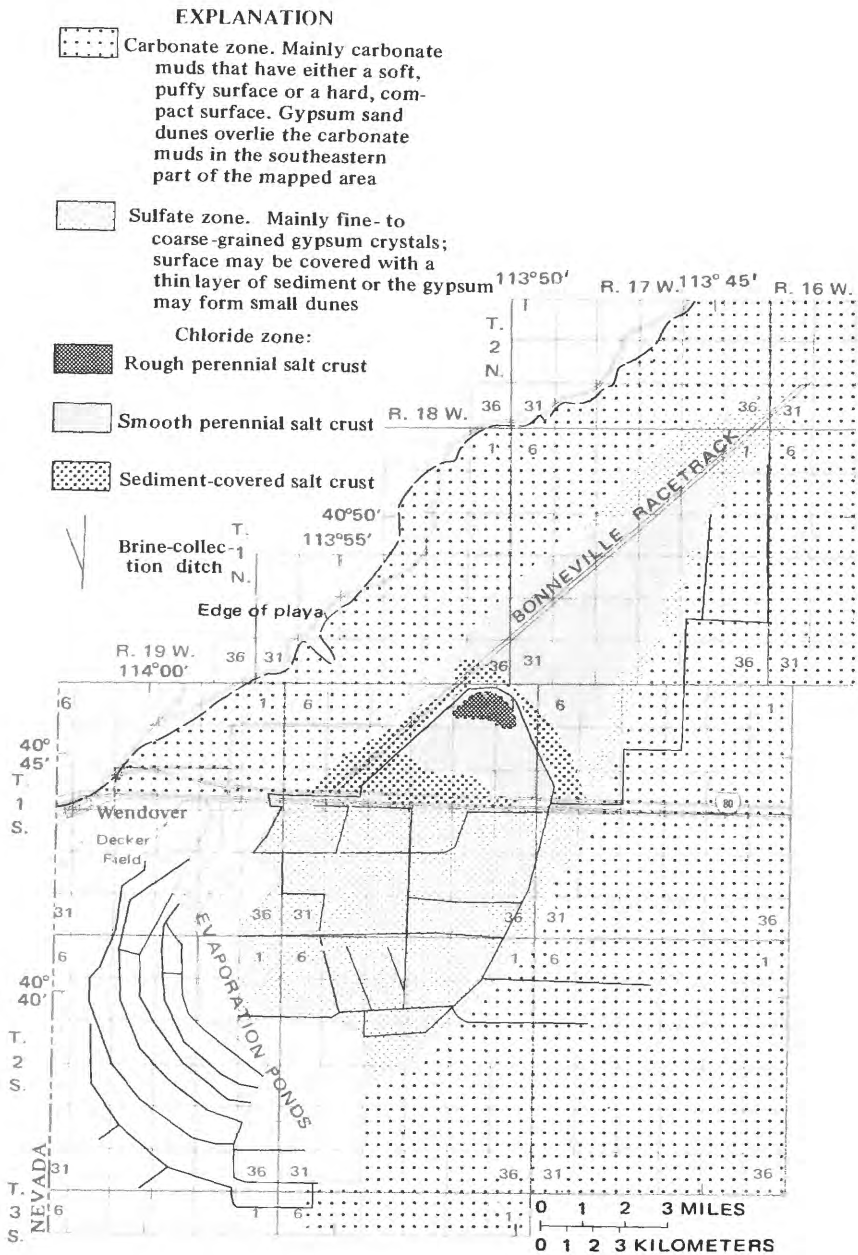

FIGURE 10.—Extent of the salt crust and other geomorphic features on the Bonneville Salt Flats, fall of 1975.

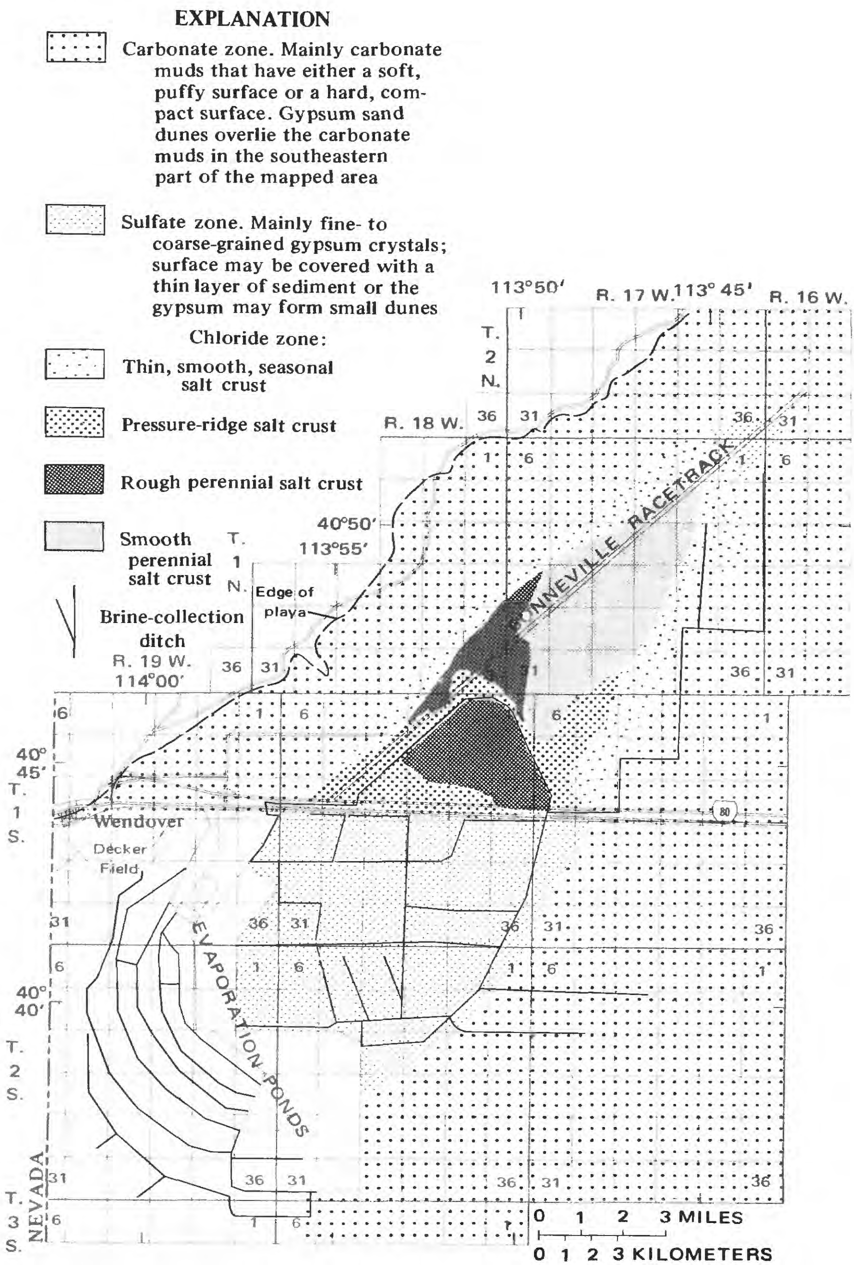

FIGURE 11.—Extent of the salt crust and other geomorphic features on the Bonneville Salt Flats, fall of 1976.

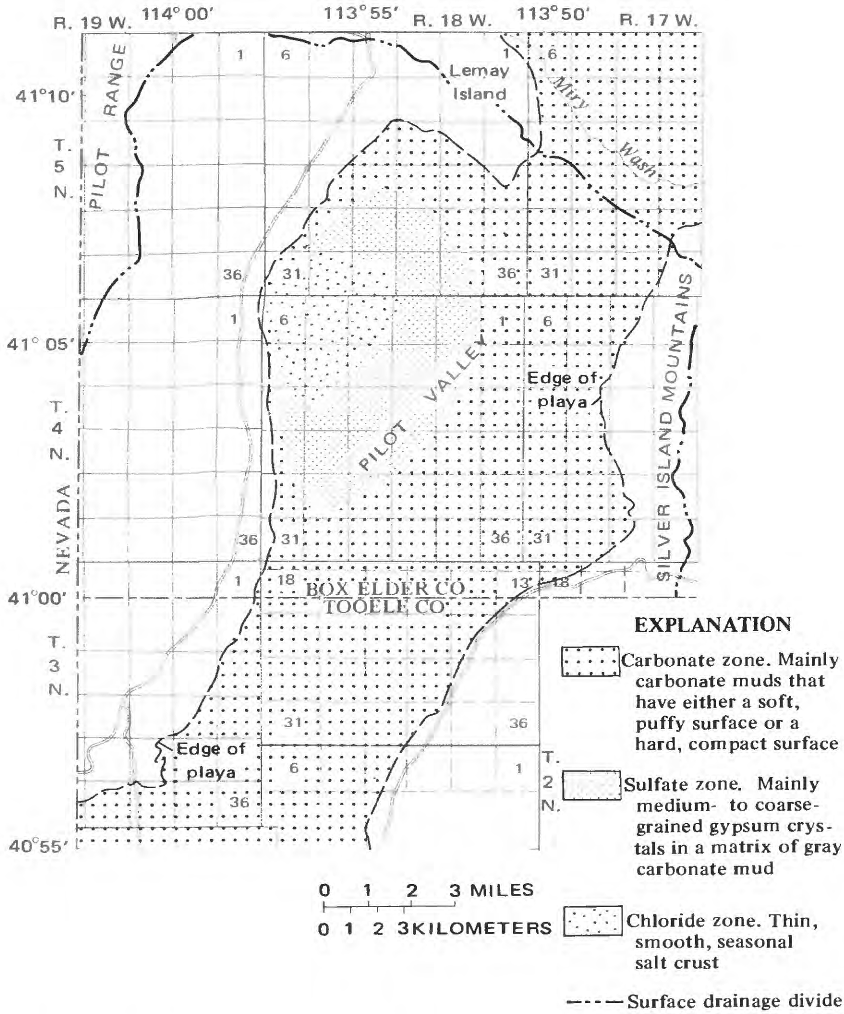

FIGURE 12.—Extent of the salt crust and other geomorphic features on the Pilot Valley playa, fall of 1976.

are the last to crystallize, and they form in the deepest part of the dish or lake on top of the sulfates. The zones of carbonate, sulfate, and chloride salts are transitional, and the volume of salt in each zone is proportional to their respective starting concentrations in the original liquid. The size of the area covered by each zone, in addition to being related to starting concentrations, is also related to the shape of the dish or lake basin.

Because of the addition of relatively fresh water to the areas from precipitation, surface-water runoff, and ground-water inflow, the crystallization of salts has not reached an end stage. Much of the sodium chloride and most of the more soluble potassium chloride and magnesium chloride remains in solution on the Bonneville Salt Flats and in Pilot Valley.

The reworking of the more dynamic chloride zone (the salt crust) by floods of surface brine changes its distribution from year to year on both playas. The distribution, thickness, and geomorphic features of the Bonneville salt crust have also been affected by man's activities.

THE CARBONATE ZONE

The carbonate zone on both playas (figs. 10-12) consists mainly of carbonate muds and interbedded thin lenses of brine shrimp fecal pellets that were deposited on the bottom of Lake Bonneville. X-ray diffraction data on the carbonate muds indicate that the muds are mainly clay-size calcite (trigonal form of $CaCO_3$), aragonite (orthorhombic form of $CaCO_3$), and dolomite ($CaMg(CO_3)_2$) (Richard Glanzman, written commun., March 2, 1977). The carbonate muds are mainly authigenic and contain only small amounts of detrital material. The muds are composed mainly of clay-size crystals, but they contain only minor amounts of actual clay minerals. Turk and others (1973, p. 68) presented X-ray diffraction data for five samples of playa material from the Bonneville Salt Flats; montmorillonite varied from 0 to 8 percent of the total of each sample, and illite varied from 0 to 0.7 percent.

Two major playa-surface types were observed in the carbonate zones on the Bonneville Salt Flats and in Pilot Valley. One surface can best be described as being soft and puffy and the other as smooth, hard, and compact. The differences between these two surfaces are due to differences in their hydrologic environment. Because the major emphasis of the study was on the crystalline salt crusts, no differentiation was made between the two types of carbonate surface when mapping surface morphology. However, generalizations can be made on their distribution and how they are formed.

The soft, puffy surface is most commonly found near the edges of the playas where there is no flooding of the playa by surface waters except in distributary channels. A puffy surface on the playa west of the Bonneville salt crust is shown in figure 8. The major portion of the puffy surface becomes wet only after rain or snow. The puffy surface is susceptible to wind erosion, and it commonly gives rise to dust clouds. Phreatophyte mounds, whose growth is aided by windblown material, are most commonly found on puffy surfaces. The surface is more compact during wet periods than during dry summer months.

When vehicles cross the puffy surface during dry periods, tire ruts 3-4 inches deep are made in the soft carbonate material. A very thin crust of white carbonate minerals, left from evaporating ground water, forms on the puffy surface and on the surface of phreatophyte mounds during dry summer months.

Motts (1970, p. 134) attributed puffy ground on Coyote Playa in California to the discharge of ground water through the playa surface in areas not flooded by surface water. Observations on the Bonneville and Pilot Valley playas support Motts' theory.

The smooth, hard, compact surface most commonly occurs in those areas of the playa between the puffy surface along the margins and the sulfate zone. The boundary between hard and puffy surfaces is transitional. The hard mud surface west of the Bonneville salt crust in an area of the playa that was flooded during the period October 1975-May 1976 is shown in figure 13. Groat (1970, p. 192), in studying Troy Playa in California, attributed hard, compact playa surfaces to alternate flooding by surface water and subsequent desiccation during dry periods. The flooding apparently compacts the surface muds and reduces its permeability; subsequent ground-water evaporation is reduced.

FIGURE 13.—Hard, compact carbonate mud surface west of salt crust on the Bonneville playa showing a playa scraper and trail left in playa surface. Mud crack polygons are 2–6 inches across.

When the hard, compact mud surface is flooded, the surface is very slippery due to a top layer of clay-size material one-eighth to one-half inch thick. Sharp and Carey (1976, p. 1716), in their study of playa scrapers on Racetrack Playa in California, attributed the movement of stones and other objects across the playa surface primarily to strong winds and a thin layer of slippery clay on the surface when it is wet. They postulated that this thin layer of clay was the last material to settle from suspension during playa flooding. A playa scraper and its trail in the hard mud surface on the Bonneville Salt Flats is shown in figure 13. The trail of this and other scrapers observed on the playa trended south to southeast in the direction of prevailing winter winds; all the scrapers were observed in areas that are commonly flooded and that are very slippery when wet.

When the surface of the hard, compact mud dries, small desiccation polygons 2-6 inches across form on the surface. If the area receives no precipitation over a period of 2-3 weeks during the summer, a thin coating of white salt forms on the surface of the hard mud due to a small amount of evaporation of shallow brine. The desiccation polygons and salt coating disappear with only a small amount of precipitation.

FIGURE 14.—Hard, compact ground formed around iodinebush in an area that has mainly a puffy surface, west of the salt crust on the Bonneville playa.

Small areas of hard, compact ground also form around iodinebush in areas that are mostly puffy but where the plants do not grow on large mounds (fig. 14). Evaporation from the playa surface in the immediate vicinity of the plants is reduced because water levels are lowered as the plants derive their water supply from the shallow ground water. This reduction in evaporation from the playa surface retards the formation of puffy ground in a circular area around the plant. The lowering of water levels and the desiccation of the playa surface around phreatophytes is common on playas in the Western United States as noted by Neal and Motts (1967, p. 517 and 518).

Where the moundless iodinebush has died, the hard, compact ground around the old plant site changes to a puffy surface. The change is accelerated because of the relatively high permeability of the surface due to the old plant roots. The old plant sites are marked by circular puffy ground that stands a fraction of an inch higher than the surrounding puffy surface. Greater evaporation from the surface at old plant sites is also evident from the greater amount of salt that accumulates at the surface of the old sites.

Surface runoff has altered the surface of the carbonate muds along the west side of the ditch that is north of the interstate highway and east of the Bonneville Racetrack (fig. 15). Brine that accumulates on

FIGURE 15.—Erosional channels in the carbonate muds along the west side of the brine-collection ditch in sec. 26, T. 1 N., R. 17 W., about 2.5 miles southeast of the Bonneville Racetrack.

the playa during most winters and springs is blown southeast into the ditch by strong winds from the northwest, and flow of the brine cuts erosional channels in the muds. The tailings pile along the ditch in this area is on the leeward or east side of the ditch, and there is no barrier to keep dissolved salt from the racetrack side from being carried into the ditch by surface brine.

Neither the puffy nor the hard, compact mud surfaces of the carbonate zone are suitable for racing. The surfaces do not offer enough support for racing cars, and traction is poor when the surfaces are wet.

THE SULFATE ZONE

The sulfate zone on the Bonneville Salt Flats (figs. 10 and 11) consists of authigenic medium- to coarse-grained gypsum crystals and minor amounts of brine shrimp fecal pellets. The pore spaces between the gypsum crystals are usually filled with a bluish-black mud that has a putrid odor, indicating hydrogen sulfide. Turk (1973, p. 68) reports that the black mud contains a hemihydrate of calcium sulfate which is intermediate between anhydrite and gypsum, or approximately $CaSo_4 \cdot {}^1/_2H_20$. The thickness of the sulfate zone on the Bonneville Salt Flats varies from a featheredge along its margins to as much as 2 feet underlying the salt crust (Eardley, 1962, fig. 5).

Krinsley and others (1968, p. 96 and 97) report a similar gypsum zone and interstitial black mud underlying a salt crust of Lake Austin playa in Western Australia. In Death Valley, Calif., Hunt and others (1966, p. B55) report a gypsum zone that separates a halite crust on the surface and an underlying zone of lacustrine carbonate muds.

The sulfate zone east of the Bonneville salt crust in the spring of 1976 is shown in figure 16. The gypsum in this area was covered with a layer of sediment as much as 1 inch thick at the time the photograph was taken. Later in the year, the surface of this area was covered with a crystalline crust of halite that extended beyond the sulfate zone onto carbonate muds to the east.

The ridges in figure 16 that extend several inches above the surface consist of wind- and water-carried sediment, which accumulated along ridges of halite that formed when brine evaporated at the surface along fissures during the previous summer and fall. The buildup of halite along the fissures was dissolved by relatively fresh water that flooded the area the previous winter; thus during and after wet periods, the ridges of sediment are the only surface expression of fissuring on the sulfate zone. The fissures form giant polygons, generally orthogonal, which are as much as 300 feet across. These giant

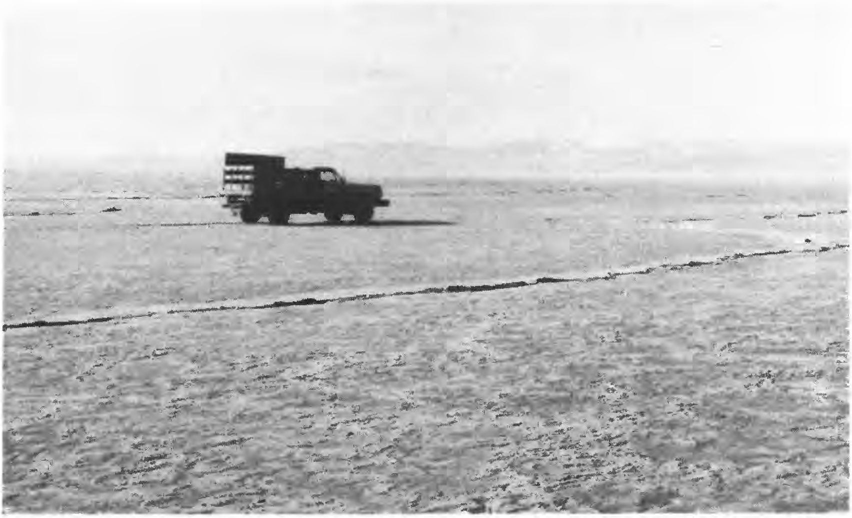

FIGURE 16.—Sediment-covered gypsum surface of the sulfate zone east of the salt crust on the Bonneville playa, spring of 1976. The ridges extending several inches above the surrounding surface are wind- and water-carried sediment that has accumulated along fissures of giant polygons.

polygons were found only in the sulfate zone and along the margins of the salt crust on the Bonneville Salt Flats.

The development of a thin salt crust on the gypsum surface near the north end of the Bonneville Racetrack is shown by a series of photographs in figure 17.

Large areas of the sulfate zone are exposed at the surface south of Interstate Highway 80 on the Bonneville Salt Flats where shallow brine has been withdrawn for many years for the production of potash (figs. 10 and 11). The brine withdrawals have lowered the potentiometric surface in the shallow-brine aquifer below the gypsum layer. With the lowering of the potentiometric surface, the salt crust that covered much of the area south of the present interstate highway in 1925 (Nolan, 1928, pl. 3) has been redissolved, and the underlying gypsum has been exposed at the surface. The small amount of crystalline halite remaining in these areas has been concentrated in isolated thin beds that now directly overlie the less permeable carbonate muds in an unsaturated zone at the base of the gypsum.

The lowering of the potentiometric surface in the shallow-brine aquifer and the resulting loss of salt crust has made the sulfate zone more susceptible to change, mainly by wind. Figure 18 shows drifting gypsum sand from the sulfate zone in an area south of Interstate Highway 80. At well (C-1-18)19adc-2, about 0.75 mile east of the site of figure 18, 2.1 feet of gypsum sand were augered before penetrating

A. February 11, 1976. Thin layer of sediment on gypsum surface. Area flooded with about 1 inch of brine.

B. April 8, 1976. Thin coating of halite on the surface left from evaporated surface brine. Dark line just to left of center is surface expression of fracture of giant polygon.

FIGURE 17.—Development of a thin, smooth gypsum surface at photographic site (B-1-17) (Circles show location of reference ground

C. July 9, 1976. Thin, smooth salt crust formed mainly from ground water evaporating at the surface. Slightly greater salt buildup along fracture of giant polygon just to right of center.

D. December 1, 1976. Salt buildup mainly along fracture of giant polygon where ground water has evaporated at the surface. Pressure ridges just starting to form on smooth surface. Salt crust about one-eighth of an inch thick.

salt crust on the sediment-covered
11aaa on the Bonneville Salt Flats.
stake.)

carbonate muds. The bottom 0.6 foot of gypsum sand contained halite crystals.

The surface of the sulfate zone on the Bonneville Salt Flats is not suitable for racing because much of the surface is too soft to support vehicles. Also, when the surface is smoothed by having a weight dragged over it, a ridge of silt and gypsum forms along the edges of the track. The ridge creates a hazard for fast moving vehicles.

The sulfate zone in Pilot Valley, which is not as well developed as on the Bonneville Salt Flats, consists of authigenic gypsum crystals in a matrix of gray carbonate mud. The maximum thickness that was found was 6 inches. The boundary between the carbonate and sulfate zones is transitional rather than sharp as indicated in figure 12. The amount of gypsum in the near-surface deposits gradually increases toward the Pilot Valley salt crust. Throughout the course of this study, the surface of most of the sulfate zone in Pilot Valley was moist and very soft. It was apparently in this zone that Stansbury's mules "sank at every step" when they crossed the playa in 1849. During extended dry periods, such as the fall of 1976, the surface of the sulfate zone is covered with crystalline halite ranging from a few

FIGURE 18.—Drifting gypsum sand in the sulfate zone south of Interstate Highway 80 on the Bonneville Salt Flats.

scattered crystals to a firm crust as much as 0.75 inch thick. The surface of the sulfate zone in Pilot Valley is shown in figure 19.

A second zone rich in gypsum was found 7-8 feet below the surface while augering three observation wells in the northwest part of the Pilot Valley playa. The zone is about 1 foot thick and consists of medium- to coarse-grained gypsum crystals and bluish-black mud. This second layer of gypsum is similar to the sulfate zone at the surface and the zone that directly underlies the salt crust on the Bonneville Salt Flats. Because this second zone of gypsum is not exposed on the surface and its extent is largely unknown, it is not shown in figure 12.

Much of the history of evaporite deposition, stages of Lake Bonneville desiccation, rebound of the lake bottom, and subsequent erosion and deposition is unknown for both the Bonneville Salt Flats and Pilot Valley. Gypsum layers found at different depths in both basins probably are evaporites deposited during different periods of lake desiccation; however, much additional detailed study is needed on subsurface stratigraphy and structure to work out a complete geologic history for the area.

FIGURE 19.—The sulfate zone on the Pilot Valley playa, showing the salt crust and Pilot Peak in background, fall of 1976.

THE CHLORIDE ZONE

Five major types of salt crust were mapped in the chloride zone of the Bonneville Salt Flats as shown in figures 10 and 11. Of these five types, only one was found in Pilot Valley in the fall of 1976 (fig. 12). Salt crust was mapped on both playas where the crust had a thickness greater than one-eighth inch. The boundaries between different types of salt crust are transitional. Because of the greater solubility of halite, the chloride zone is more responsive to climatic changes than the sulfate and carbonate zones, and it is susceptible to change from day to day. Geomorphic differences between the five types of salt crust are caused by differences in their hydrologic environments. As the hydrologic environment changes, either naturally or because of man's activities, the geomorphic features and the thickness of the salt crust also change.

THIN SEASONAL SALT CRUST

The Pilot Valley salt crust and a large part of the Bonneville salt crust consisted of a thin layer of smooth halite in the fall of 1976. This thin, smooth crust was largely the product of the evaporation of surface brine that flooded parts of each playa during October 1975-May 1976. A small part of the thin, smooth salt crust also resulted from evaporation of shallow brine during the summer and fall of 1976.

The Pilot Valley salt crust was completely in solution in the surface brine and in brine of the shallow aquifer during the fall of 1975 and the winter and spring of 1976. During the following summer and fall, the surface brine evaporated after collecting in the lowest part of the playa, in the northwest corner. In the fall of 1976 the salt crust in the Pilot Valley covered about 7 mi^2. It had a maximum thickness of about 0.75 inch. The eastern edge of the Pilot Valley salt crust in the fall of 1976 is shown in figure 20. Had the spring and summer months during 1976 been drier, the extent of the salt crust probably would have been much greater because the surface brine would have evaporated faster and there would have been greater evaporation of the shallow brine. Portions of the crust probably would have formed an expansion-ridge surface like that observed by Stansbury (1852, p. 110).

A large part of the Bonneville salt crust was also in solution in surface brines and in the shallow brine during the fall of 1975 and the winter and spring of 1976. The extent of the thin, smooth crust north of Interstate Highway 80 in the fall of 1976 was largely gov-

FIGURE 20.—Thin, smooth salt crust on the Pilot Valley playa, fall of 1976. Silver Island Mountains in background.

erned by surface relief and by winds that positioned the surface brines on the playa as the brine reached its final stages of evaporation. As shown in figures 10 and 11, most areas of the sulfate zone north of the highway that were exposed by re-solution of the salt crust during the fall of 1975 were covered with a thin, smooth salt crust a year later. The thin, smooth salt crust that covered a large area west of the racetrack in the fall of 1976 is shown in figure 21. The maximum amount of salt that was deposited on the Bonneville Salt Flats by the evaporation of surface brines during 1976 was about 1.5 inches in the area of thin, smooth crust west of the racetrack.

Evaporation of shallow brine also contributed to the extent of the thin seasonal salt crust and the thickness of other crust types. However, the maximum buildup of salt during the summer and fall of 1976 that could be attributed solely to evaporation of ground water was about 0.25 inch, and the maximum salt buildup occurred in areas covered with a thick perennial salt crust that was broken by many fissures. The amount of salt that accumulated in areas of thin, smooth crust after the surface brine had evaporated was much less.

FIGURE 21.—Thin, smooth seasonal salt crust west of the Bonneville Racetrack in the fall of 1976. Dust clouds rising from alluvial fan along the flanks of the Silver Island Mountains in background.

FIGURE 22.—Pressure ridges in the salt crust about one-half mile west of the Bonneville Racetrack, fall of 1976.

PRESSURE-RIDGE SALT CRUST

Salt crust with pressure ridges, like that shown in figure 22, covered large areas of the Bonneville Salt Flats during the fall of 1976. This type of salt crust, as pointed out by Stoertz and Ericksen (1974, p. 34 and 35) in their study of Chilean salars (salt-encrusted playas), is flat and smooth when first deposited from evaporating surface brines. Initially it has an appearance like that of the thin, smooth seasonal crust described above. As the thin, smooth crust dries and additional salt is deposited on the surface by evaporating ground water, the crust expands and forms sharp pressure ridges. The tops of the ridges rupture with continued buildup of salt on the surface. On the Bonneville Salt Flats the buckled layers of salt are usually 0.5-1 inch thick, and the upturned pressure ridges are as much as 5 inches high. As shown in figure 21, the thin, smooth seasonal salt crust west of the racetrack was beginning to form pressure ridges in the fall of 1976.

Most of the pressure-ridge salt crust in the fall of 1976 formed in areas where a thicker underlying layer of salt had been flooded with surface brine and covered with a layer of water-carried sediment. The surface on which the new salt layer was deposited, in addition to being covered with sediment, was also commonly uneven due to solution. The cohesiveness of the underlying salt and the new surface crust seemed to be broken by the sediment layer. The development of a pressure-ridge salt crust is shown in the series of photographs in figure 23.

Small stalagmitic and stalactitic structures, as shown in figure 24, commonly form under the upturned plates of the pressure ridges. The halite stalagmites and stalactites are as much as 3 inches long and appear to result from the partial re-solution of the upturned plate by rainwater and fog, evaporation, and subsequent recrystallization.

The pressure-ridge salt crust is not completely suitable for racing because a ridge of sediment builds up along the edges of the track when the surface is dragged. It is also difficult to smooth out the layer of salt that underlies the surface crust and sediment.

SEDIMENT-COVERED SALT CRUST

Large areas of the Bonneville salt crust north of Interstate Highway 80 were covered with a layer of sediment as much as 6 inches thick during the fall of 1975 (fig. 10). Most of these areas developed a pressure-ridge crust through the following summer and fall (fig. 11).

Some deposition of sediment on the salt crust is a natural phenomenon. However, because natural surface drainage on the Bonneville

A. December 9, 1975. Rough sediment-covered salt crust with depressions flooded with brine. Note crater-shaped solution tubes.

B. January 8, 1976. Surface brine nearly completely evaporated; some halite crystallizing in depressions.

FIGURE 23.—Development of a pressure-ridge at photographic site (B-1-18)36cdd on the location of reference ground stake).

C. February 11, 1976. Surface completely flooded with brine about 3 inches deep. Note ripple marks in sediment.

D. April 8, 1976. Surface is dry and salt on surface is mainly that left by evaporated surface brine.

salt crust on sediment-covered halite
Bonneville Salt Flats (circles show

E. July 9, 1976. A smooth salt crust with depressions half filled with salt from evaporation of ground water.

F. December 1, 1976. A pressure-ridge salt crust has formed with continued evaporation of ground water and crystallization of salt.

FIGURE 23.—Continued.

FIGURE 24.—Stalagmitic and stalactitic halite structures that form under the upturned plates of pressure-ridge salt crust on the Bonneville Salt Flats (ballpoint pen in center of photograph for scale).

Salt Flats has been altered by manmade drainage barriers, the ponding of surface brines and the buildup of sediment on the surface have been concentrated in small areas on the windward side of the barriers. An example of such an area is shown in figure 25, which is about 0.5 mile north of the interstate highway along the boundary between secs. 9 and 16, T. 1 S., R. 18 W.; the flooded south end of the racetrack is about 0.25 mile beyond the tailings pile shown in the photograph. Some sediment-laden brine that would normally be ponded north of the interstate highway on the south end of the racetrack has been allowed to flow eastward into this area because of a break in the tailings pile along an abandoned brine-collection ditch. The rough pocked surface of the salt that characteristically underlies the sediment is also apparent in figure 25.

The sediment is deposited on the salt crust by brine that normally floods the flats during wet periods. Possible sources of sediment are the carbonate muds west of the Bonneville salt crust, carbonate muds from the tailings piles along brine-collection ditches, and the thin partings of sediment that are naturally interbedded in the salt crust.

FIGURE 25.—Sediment-covered salt crust one-half mile north of Interstate Highway 80. Flooded south end of Bonneville Racetrack is in background beyond tailings pile along an abandoned brine-collection ditch.

Collapse structures are common in areas of sediment-covered salt crust near brine-collection ditches. The collapse structures shown in figure 26 are between the interstate highway and the railroad in sec. 14, T. 1 S., R. 18 W., and such structures were also observed on the south end of the racetrack. The collapse structures are formed by the re-solution of the salt crust and slumping of the overlying sediment into the void. Roadfills for the railroad and old U.S. Highway 40 were laid on the salt crust, and both have had a long history of slumping where they cross the salt. In building Interstate Highway 80, the salt was removed, and the roadfill was laid on the carbonate muds. No major slumping has occurred along the interstate highway where it crosses the salt crust, and the slumping of the earlier roadbeds seems to have been related to re-solution of the salt crust.

The sediment-covered salt crust is not suitable for racing because a ridge of sediment builds up along the edges of the track when the surface is dragged. The rough pocked surface of the salt that characteristically underlies the sediment is also difficult to smooth by dragging.

FIGURE 26.—Collapse structures in an area of sediment-covered salt crust on the Bonneville Salt Flats.

SMOOTH PERENNIAL SALT CRUST

In those areas of the Bonneville Salt Flats where the salt crust is 1-3 feet thick and where sediment-laden surface waters are not ponded behind manmade drainage barriers, a smooth salt crust develops during periods of flooding. Figure 27 shows a smooth salt crust in an area that was flooded during the fall of 1975 and the winter and spring of 1976. The salt was about 2 feet thick, with little surface relief except for isolated ridges of salt and sediment along fissures that form giant orthogonal polygons. The ridges of salt had been almost completely redissolved when the photograph was taken on January 8, 1976. During the summer and fall of 1976, this same area developed a rough surface as the evaporation of shallow brine and buildup of salt were concentrated along the many fissures that form the giant polygons and also smaller desiccation polygons.

A smooth salt crust was maintained through the summer and fall of 1976 in the central part of the Bonneville salt crust where the evaporation of shallow brine and salt buildup occurred fairly evenly over the surface as shown in photographs in figure 28. The smooth perennial salt crust, after dragging, produces the best surface for racing.

FIGURE 27.—Flooded area on the Bonneville Salt Flats where a smooth surface has formed on a thick perennial salt crust. Ridge of salt along fissure of giant orthogonal polygon in center of photograph is about 8 inches tall as indicated by hammer.

ROUGH PERENNIAL SALT CRUST

Many areas of perennial salt crust on the Salt Flats, which had a smooth surface during flooding in the fall of 1975 and the winter and spring of 1976, had a rough surface in the fall of 1976 (fig. 11). The surface roughness is caused mainly by the buildup of salt ridges, which form along the fractures of small desiccation polygons where shallow brine evaporates at the surface. The boundary between the smooth and rough perennial salt crusts during the fall of 1976 was, in most areas, transitional.

Only a small area of rough salt crust was mapped in the fall of 1975 on the Bonneville Salt Flats (fig. 10) during a period when most of the playa was flooded. The surface of this small area of rough salt crust was slightly higher than the surrounding crust. Because of this and because the area (fig. 10) is protected from floods on three sides by tailings piles along an unused brine-collection ditch, the surface becomes wet only when rained or snowed upon. As a result, the ridges of salt that form along fissures during dry periods are only partly redissolved during wet periods. As shown in figure 29, the salt between the polygon salt ridges in this area has developed a popcorn or blister structure where shallow brine evaporated at the surface over solution tubes. The ridges of salt along the fissures actually

A. December 9, 1976. Smooth perennial salt crust. Newly formed salt veinlets along fractures of desiccation polygons.

B. January 8, 1976. Surface slightly roughened by precipitation.

FIGURE 28.—Changes in smooth perennial salt crust at photographic site (B-1-17)32bdd on the Bonneville Salt Flats (circles show location of reference ground stake). Figure continued on following two pages.

C. February 11, 1976. Surface flooded with about 1 inch of brine.

D. April 8, 1976. Very smooth surface formed by crystallization of halite from evaporated surface brine.

FIGURE 28.—Continued.

E. July 9, 1976. Smooth surface with buildup of salt and evaporation of ground water mainly along fractures of old desiccation polygons.

F. December 1, 1976. Smooth surface with some salt buildup between fractures but mainly along the fractures of desiccation polygons.

FIGURE 28.—Continued.

FIGURE 29.—Rough surface formed on a thick salt crust in an area that is seldom flooded on the Bonneville Salt Flats.

formed a large number of basins 3-10 feet in diameter. Rainwater and snowmelt collected in the lowest parts of the basins, and the solution tubes were the conduits through which the water drained into the underlying salt.

Rough perennial salt crust produces a good racing surface, but it requires more dragging than the smooth perennial crust to level the surface.

THE GROUND-WATER SYSTEM

AQUIFER RELATIONSHIPS

Ground water occurs in three distinct aquifers in much of the western Great Salt Lake Desert. Inferred subsurface stratigraphic relationships are shown diagrammatically in figure 30. The most extensive aquifer, the basin-fill aquifer, yields brine to several wells on the Bonneville Salt Flats from conglomerate in the lower part of the basin fill. The basin-fill aquifer is confined by relatively impermeable lacustrine deposits, and hydraulic connection between the aquifer and playa surfaces is poor.

The alluvial-fan aquifer yields water to wells along the mountain flanks. The degree of hydraulic connection between the basin-fill and alluvial-fan aquifers is unknown. The degree of connection probably varies, as it is dependent on the continuity between the sand and gravel of alluvial fans and the conglomerates in the basin fill. As

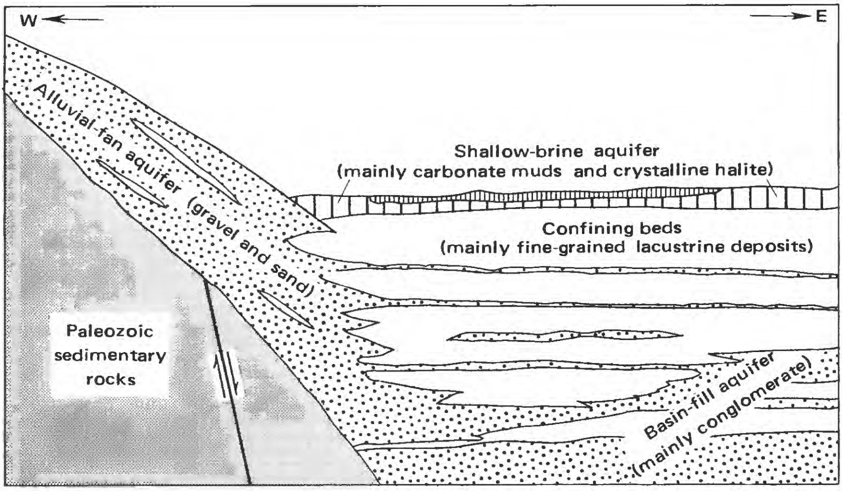

FIGURE 30.—Diagrammatic section showing the inferred subsurface stratigraphic relationships of the three major aquifers in the western Great Salt Lake Desert (modified from Stephens, 1974, fig. 4).

depicted in figure 30, the hydraulic connection would be excellent, as the continuity between the alluvial fan and conglomerate in the basin fill is broken by only one thin zone of lacustrine deposits.

The shallow-brine aquifer consists of both the near-surface carbonate muds and the crystalline halite and gypsum deposits on the surface of the playas. The shallow-brine aquifer yields brine to collection ditches and is the main source of potassium chloride for Kaiser's potash operation on the Bonneville Salt Flats. Sand and gravel of alluvial fans are interbedded with the near-surface carbonate muds of the playas, and hydraulic connection is good.

BASIN-FILL AQUIFER

AQUIFER LITHOLOGY AND CHARACTERISTICS

The basin-fill aquifer, as tapped by wells on the Bonneville Salt Flats, consists mainly of conglomerate that overlies Tertiary volcanic rocks or pre-Tertiary rocks. As much as 840 feet of conglomerate was logged in Kaiser's deep-brine wells. The upper few hundred feet of the basin fill consists of clay-sized lacustrine deposits, and they are not considered as part of the aquifer.

Aquifer tests indicate that the transmissivity[2] of the basin-fill aquifer in the area of the potash operation averages 13,000 ft^2/d, and

[2]Transmissivity is the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The units for transmissivity are cubic feet per day per foot [$(ft^3/d)ft$], which reduces to ft^2/d. The term transmissivity replaces the term coefficient of transmissibility, which was formerly used by the U.S. Geological Survey and which was reported in units of gallons per day per foot. To convert a value for coefficient of transmissibility to the equivalent value of transmissivity, divide by 7.48; to convert from transmissivity to coefficient of transmissibility, multiply by 7.48.

the storage coefficient[3] is about 4×10^4 (Stephens, 1974, p. 21). Regional gravity surveys (Cook and others, 1964, pl. 1) indicate that the Kaiser wells that tap the aquifer are approximately in the deepest part of the basin; thus, the thickness of conglomerate and the transmissivity of the aquifer are probably not as great in other areas underlying the Salt Flats. No wells tap the basin-fill aquifer in Pilot Valley.

POTENTIOMETRIC SURFACE

The potentiometric surface of the basin-fill aquifer was 20-30 feet below land surface at Kaiser's deep-brine wells at the time they were drilled between 1949 and 1951 (Stephens, 1974, p. 21). In 1976, the water level in one of the wells, (C-1-19)35bca-1, was 47-80 feet below land surface. The water level was affected by pumping from nearby wells, and during nonpumping periods it varied from 47-50 feet below land surface. Water-level data are lacking in most of the area, and no precise determination can be made of the configuration of the potentiometric surface and direction of brine movement through the basin-fill aquifer.

RECHARGE AND DISCHARGE

The amount of recharge to the basin-fill aquifer cannot be determined from available data. There is no direct recharge from precipitation, as the aquifer is overlain by several hundred feet of relatively impermeable lacustrine deposits. Recharge is from subsurface inflow from adjacent aquifers in the alluvial fans and probably from underlying Tertiary volcanic rocks or Paleozoic rocks.

Discharge from the basin-fill aquifer is mainly from wells, and subsurface overflow is probably negligible. Detailed regional studies would be required to fully determine inflow-outflow relations in the aquifer. Based on data in the files of the Geological Survey, Stephens (1974, p. 22) estimates that an average of about 2,900 acre-feet per year of brine was pumped from the aquifer by four of Kaiser's deep-brine wells during the period October 1969-September 1972. Four wells were also pumped during 1976, but no data are available to further refine Stephens' estimate of pumpage. The brine pumped from the basin-fill aquifer is used mainly in "seal" ditches around evaporation ponds to reduce leakage from the ponds.

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[3]The storage coefficient of an aquifer is the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in head. Storage coefficient is a dimensionless number. Under confined conditions, the storage coefficient is typically small, generally between 0.00001 and 0.001. Under unconfined conditions, it is much larger, typically from 0.05 to 0.30.

BRINE CHEMISTRY

Brine in the basin-fill aquifer underlying the Bonneville Salt Flats contains between 130,000 and 160,000 mg/L of dissolved solids. Results of a chemical analysis of brine collected from well (C-2-19)3bcd-1 are shown in table 4. The temperature of the brine ranges from 22° to 88°C (Turk, 1969, p. 97) and indicates that the aquifer is probably receiving some deeply circulated water either from underlying Tertiary rocks or Paleozoic rocks along the edges of the basin. Temperature data from five of Kaiser's deep-brine wells and from the Shell Oil Co. test well indicate that the geothermal gradient is about 77°C/mi and heat flow is about 1.6 hfu (heat-flow units, in microcalories/cm^2s). Sass and others (1971, p. 6407) report that most heat-flow values in the Basin and Range province are in the range of 1.5 to 2.5 hfu. A heat-flow value of 1.6 hfu thus is not abnormally high and indicates that in much of the aquifer there is no significant contribution from deeply circulated water. The temperature of 88°C was measured in the drilling mud for one of the deep-brine wells at a depth of 1,636 feet below the land surface; the geothermal gradient and heat flow are both abnormally high and are 250°C/mi and 5.2 hfu, respectively. A heat-flow value of 5.2 hfu indicates a significant contribution from deeply circulated water.

ALLUVIAL-FAN AQUIFER

AQUIFER LITHOLOGY AND CHARACTERISTICS

Sand and gravel of alluvial fans along the flanks of the Silver Island Mountains and the Pilot Range compose the alluvial-fan aquifer. The alluvial fans are interbedded with the fine-grained lacustrine deposits that underlie the playas, and the lacustrine deposits act as confining layers to the alluvial-fan aquifer.

Between 1946 and 1949, 27 wells that tapped the alluvial-fan aquifer were drilled along the western edge of the Bonneville playa. During 1976, water was pumped from four of the wells, one well was equipped with a continuous water-level recorder, and another was used for periodic water-level measurements. (See fig. 2.) Drillers' logs, which are available for 12 of the wells (Stephens, 1974, p. 46 and 47), indicate that the thickness of sand and gravel and the number and thickness of interbeds of lacustrine deposits varies greatly within short distances. The 12 wells range in depth from 104 to 364 feet, and the percentage of material that is logged as sand and gravel ranges from 12 to 52 percent. The remainder of the material was logged as "clay" (mostly lacustrine deposits) and occurred in a number of zones separating the beds of sand and gravel.

TABLE 4.—*Chemical analyses of ground water from selected*

Aquifer: Qal, alluvial-fan aquifer; Qbf, basin-fill aquifer, Qsc, carbonate mud zone of shallow-brine
U.S. Geological Survey; K, Kaiser Aluminum

Location	Date of collection	Aquifer	Temperature (°C)	Milligrams						
				Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)	Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)
(B-1-16)19aaa-1	9-23-76	Qsc	17.5	1,500	1,900	85,000	3,100	53	--	4,600
(B-1-17)11aaa-1	9-24-76	Qsc	16.5	1,100	4,900	100,000	7,500	195	--	5,700
11aaa-2	9-24-76	Qsh	17.0	1,300	3,000	110,000	6,400	29	--	4,300
28bbb-1	9-24-76	Qsc	18.5	1,000	5,500	100,000	9,600	193	--	6,200
28bbb-2	9-24-76	Qsh	18.5	960	5,500	110,000	9,300	99	--	5,900
(B-1-18)13ccc-1	9-22-76	Qsc	21.0	1,200	1,900	88,000	3,600	42	--	4,500
29ccc-1	3-29-72	Qal	28.0	91	71	2,200	130	180	0	240
(B-2-16)19ccc-1	9-21-76	Qsc	20.0	1,500	980	89,000	2,000	37	--	4,600
(B-2-18)5	9-30-76	Qsc	18.0	270	410	20,000	1,200	447	--	1,100
(B-3-18)8	9-30-76	Qsc	21.5	2,200	2,400	98,000	6,900	109	--	3,300
(B-4-17)4bbb-1	10-01-76	Qsc	20.0	1,200	500	29,000	1,500	73	--	2,200
(B-4-18)6bbb-1	10-01-76	Qsc	18.5	2,000	1,300	78,000	4,500	37	--	2,900
(B-4-19)13ddb-S1	9-23-71	Qal	15	17	54	86	7.8	101	0	13
36acc-S1	9-22-71	Qal	16	100	24	180	5.4	115	0	13
(C-1-18)11ccc-1	9-27-76	Qsc	22.0	1,400	1,400	120,000	2,900	42	--	4,000
11ccc-2	9-27-76	Qsh	22.5	1,500	960	110,000	2,400	33	--	4,100
(C-1-19)2adb-1	3-29-72	Qal	24.5	79	63	2,000	120	212	0	190
10bac-1	9-08-67	Qal	31	100	80	2,100	100	--	--	300
34bdc-1	9-13-67	Qbf	28	1,760	1,540	45,400	1,980	--	--	6,590
(C-2-17)4aac-1	9-28-76	Qsc	21.0	1,200	980	70,000	1,900	37	--	3,600
(C-2-18)27cbb-1	9-28-76	Qsc	22.0	1,100	8,000	96,000	13,000	206	--	6,300
(C-2-19)3bcd-1	11-12-76	Qbf	28.0	1,600	1,500	47,000	2,100	135	--	5,600

Aquifer tests at two of the alluvial-fan wells were conducted by personnel of Bonneville Ltd., and transmissivity values reported by Turk (1969, p. 67) range from 2,300 to 63,600 ft^2/d. Storage coefficients of 2×10^{-4} and 5×10^{-4} were calculated from these two tests, and they are typical of confined aquifers. The aquifer-test data also indiate that the alluvial-fan aquifer responds as a leaky aquifer and that over a long period of pumping a significant amount of water would be contributed by the confining layers.

POTENTIOMETRIC SURFACE

Most of the alluvial-fan wells along the western edge of the Bonneville playa yielded water under sufficient hydrostatic pressure to rise 10-20 feet above the land surface when they were drilled between 1946 and 1949 (Stephens, 1974, p. 44 and 45). By 1960, pressures in the aquifer had decreased so much that static water levels in the *wells and springs on the Bonneville Salt Flats and in Pilot Valley*

aquifer; Qsh, halite and gypsum zones of shallow-brine aquifer. Laboratory making analysis: GS, and Chemical Corp., San Leandro, Calif.

per liter								Specific conductance (micromhos per centimeter at 25°C)	Density (g/mL at 20°C)	pH	Laboratory making analysis
Dissolved chloride (Cl)	Dissolved bromide (Br)	Dissolved boron (B)	Dissolved lithium (Li)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Dissolved solids: Residue on evaporation at 180°C	Dissolved solids: Calculated				
130,000	22	1.9	26	12,000	12,000	228,000	--	--	1.145	--	GS
170,000	56	5.6	68	23,000	23,000	300,000	--	--	1.187	--	GS
190,000	37	3.4	54	16,000	16,000	329,000	--	--	1.204	--	GS
180,000	72	7.5	88	25,000	25,000	319,000	--	--	1.197	--	GS
200,000	68	6.8	43	25,000	25,000	336,000	--	--	1.201	--	GS
150,000	32	1.9	30	11,000	11,000	249,000	--	--	1.156	--	GS
3,400	--	.96	--	520	370	--	6,260	11,000	--	7.7	GS
140,000	16	1.4	16	7,800	7,800	251,000	--	--	1.158	--	GS
34,000	8.4	6.8	11	2,400	2,000	56,500	--	--	1.036	--	GS
170,000	48	2.5	69	15,000	15,000	288,000	--	--	1.179	--	GS
50,000	10	1.1	14	5,100	5,000	87,000	--	--	1.055	--	GS
130,000	26	1.8	41	10,000	10,000	225,000	--	--	1.142	--	GS
130	--	--	--	65	0	--	329	594	--	7.4	GS
520	--	--	--	350	250	--	918	1,640	--	7.5	GS
190,000	8.0	2.5	22	9,300	9,200	324,000	--	--	1.202	--	GS
180,000	10	1.7	17	7,700	7,700	302,000	--	--	1.189	--	GS
3,100	--	--	--	460	280	--	5,700	10,200	--	7.5	GS
3,700	--	--	1.2	--	--	--	--	--	--	--	K
76,800	--	--	18	--	--	--	--	--	--	--	K
110,000	8.4	1.5	16	7,000	7,000	196,000	--	--	1.125	--	GS
180,000	110	8.1	140	36,000	36,000	314,000	--	--	1.194	--	GS
77,000	33	13	21	10,000	10,000	136,000	--	--	1.087	--	GS

wells were approximately at the land surface; by the end of 1965, water levels were 18-20 feet below the land surface (Turk, 1969, p. 74). As hydrostatic pressure in the alluvial-fan aquifer was lowered by pumping, the prepumping hydraulic gradient toward the playa and direction of leakage from the aquifer to the playa was reversed. The potentiometric surface in the alluvial-fan aquifer was lowered below the head in the lacustrine deposits, and brine from the playa leaked into the aquifer.

Stephens (1974, p. 16) reports that one of the wells along the western edge of the Bonneville playa was flowing again in 1972. The potentiometric surface in the aquifer was raised by increased recharge from above-normal precipitation throughout most of the 1960's and early 1970's. (See fig. 5.) The hydrograph in figure 31 shows water-level fluctuations since 1962 in the alluvial-fan aquifer at well (C-1-19) 3ddb-1. The peaks and troughs in the hydrograph do not cor-

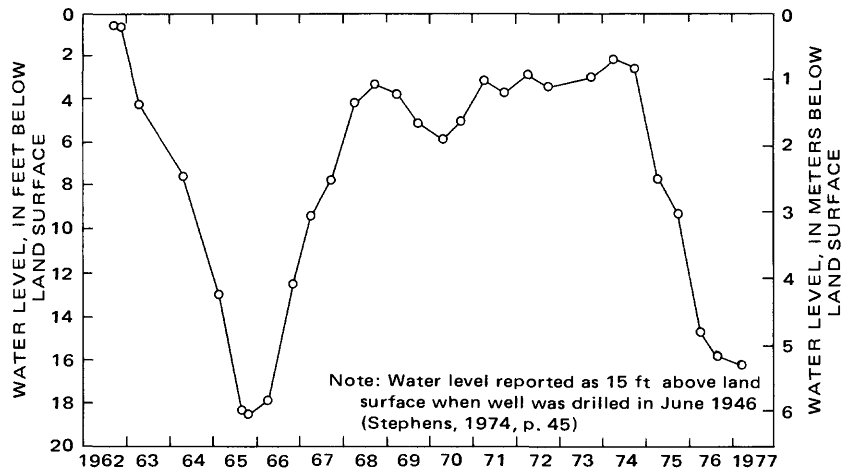

FIGURE 31.—Water level in the alluvial-fan aquifer at well (C-1-19)3ddb-1 along the western margin of the Bonneville playa, August 1962-March 1977.

relate precisely with highs and lows in precipitation recorded at Wendover, but the correlation is fairly good.

Continuous water-level data in the alluvial-fan aquifer were collected at well (B-1-18) 31acc-1 during the course of this study. (See fig. 32.) Comparison of the hydrograph with monthly precipitation (fig. 6) shows that the aquifer responds quickly to changes in precipitation and that the aquifer receives a significant percentage of total recharge from precipitation. The water level in the well was low in March 1976 following a relatively dry winter, and it peaked in June 1976 following wet months during the preceding April and May. Water levels were again low during the latter part of December 1976 following abnormally low precipitation during the fall of 1976.

Pumping from the alluvial-fan aquifer along the western margin of the Pilot Valley playa for irrigation and domestic use has not been great enough to reverse the hydraulic gradient and movement of water through the aquifer toward the playa. During the course of this study, the potentiometric surface in the alluvial-fan aquifer was several feet higher than the surface of the playa, and water was leaking from the aquifer into the lacustrine deposits. In fact, the quantity of water moving through the alluvial fan toward the playa exceeded the amount of water that could be transmitted through the lacustrine deposits under existing hydraulic gradients; thus, much of the water was discharged by springs and was evaporated and transpired by plants at the toe of the alluvial fan.

RECHARGE AND DISCHARGE

Recharge to the alluvial-fan aquifer along the east flank of the Silver Island Mountains is from infiltration of precipitation and subsurface inflow from adjacent aquifers. Discharge from the aquifer is primarily by transpiration of phreatophytes and pumping from wells.

Stephens (1974, p. 10 and 19) estimates that an average of about 1,200 acre-feet per year is recharged to the alluvial-fan aquifer along the east flank of the Silver Island Mountains by infiltration of precipitation and that a slightly smaller amount is transpired by phreatophytes. Prior to pumping from the aquifer, a small amount of water—about 30 acre-feet—is estimated to have been discharged by leakage to the shallow-brine aquifer on the playa. Estimated discharge from the four wells that supply water for the potash operation is about 800 acre-feet per year. Because the potentiometric surface in the aquifer along the edge of the playa has dropped 25-35 feet since the wells were drilled in the late 1940's, some water has been removed from storage in the aquifer and confining layers. In addition to the reversal of the hydraulic gradient so brine now leaks from the playa into the aquifer, there has probably been an increase in upward leakage of warm water from Paleozoic rocks or the basin-fill aquifer. Available data are inadequate to provide a basis for estimating leakage to the aquifer from each source, but total leakage is less than the 800 acre-feet per year that is pumped.

In Pilot Valley, the alluvial-fan aquifer is recharged mainly by infiltration of precipitation and subsurface inflow from adjacent aquifers. Discharge from the aquifer is mainly by evapotranspiration of phreatophytes. Small amounts of water are also discharged by wells and springs, and some water leaks to the shallow-brine aquifer.

WATER CHEMISTRY

Water from the alluvial-fan aquifer along the western edge of the Bonneville playa, at least in the vicinity of pumping wells, contains about 6,000 mg/L of dissolved solids. Water from the aquifer along the western margin of the Pilot Valley playa contains less than 1,000 mg/L of dissolved solids. Chemical analyses of water from the alluvial-fan aquifer at selected wells and springs are listed in table 4.

Water in the alluvial-fan aquifer along the western edge of the Bonneville playa has probably become more saline since pumping from the aquifer started in the late 1940's because of leakage of playa brine into the aquifer. Unfortunately, chemical analyses of water from the aquifer that may have been collected prior to 1967 were unavailable to the writer. Turk (1969, p. 76) states that mixing of

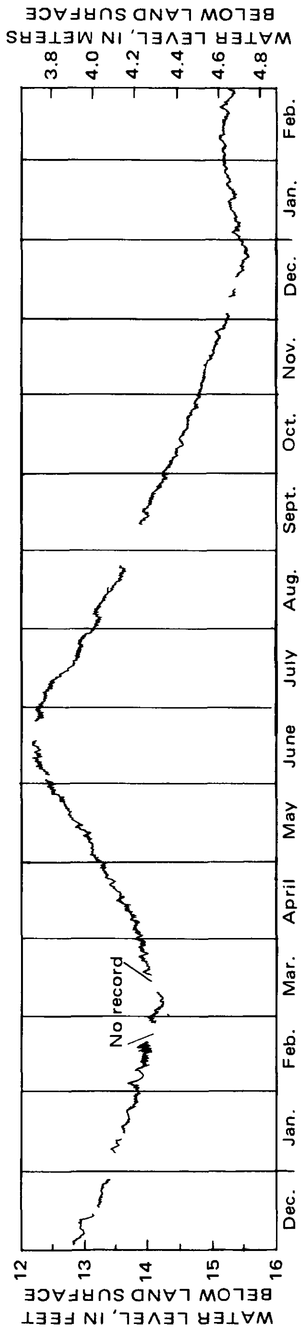

FIGURE 32.—Water level in the alluvial-fan aquifer at well (B-1-18)31acc-1, December 1975-February 1977.

relatively fresh water in the alluvial-fan aquifer with smaller amounts of playa brine has created a more saline water that now predominates in the lower reaches of the fans. Turk presents no early (prior to 1967) chemical analyses to document the degree of deterioration of water quality.

Temperatures of water pumped from the alluvial-fan aquifer are abnormally high along the western margin of the Bonneville playa and indicate that some water in the aquifer has experienced deep circulation to depths of 1,000-2,000 feet. At the time Kaiser's wells were drilled in the late 1940's, the temperature of water was reportedly a consistent 24°C (Stephens, 1974, p. 44 and 45), or about 13°C higher than the mean annual air temperature. By August 1967, water temperatures in at least four of the wells had risen 1.5°-11°C (Turk, 1969, p. 78). In April 1977, the temperature of water that was discharged by the four pumping wells ranged from 24.5° to 33.5°C. The large variation in temperature (9°C) of water discharged from the four wells may indicate that in short distances there are large variations in the relative percentages of water recharged to the aquifer from different sources (precipitation, leakage from the shallow-brine aquifer, and upward leakage of deeply circulated water). Temperatures of water from the alluvial-fan aquifer that is discharged by wells and springs along the western margin of the Pilot Valley playa range from 13.5° to 16.0°C (Stephens, 1974, p. 32 and 33). This is only a few degrees warmer than the mean annual air temperature.

SHALLOW-BRINE AQUIFER

LITHOLOGY AND THICKNESS

The near-surface carbonate muds and interbedded oolitic sands and the crystalline gypsum and halite (salt crust) compose the shallow-brine aquifer. Because almost all the brine that is used for the production of potash on the Bonneville Salt Flats is obtained from the shallow-brine aquifer and the salt crust provides the racing surface, this aquifer was studied in greater detail than the rest of the ground-water system.

The carbonate muds extend to considerable depth beneath both the Bonneville Salt Flats and the Pilot Valley playa. But only the muds in the upper 15-25 feet, in a zone of relatively high permeability, are considered as part of the aquifer on the Salt Flats. Where the carbonate muds are exposed along the edges of brine-collection ditches, they are broken by numerous open vertical fissures that have a maximum width of about 1 inch. The depth to which the fissures extend undoubtedly varies, but the maximum depth is probably about 25 feet.

The carbonate muds of the shallow-brine aquifer on the Salt Flats are strikingly similar to zones of relatively high permeability found near the surface on numerous other playas in the Southwestern United States. Motts (1970, p. 122), in studying Coyote Playa in southern California, finds that the playa muds have a zone of high permeability in the upper 10-25 feet. Motts attributes the high permeability to fissures of giant polygons that range from 100 to 250 feet across. The fissures on Coyote Playa, like those on the Bonneville Salt Flats, are considerably more extensive than their surface expression indicates. On the Salt Flats, the giant polygons are evident on the surface only on the sulfate and chloride zones where there is a seasonal buildup of salt ridges from evaporation of ground water along the fissures. On the carbonate zone, where the muds are exposed on the surface, the fissures have probably been filled with reworked mud, and they have no surface expression.

The Bonneville salt crust is also broken by a large number of fissures that form small desiccation polygons. These range in width from about 3 to 10 feet, and the fissures extend down through that part of the crust that is affected by seasonal desiccation, usually the upper few inches.

Neal and others (1968, p. 83), in their study of giant polygons on playas throughout the Great Basin, state that the fissure spacing (the width of polygons) is generally about 10 times the fissure depth. Most of the giant polygons on the Salt Flats are between 150 and 200 feet wide. Applying the findings of Neal and others to the Salt Flats, most of the fissures of giant polygons may extend to a depth of 15-20 feet, and fissures of smaller polygons may extend to a depth of less than 1 foot.

Several hypotheses have been suggested for the formation of the fissures in carbonate muds. Neal and others (1968, p. 88) believe that the fissures of giant polygons are due to desiccation over a long period of time. Turk and others (1973, p. 76 and 77) believe that the most reasonable explanation of the mechanism of fissuring is that the sediments have undergone subaqueous shrinkage by a process of osmosis or syneresis, or both.

No fissures were observed on the surface of the Pilot Valley playa, but this does not preclude their existence because the fissures also have no surface expression on much of the Bonneville playa. In augering the 14 observation wells in Pilot Valley, less permeable material was found with increased depth, and brine flow into the holes decreased with an increase in depth to water. In none of the auger holes in Pilot Valley was a flow of brine found that would indicate an open fissure. The permeability of the aquifer decreases with depth, and the shallow-brine aquifer in the center of the playa appears to be limited to about the upper 10 feet of carbonate muds, oolitic sands, and gypsum.

AQUIFER CHARACTERISTICS

The porosity of the carbonate muds of the shallow-brine aquifer on the Bonneville Salt Flats has been determined from numerous wet and dry bulk-density measurements, and the porosity averages 45 percent (Turk, 1969, p. 104). Turk and others (1973, p. 69) report that gravity drainage of saturated material from the shallow-brine aquifer indicates a specific yield of about 10 percent.

Aquifer tests indicate a large variation in the transmissivity of the shallow-brine aquifer on the Bonneville Salt Flats. The transmissivity map (fig. 33) is based on aquifer tests that were conducted by Turk and by Kaiser personnel between 1965 and 1967 and that had results rated as "good" or better by Turk (1973, table 9). Four aquifer tests conducted in 1976 for this study were also used. Figure 33 is based on aquifer tests that were conducted over a 12-year span, and in some areas it may not accurately depict transmissivity values as they were in 1976. Thus, the map is presented only to show the general pattern of variability of the transmissivity.

Transmissivity is the arithmetic product of the hydraulic conductivity[4] of aquifer material and its thickness. Because of water-level fluctuations, the thickness and transmissivity of the aquifer are subject to change, particularly in the unconfined portions of the aquifer. However, the water-level changes during the 12-year period of 1965-76 have not been great enough to appreciably alter the general pattern of increasing transmissivity from the edges of the playa toward the salt crust.

A summary of the four aquifer tests conducted for this study is presented in table 5. Three of the tests were designed so that pumping wells would tap only the carbonate muds and interbedded oolitic sands that underlie the crystalline halite and gypsum. The fourth test, at site (B-1-17)11aaa, was in an area with an insignificant thickness of halite and gypsum. Values of transmissivity determined from the four tests range from 490 to 8,100 ft^2/d. The values of several thousand feet squared per day were determined from two tests in areas where the crystalline halite and gypsum had a thickness of 2-

[4]The hydraulic conductivity of a water-bearing material is the volume of water that will move through a unit cross section of the material in unit time under a unit hydraulic gradient. The units for hydraulic conductivity are cubic feet per day per square foot $[(ft^3/d)/ft^2]$, which reduces to ft/d. The term hydraulic conductivity replaces the term field coefficient of permeability, which was formerly used by the U.S. Geological Survey and which was reported in units of gallons per day per square foot. To convert a value for field coefficient of permeability to the equivalent value of hydraulic conductivity, divide by 7.48; to convert from hydraulic conductivity to coefficient of permeability, multiply by 7.48.

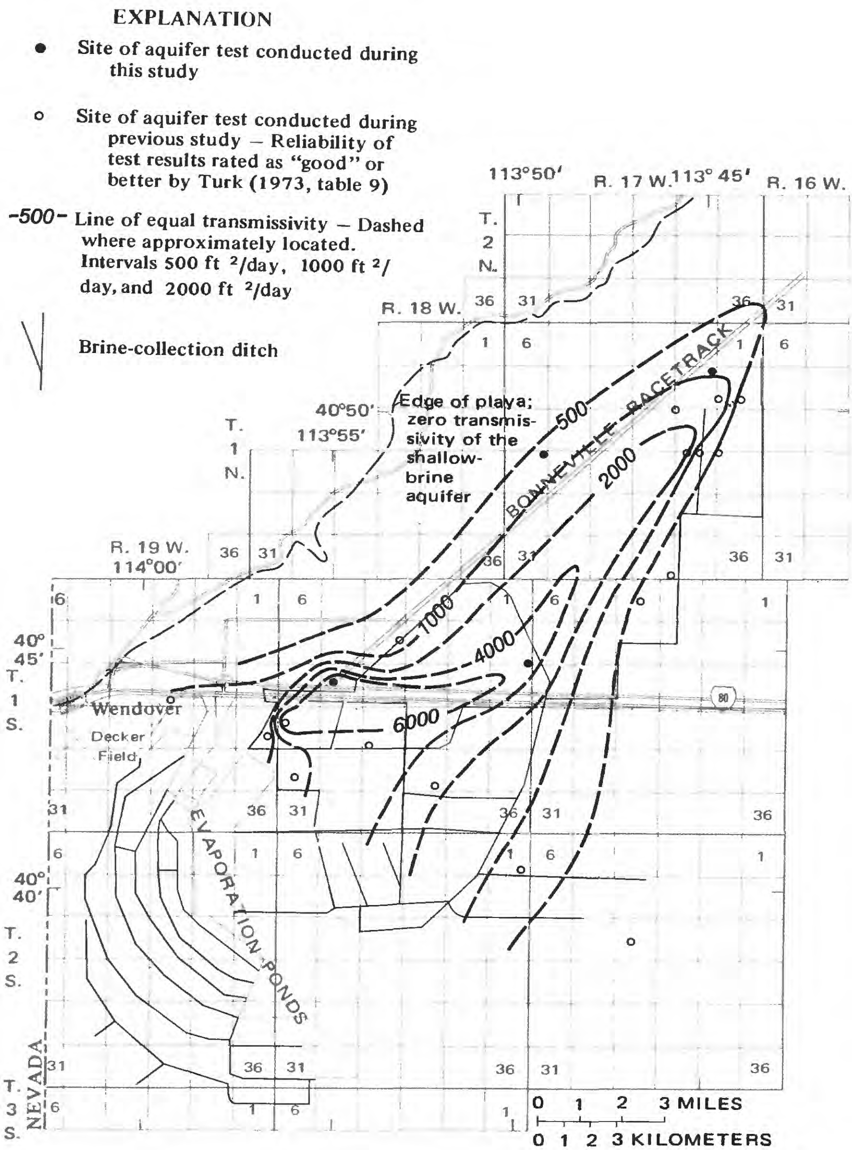

FIGURE 33.—Transmissivity of the shallow-brine aquifer on the Bonneville Salt Flats.

3 feet; such high values reflect the presence of fissures in the carbonate muds, the presence of the halite and gypsum, and the hydraulic connection of the halite and gypsum with the underlying muds.

Storage coefficients determined from the four tests ranged from 3.8×10^{-3} to 4.1×10^{-4} indicating that water in the carbonate muds

TABLE 5—*Summary of four aquifer tests conducted on the Bonneville Salt Flats during the summer of 1976 to determine properties of the shallow-brine aquifer and hydraulic connection between the carbonate muds and overlying salt crust and gypsum*

Methods used to analyze test data: 1, Boulton method for unconfined aquifers having delayed yield from storage (Lohman, 1972, p. 34-40); 2, Boulton-Stallman method for anisotropic unconfined aquifers (Lohman, 1972, p. 34-38); 3, Hantush modified method for leaky confined aquifers (Lohman, 1972, p. 30-32).
Remarks: Sp.C, specific capacity of pumped well in gallons per minute per foot of drawdown; C, salt crust and gypsum on surface were cemented off and well taps only the underlying carbonate muds; S, well taps only the salt crust and gypsum on the surface.

Location of test	Time-weighted average discharge (gal/min)	Duration of test (min)	Depth of well (ft)	Perforated interval (ft below land surface)	Distance from pumped well (ft) and direction	Static water level (ft below land surface)	Maximum draw-down (ft)	Transmissivity (ft^2/d)	Storage coefficient	Methods used to analyze test data	Remarks
(B-1-17)11aaa ---------	9.9	500	19	4-19	--	0.76	4.54	---	---	---	Sp.C 2.2
			19	9-19	100, south	.77	.60	800	2.9×10^{-3}	1; 2	
								760	2.9×10^{-3}	3	
(B-1-17)19aaa ---------	11	500	19	4-19	--	.97	3.40	---	---	---	Sp.C 3.2; C
			16	6-16	100, east	1.10	.65	620	1.7×10^{-3}	1	C
								720	2.0×10^{-3}	2	
								490	1.6×10^{-3}	3	
			2	1-2	100, east	1.03	.11	(1)	(1)	---	S
(C-1-18)12ddd --------	110	4,200	19	4-19	--	.66	9.79	---	---	---	Sp.C 11; C
			16	6-16	100, northeast	.62	1.86	5,300	5.9×10^{-4}	2	C
								5,800	4.8×10^{-4}	3	
			9	7-9	250, southwest	.68	1.45	5,000	5.6×10^{-4}	2	
								6,000	4.3×10^{-4}	3	
			9	7-9	500, northwest	.69	1.04	6,400	4.1×10^{-4}	2	
								5,600	4.4×10^{-4}	3	
			2	1-2	100, northeast	.52	.50	(1)	(1)	---	S
(C-1-18)17bd ----------	90	2,800	19	4-19	--	.68	4.91	---	---	---	Sp.C 18; C
			19	9-19	100, north	.77	1.26	5,500	3.8×10^{-3}	1	C
								6,000	3.4×10^{-3}	3	
			19	4-9	250, west	1.67	.79	7,300	2.1×10^{-3}	1	
								8,100	2.1×10^{-3}	3	
			19	9-19	570, south	1.84	.52	6,900	2.1×10^{-3}	1	
								8,100	2.1×10^{-3}	3	
			2	1-2	100, north	.55	.38	(1)	(1)	---	S

[1]Could not be determined as time-drawdown data did not fit any of the type curves for aquifer-test analysis.

and oolitic sands is semiconfined to confined. Storage coefficients determined from the tests conducted between 1965 and 1967 range from 1.2 x 10^{-1} to 5 x 10^{-5} (Turk, 1973, table 9), indicating that both unconfined and confined conditions exist. The larger values of storage coefficient from these earlier tests can be attributed to a significant amount of water being pumped from the crystalline halite and gypsum, which contain brine under unconfined conditions.

The range in values of storage coefficients is reasonable in view of the manner in which water is transmitted by the aquifer: by flow through the spaces between halite and gypsum crystals, by intergranular flow through the thin beds of oolitic sand, and by flow through open fissures. Confinement in the carbonate muds would be expected in areas where the vertical fissures are sparse and hydraulic continuity is poor. Where fissures are abundant, hydraulic continuity would be greater, and unconfined to semiconfined conditions in the carbonate muds and oolitic sands would exist.

In three of the aquifer tests conducted for this study, the pumping wells were sealed from the crystalline halite and gypsum by cementing around the well casings to a depth of at least 0.5 foot into the underlying carbonate mud. By drilling 24-inch wells and using a gravel pack between the casing and the mud, well yields of 90 and 110 gal/min were obtained in areas where the transmissivity of the aquifer was greatest. As shown in table 5, by pumping 110 gal/min for 4,200 minutes from the carbonate muds at test site (C-1-18)12ddd, 1.86 feet of drawdown was induced in the carbonate muds 100 feet from the pumped well, whereas the drawdown in the observation well that tapped the overlying halite and gypsum 100 feet from the pumped well was 0.50 foot. Drawdown in the halite and gypsum was also induced at two of the other sites (C-1-18)17bd and (B-1-17)19aaa, by pumping from the underlying carbonate muds.

The amount of drawdown that was induced in the halite and gypsum during the three tests was proportional to the rate and duration of pumping from the carbonate muds. Drawdowns in the carbonate muds and in the halite and gypsum at the same distance from the pumping well were not the same, thus indicating that the vertical continuity is affected by changes in vertical hydraulic conductivity. But the carbonate muds and overlying salt crust are hydraulically connected; in even the relatively short time periods of the tests, brine from the salt crust and gypsum leaked into the underlying carbonate muds. Vertical hydraulic conductivities computed from the aquifer tests ranged from 30 to 140 ft/d.

No aquifer tests were conducted on the shallow-brine aquifer in Pilot Valley. However, transmissivity of the aquifer is probably on the order of a few hundred feet squared per day, and the storage coefficient probably ranges from 10^{-5} to 10^{-3}.

POTENTIOMETRIC SURFACE

The configuration of the potentiometric surface in the carbonate muds of the shallow-brine aquifer on the Bonneville Salt Flats in the spring of 1976, prior to the seasonal withdrawal of brine, is shown in figure 34 (uncorrected for brine density). Hydraulic gradients indicate that the movement of brine through the aquifer was from the

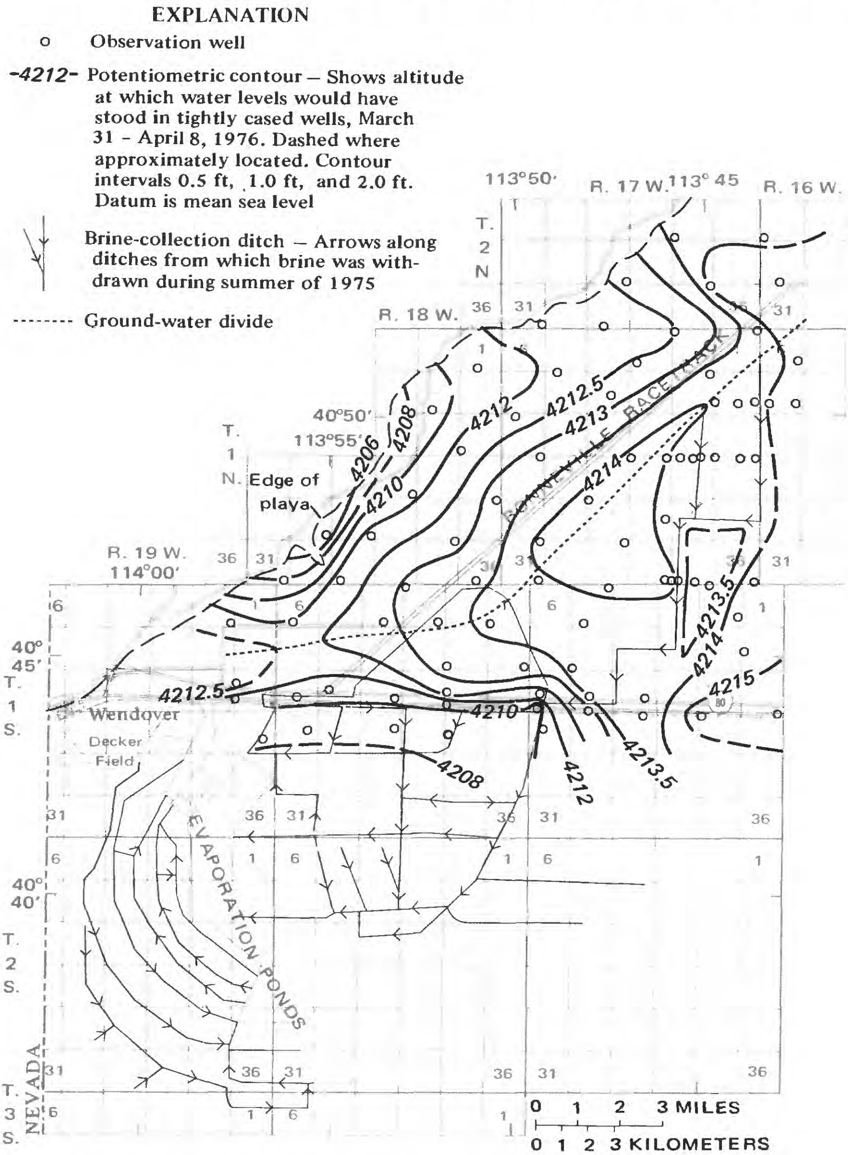

FIGURE 34.—Potentiometric surface in the carbonate muds of the shallow-brine aquifer on the Bonneville Salt Flats, spring of 1976.

area of the salt crust toward points of discharge—the brine-collection ditches both east and south of the Bonneville Racetrack and the alluvial-fan aquifer along the western edge of the playa.

Figure 35 shows the potentiometric surface in the fall of 1976 (uncorrected for brine density) following the seasonal withdrawal of brine during the previous summer. Comparison of figures 34 and 35 indicates little change in the configuration of the potentiometric surface in the areas west and south of the racetrack. But there was a significant change in the area of the brine-collection ditches east of the racetrack.

In the fall of 1976, the hydraulic gradient in the center of the playa, where there is a significant thickness of salt crust, ranged from 0.3 to 0.5 ft/mi. In the immediate vicinity of brine-collection ditches, and along the western edge of the playa, the gradient was steeper and was as much as 6 ft/mi.

The configuration of the potentiometric surface in the shallow-brine aquifer in Pilot Valley in the fall of 1976 is shown in figure 36 (uncorrected for brine density). Hydraulic gradients indicate that the movement of brine is toward the salt crust. Gradients in Pilot Valley ranged from as little as 0.2 ft/mi in the area underlying the salt crust to as much as 6 ft/mi along the southeastern edge of the playa.

To determine the directions of brine movement and locations of ground-water divides more accurately, the potentiometric surface was corrected for differences in the density of the brine. In both the Bonneville and Pilot Valley playas, the density of brine in the shallow-brine aquifer generally increases from the edges of the playa toward the salt crust. Densities in the shallow-brine aquifer vary from about 1.01 to 1.21 g/mL on the Bonneville Salt Flats and from about 1.02 to 1.20 g/mL in Pilot Valley. A column of brine 10 feet high with a density of 1.02 g/mL could be balanced with a column of brine with a density of 1.20 g/mL that is only 8.5 feet high. Thus, if there was a 0.18 g/mL change in brine density over a distance of 5 miles, an apparent hydraulic gradient of 0.3 ft/mi could be balanced by the density difference, and no flow would occur through the aquifer.

On the Bonneville Salt Flats, gradients indicated by the density-corrected potentiometric surface (fig. 37) are generally greater than the apparent gradients (fig. 35) because brine densities are generally greatest in areas with the highest potentiometric surface. On the Pilot Valley playa, just the opposite is true; the gradients of the density-corrected potentiometric surface (fig. 38) are less than the apparent gradients (fig. 36) because brine densities are generally least in areas with the highest potentiometric surface.

To correct the potentiometric surface for differences in water density, the base of the shallow-brine aquifer was assumed to be at a uniform altitude of 4,190 feet on the Bonneville Salt Flats and at 4,230 feet in Pilot Valley. The base of the aquifer in both areas undoubtedly is not uniform. Considering other hydrologic properties, such as depth of fissuring and a decrease in permeability with depth,

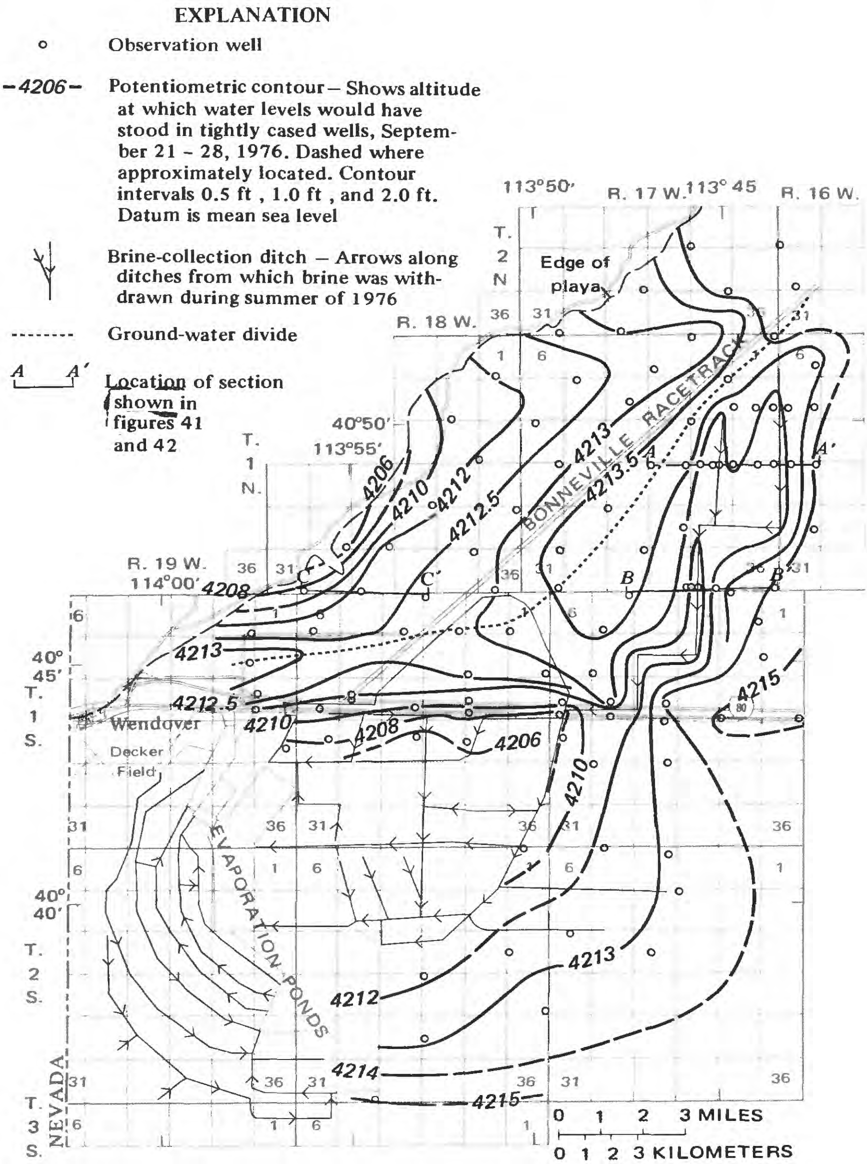

FIGURE 35.—Potentiometric surface in the carbonate muds of the shallow-brine aquifer on the Bonneville Salt Flats, fall of 1976.

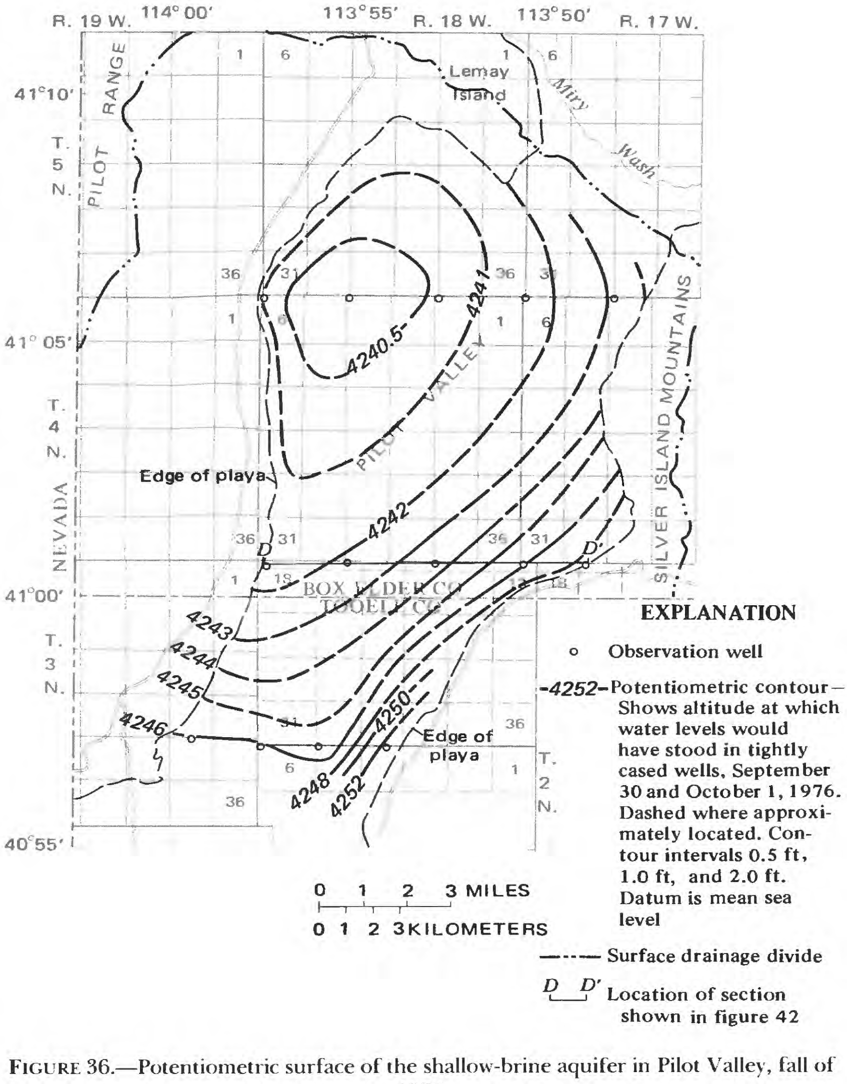

FIGURE 36.—Potentiometric surface of the shallow-brine aquifer in Pilot Valley, fall of 1976.

however, the assumed uniform base is probably a good approximation, particularly in the central parts of both playas.

Ground water moves approximately at right angles to potentiometric contours. The major ground-water divide on the Salt Flats in the fall of 1976 (fig. 37) indicates that brine in the shallow-brine aquifer underlying the south end of the racetrack was draining toward brine-collection ditches south of Interstate Highway 80. Toward the north, the divide turned to the east and was as much as 1.5 miles east of the central part of the racetrack. Brine under the central part

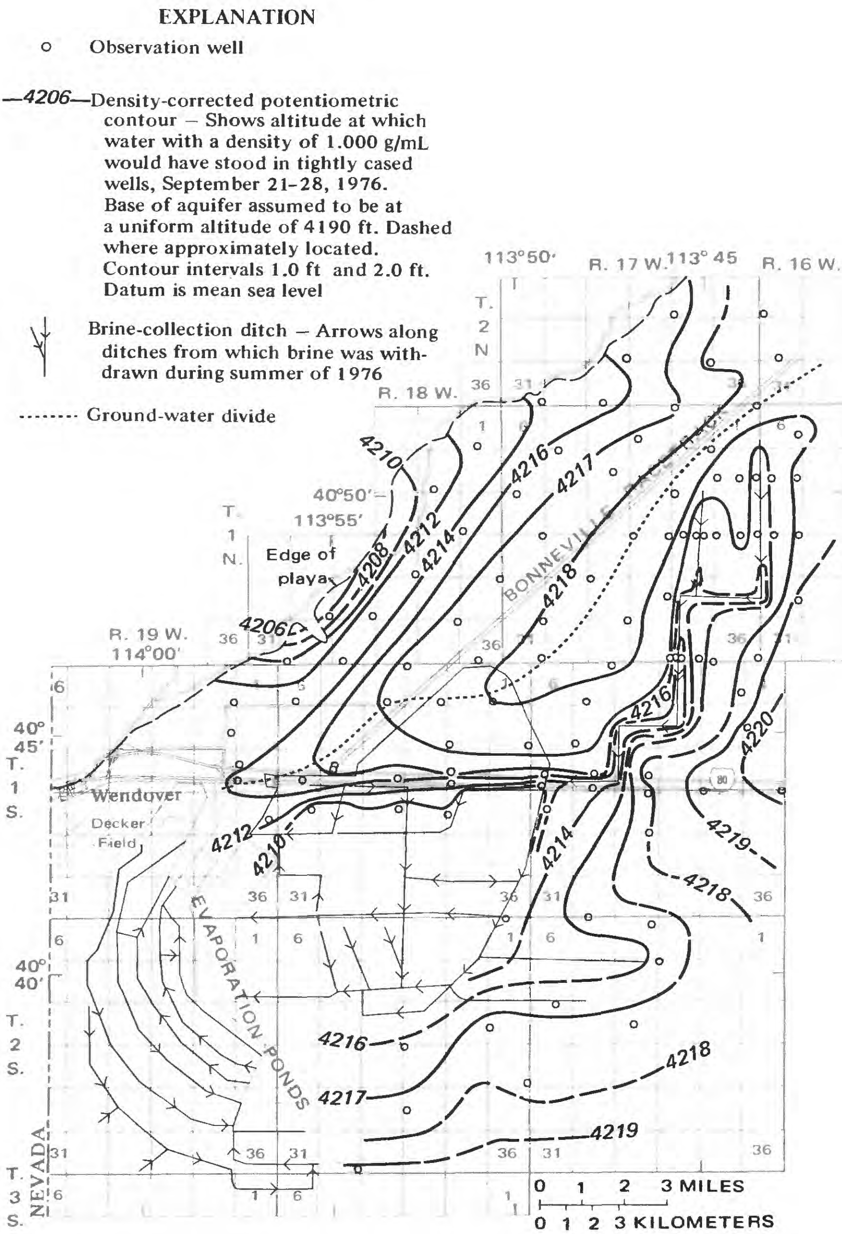

FIGURE 37.—Density-corrected potentiometric surface in the carbonate muds of the shallow-brine aquifer on the Bonneville Salt Flats, fall of 1976.

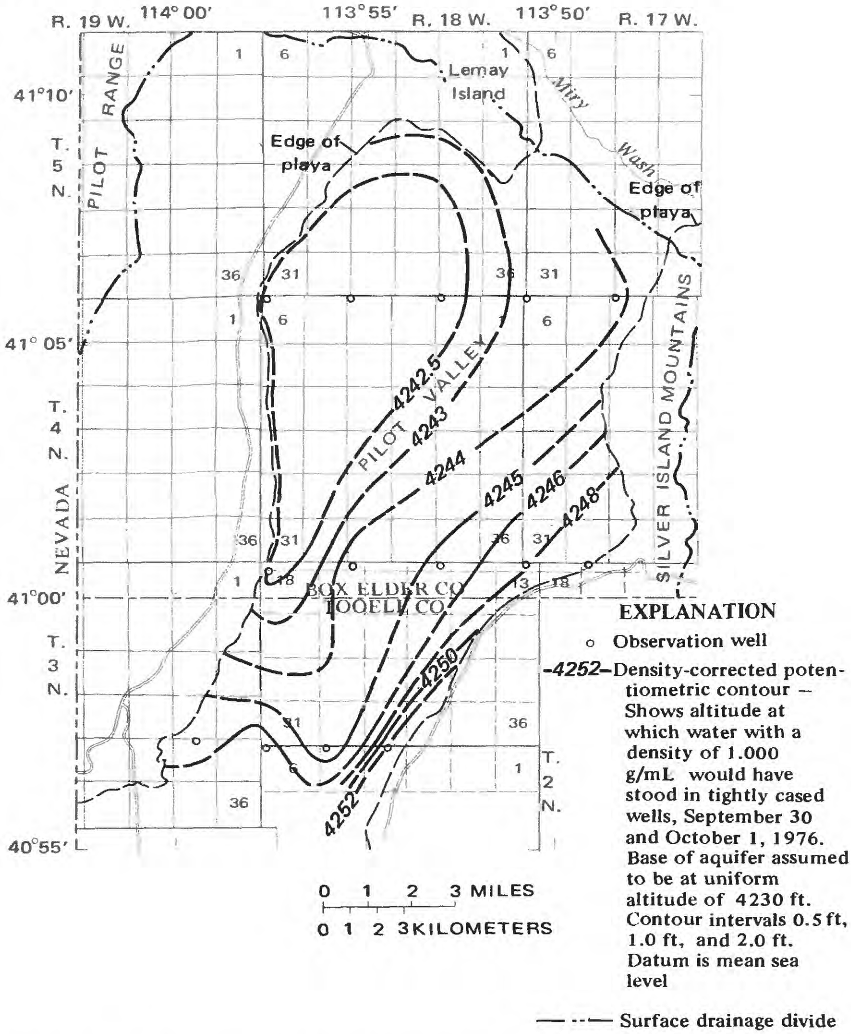

FIGURE 38.—Density-corrected potentiometric surface of the shallow-brine aquifer in Pilot Valley, fall of 1976.

of the racetrack was flowing toward the Silver Island Mountains where leakage of brine from the playa has been induced by pumping from the alluvial-fan aquifer. Continuing north, the divide turned back to the west and was within a few hundred feet of the racetrack.

The location of the ground-water divide east and south of the brine-collection ditches is unknown, but it is probably several miles beyond the limits of the map. Southeast of the evaporation ponds, brine was flowing through the shallow-brine aquifer toward brine-collection ditches from a distance exceeding 3 miles.

The major ground-water divide in the shallow-brine aquifer on the Salt Flats does not conform to any surface-drainage divide. The ground-water divide has no influence on the movement of wind-driven floods of surface brine which have been observed carrying dissolved salt across the ground-water divide, mainly in a southeast direction.

Comparison of figures 34 and 35 indicates that during the brine-collection season of 1976, the divide migrated about 0.5 mile northwest along the northern part of the racetrack but was fairly stable in other areas. The position of the ground-water divide is subject to change and is dependent upon such factors as discharge from the brine-collection ditches, discharge from the alluvial-fan aquifer, and variability of recharge to the aquifer. Recharge to the aquifer depends on variable precipitation and the direction of winds that position surface brine in different areas of the playa during periods of winter flooding.

In addition to lateral changes in the potentiometric surface, the head in the shallow-brine aquifer varies with depth. Figures 34-38 show the head in the lower part of the aquifer in the carbonate muds and oolitic sands. The altitude of the water table in the halite and gypsum, where the brine is at atmospheric pressure, varies somewhat from the potentiometric head for the lower part of the aquifer. The differences in head are due to upward and downward components of flow in the aquifer.

Figure 39 shows that much of the sulfate and chloride zones, particularly south of Interstate Highway 80, was unsaturated in the fall of 1976. North of the highway there is a fairly large area between the racetrack and the brine-collection ditch to the east where an upward component of flow existed. In most of the area, however, the water table in the halite and gypsum was higher than the potentiometric surface for the lower part of the aquifer, and a downward component of flow existed. Prior to brine withdrawals in the area, the salt crust was probably the major area of discharge from the shallow-brine aquifer; during dry periods of the year water moved upward from the carbonate muds to replace water lost by evaporation at the surface of the salt.

Short-Term Changes

Continuous water-level records were obtained at two wells that bottomed in the carbonate muds in the area between the Bonneville Racetrack and the ditch system east of the track (fig. 2). Both of the wells had been drilled to a depth of about 5 feet, gravel packed, and cased with 12-inch open-end casing (Turk, 1969, p. 122). As shown in the hydrograph for well (B-1-17)32bdd-1 (fig. 40), which is repre-

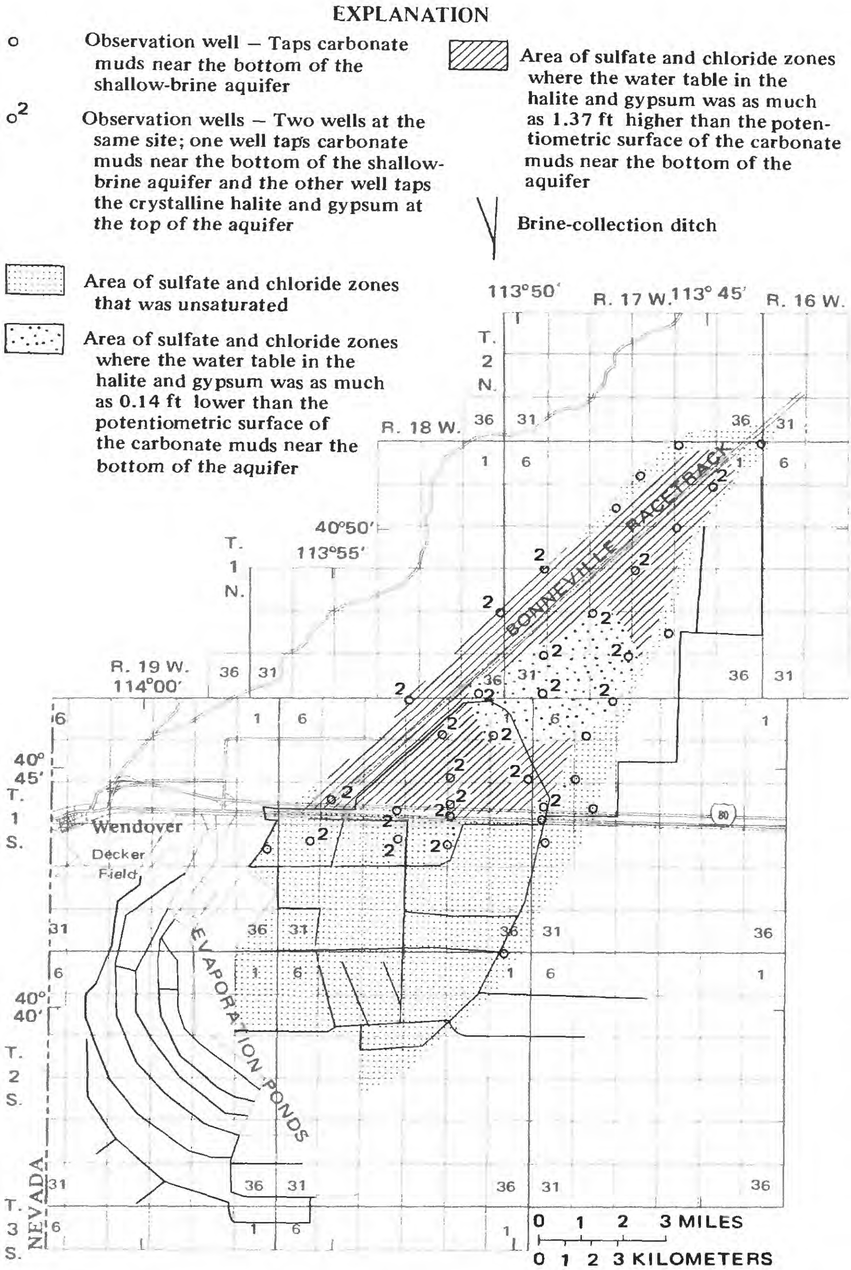

FIGURE 39.—Extent of the water-saturated sulfate and chloride zones and the relation between the water table in the halite and gypsum and the potentiometric surface of the carbonate muds on the Bonneville Salt Flats, September 21–28, 1976.

sentative of the two records, water levels were at or near land surface during the fall of 1975 and winter and spring of 1976 when most of the Salt Flats was flooded with brine. Water levels were maintained within 0.5 foot of the surface during the brine-production season in the summer of 1976 by periodic thunderstorms. All the major rises in water level are due to recharge to the aquifer either directly from precipitation or from floods of surface water moving into the area of the well. Water in the well was at its lowest level during the middle of January 1977 following abnormally low precipitation during the preceding 2 1/2 months.

The potentiometric surface and hydraulic gradients in the shallow-brine aquifer near brine-collection ditches east of the racetrack is shown in two sections in figure 41. The potentiometric surfaces shown in the sections are not corrected for differences in brine density. In the spring of 1976, the potentiometric surface in some areas had not completely recovered from the brine withdrawals made during the summer of 1975. At the section furthest to the south (B-B′), recovery was complete west of the ditch because of the large amount of brine that was ponded in this area during the preceding fall and winter. Winds blowing from the northwest had moved brine across the playa, and the water ponded behind the interstate highway and the tailings pile along the ditch. Drawdowns were greatest around the ditches in the fall of 1976, at the end of the brine-collection season. Because a very dry fall followed the 1976 brine-collection season, recovery of the potentiometric surface around the ditches was not complete as indicated by measurements made on January 5, 1977. Any recovery in the potentiometric surface near the ditches during the fall of 1976 was due entirely to lateral inflow from adjacent areas of the aquifer.

LONG-TERM CHANGES

The configuration of the potentiometric surface and directions of brine movement through the shallow-brine aquifer on the Bonneville Salt Flats has been changed by two activities of man: (1) direct withdrawals of brine from the aquifer by ditches and (2) leakage from the aquifer along the western margin of the playa that has been induced by pumping from the alluvial-fan aquifer. Figure 42 shows a section along the western edge of the Bonneville playa and the potentiometric surfaces of the shallow-brine aquifer in the summer of 1925 and in the fall of 1976. The potentiometric surface in the summer of 1925 was reconstructed from water-level measurements recorded in Nolan's (1928) field notes on file with the Geological Survey in Salt Lake City and level lines run during the course of this study. In the summer of 1925, prior to pumping from the alluvial fan, movement

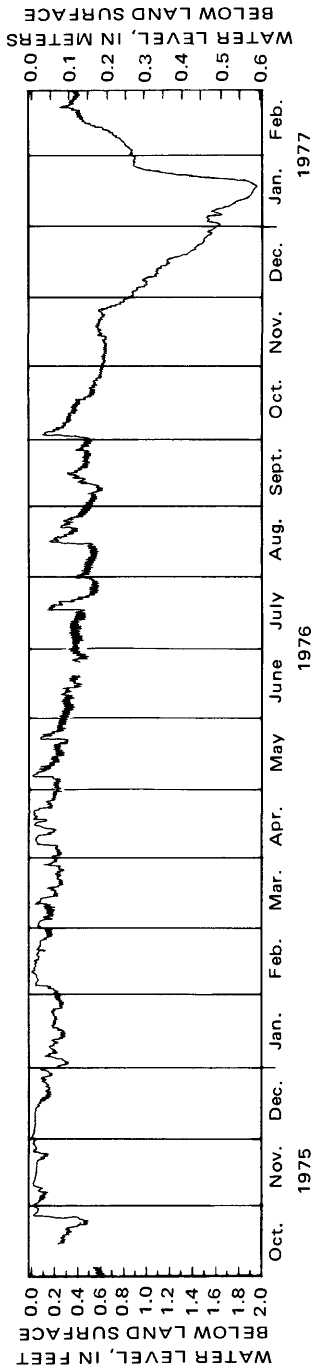

FIGURE 40.—Water level in the shallow-brine aquifer at well (B-1-17)32bdd-1, October 1975-February 1977.

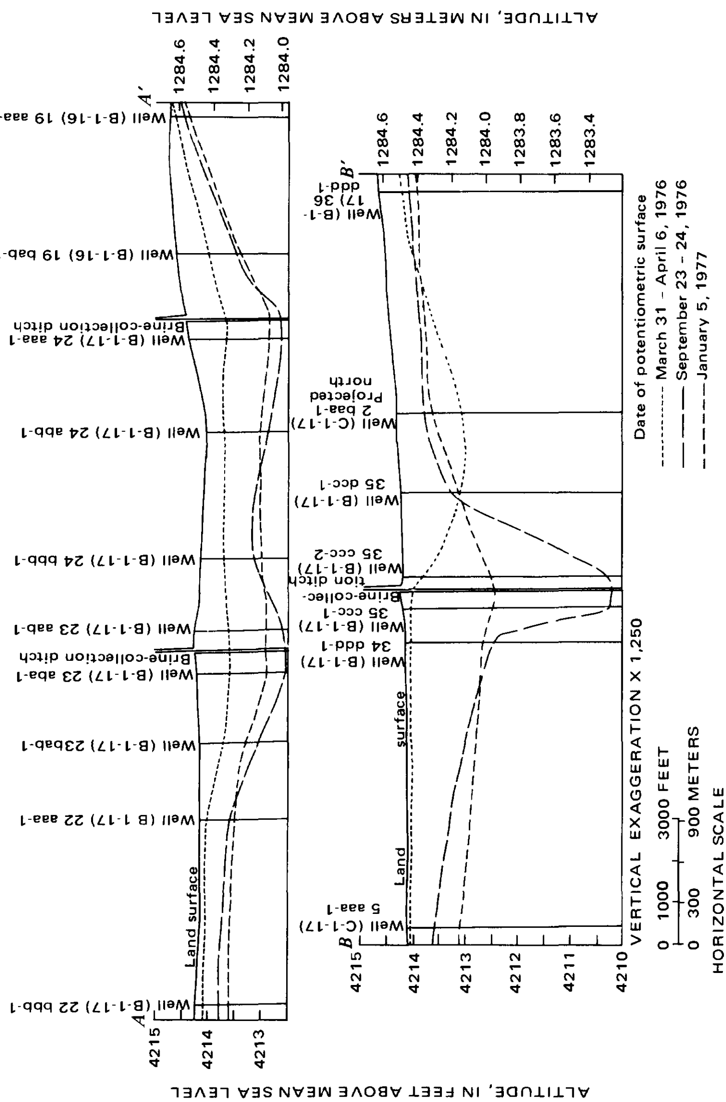

FIGURE 41.—Seasonal changes in the potentiometric surface of the shallow-brine aquifer near brine-collection ditches east of the Bonneville Racetrack. (Trace of sections shown in fig. 35.)

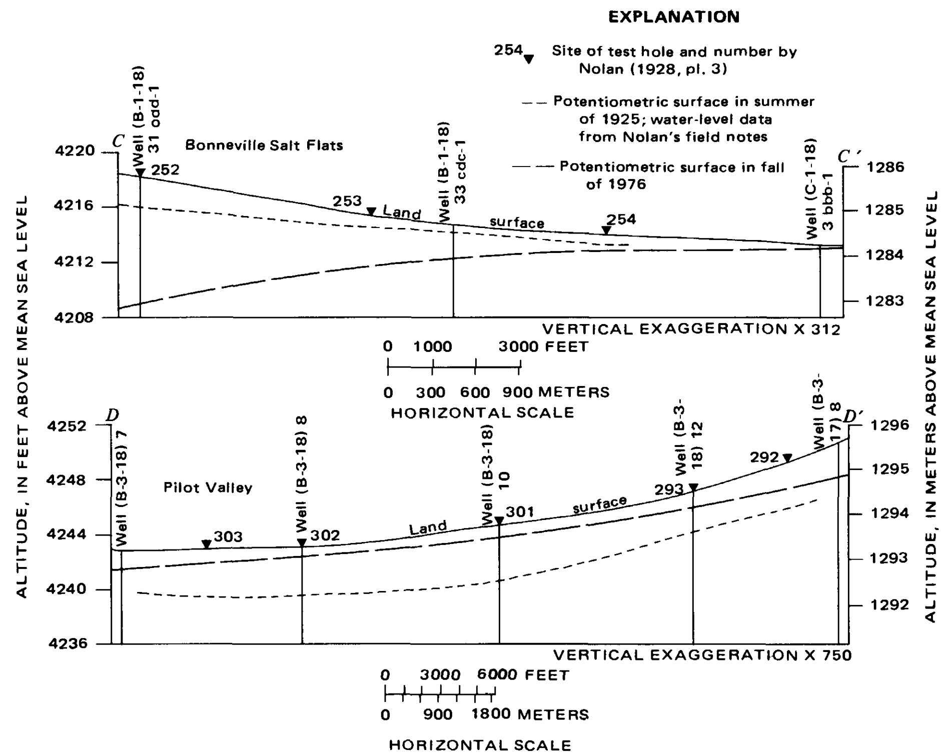

FIGURE 42.—Changes in the potentiometric surface of the shallow-brine aquifer between 1925 and 1976 along the western edge of the Bonneville Salt Flats and in the central part of Pilot Valley. (Trace of section on the Salt Flats shown in fig. 35; trace of section in Pilot Valley shown in fig. 36.)

of brine through the shallow-brine aquifer was from the edge of the playa toward the salt crust. The aquifer was receiving some subsurface recharge from the alluvial-fan aquifer. Conditions in 1925 were probably similar to those found in Pilot Valley during the course of this study (figs. 36 and 38). In the fall of 1976, however, movement in the shallow-brine aquifer was toward the edge of the Bonneville playa, and brine was leaking back into the alluvial-fan aquifer. As indicated in figure 42, at well (B-1-18)31ddd-1, the same site as Nolan's test hole 252 (Nolan, 1928, pl. 3), the water level was 7 feet lower in the fall of 1976 than in the summer of 1925.

By contrast, section D-D′ in figure 42 shows that the configuration of the potentiometric surface and directions of brine movement in Pilot Valley have not changed appreciably between 1925 and 1976. In 1925 and 1976, brine was moving from the edges of the playa toward the lowest area of the playa in the northwest corner, the area that was covered with a salt crust. Comparison of water levels in wells along this section and in other areas of the playa indicate that the potentiometric surface was 1-4 feet higher in 1976 than in 1925. The difference is attributed to a relatively recent increase in recharge to the aquifer.

Records at Wendover (fig. 5) show that precipitation during the 13-year period preceding 1925 averaged about 1 inch per year less than precipitation during the 14-year period preceding 1976, the difference being more than 20 percent of the long-term average. The magnitude of wet and dry cycles has probably been somewhat different on the Pilot Valley and Bonneville playas than those recorded at Wendover; however, it is probably safe to assume that the cycles coincide.

To partly summarize, the potentiometric surface of the shallow-brine aquifer in Pilot Valley was higher in 1976 than in 1925. By contrast, the potentiometric surface on the Bonneville Salt Flats, at least in areas where a comparison with 1925 water levels could be made, was lower in 1976 than in 1925, even though the area experienced a wet period extending through most of the 1960's and early 1970's.

Weather cycles may also explain why only 7 mi^2 of salt crust were mapped in Pilot Valley in the fall of 1976, whereas Nolan (1928, pl. 3) mapped about 22 mi^2 in 1925. Because of the wet cycle extending through most of the 1960's and early 1970's, recharge to the shallow-brine aquifer was above normal, and much of the sodium chloride in Pilot Valley was in solution in the aquifer. The same reasoning, of course, can be applied to the Bonneville Salt Flats to attempt to explain why the salt crust in the fall of 1976 covered only about 40 mi^2, whereas in 1925 it covered about 150 mi^2. Unlike Pilot Valley, however, the amount of salt held in solution in the shallow-brine aquifer on the Salt Flats has decreased, as indicated by the decline in the potentiometric surface. The potentiometric surface of the shallow-brine aquifer on the Salt Flats has not risen in response to above-normal precipitation, and discharge from the aquifer in recent years has exceeded recharge. Increased recharge from precipitation, and the accompanying re-solution of the salt crust, have not been great enough to compensate for the loss of brine that has been withdrawn from the aquifer for the production of potash.

RECHARGE AND DISCHARGE

Recharge to the shallow-brine aquifer on the Bonneville Salt Flats during the course of this study was almost all from direct infiltration of precipitation. Infiltration of runoff from precipitation on the Silver Island Mountains contributed only minor amounts of recharge. Some water was contributed by subsurface inflow to the aquifer from beyond the limits of the study area. Discharge from the aquifer was mainly by evaporation from the surface and by gravity flow to brine-collection ditches. Smaller amounts of water were also transpired by phreatophytes and leaked from the aquifer into the alluvial fan along the western edge of the playa.

In Pilot Valley, the aquifer received recharge from the infiltration of precipitation on the playa and from surface-water runoff that resulted from precipitation on adjacent uplands. The aquifer was also recharged by leakage from the alluvial-fan aquifer. Transpiration by phreatophytes and evaporation from the playa surface were the only sources of discharge from the aquifer in Pilot Valley.

Data are lacking to make precise determinations of the amounts of recharge and discharge from all the above sources; however, order of magnitude estimates can be made. Since the main area of concern on the Bonneville Salt Flats lies north of Interstate Highway 80 in the area of the Bonneville Racetrack and the collection of basic data during this study was concentrated in this area, estimates of recharge and discharge in the following sections will pertain only to that area of the Salt Flats. Table 6 is a summary of estimates made for a water budget of the shallow-brine aquifer on the Salt Flats for 1976. Not enough data were collected in Pilot Valley to further refine estimates for the water budget of the playa that were made by Stephens and Hood (1973).

RECHARGE FROM PRECIPITATION

Precipitation infiltrates rapidly on the Bonneville salt crust. Turk (1973, p. 13) estimates that daily precipitation in excess of 0.1 inch in summer and 0.05 inch in winter contributes to recharge in the

TABLE 6.—*Summary of estimates of recharge to and discharge from that part of the shallow-brine aquifer on the Bonneville Salt Flats north of Interstate Highway 80, 1976*

Source of recharge or discharge	Volume of water (acre-ft)
Recharge:	
Infiltration of precipitation and wind-driven floods of surface brine:	
Salt and gypsum surfaces	9,700
Carbonate mud surface	2,000
Subsurface inflow	40
Total (rounded)	12,000
Discharge:	
Evaporation from playa surface:	
Thick perennial salt crust	6,700
Sediment-covered salt crust and gypsum surface	1,000
Carbonate mud surface	2,900
Subsurface flow toward brine-collection ditches south of Interstate 80	2,000
Brine-collection ditch system east of Bonneville Racetrack	680
Transpiration by phreatophytes	300
Leakage to alluvial-fan aquifer	70
Total (rounded)	14,000

[The difference between total recharge and total discharge is due to a decrease in ground-water storage in the shallow-brine aquifer.]

area of thick salt crust. In the winter, however, the salt crust is often completely saturated and flooded with surface brine, and any additional precipitation merely sits on the surface until evaporated or until it can infiltrate into the salt to replace brine that has moved down into the underlying carbonate muds. Recharge to the salt crust also occurs when brine that has been ponded on the surface of the carbonate muds is pushed onto areas of salt crust by strong winds. The hydrograph for well (B-1-17)32bdd-1 in figure 40 indicates that the salt crust in the area of this well experienced 18 major periods of recharge during 1976, which resulted in a cumulative water-level rise of 3.8 feet. Assuming that the same recharge occurred over the entire 40 mi^2 of salt crust and that the specific yield of the aquifer is 10 percent, then approximately 9,700 acre-feet of water was recharged to the Bonneville salt crust north of Interstate Highway 80 either by precipitation or by infiltration of surface brine that was blown off the carbonate muds onto the salt.

Infiltration of precipitation where carbonate muds are exposed on the surface is not as fast as on the salt crust. Infiltration rates reported by Turk and others (1973, p. 73) range from 2.5 to 4.0 ft/d on the salt crust and from 0.4 to 1.4 ft/d in areas of clay and silt. During the fall of 1975 and the winter and spring of 1976, water was ponded on the surface of the carbonate zone for extended periods and yet water levels in wells were often several inches below land surface. These observations indicate that even the infiltration rate of 0.4 ft/d is high, particularly after the initial wetting of the surface muds. Infiltration rates through the muds, at best, are probably only about 10 percent of the infiltration rate through the salt crust. Assuming that the playa muds are recharged at a rate that is one-tenth the rate of recharge on the salt crust, approximately 2,000 acre-feet of water from precipitation recharged the 75 mi^2 of carbonate muds north of Interstate Highway 80 during 1976.

Subsurface Inflow

Inflow to the study area north of the interstate highway, through the shallow-brine aquifer along the eastern and northeastern sides, is very small. Using the density-corrected potentiometric surface map (fig. 37), the transmissivity data (fig. 33), and Darcy's law (Lohman, 1972, p. 10), the estimated subsurface inflow to the area was only about 40 acre-feet during 1976.

Evaporation at Playa Surface

Evaporation of ground water through the playa surface was the largest source of discharge from the shallow-brine aquifer on the Bonneville Salt Flats during 1976. The amount of halite on the playa is related to the delicate balance between recharge through the surface—either directly from precipitation or from wind-driven floods of surface brine—and discharge through the surface by evaporation. The distribution of precipitation throughout the year is also important because evaporation rates vary considerably. During 1976, some areas of the Salt Flats experienced a buildup of salt on the surface, and others experienced a loss. In those areas where recharge through the surface (which causes re-solution of the halite) exceeded discharge through the surface (which causes crystallization of halite), there was a loss of halite. In those areas where discharge through the surface exceeded recharge, there was a build-up of halite.

Areas of thick perennial salt crust experienced about a 0.25 inch net buildup of halite during 1976 due to an abnormally dry fall. Following the final evaporation of brine that flooded most of the playa during the winter and spring months, the salt buildup through the summer was small because of unusually heavy summer precipitation, particularly in August. The major buildup of halite occurred during the last four months of the year.

The buildup of halite may be used to estimate rates of groundwater evaporation. Actually, the amount of buildup is due to that amount of evaporation that exceeded recharge through the surface. Recharge to the entire Bonneville salt crust is estimated at 9,700 acre-feet during 1976. But only about half the crustal area was covered with a perennial crust; most of the other half was either covered with a layer of sediment or salt had crystallized on the gypsum surface of the sulfate zone. An estimated 4,900 acre-feet of water was recharged to areas of thick perennial crust during 1976, and evaporation must have exceeded recharge by 1,800 acre-feet to account for the buildup of halite. Thus, 6,700 acre-feet is estimated to have evaporated from the area of thick perennial salt crust during 1976.

Rates of evaporation from the gypsum surface of the sulfate zone and from the surface of sediment-covered salt crust were much less than from the surface of thick perennial salt crust. Salt was periodically scraped with a putty knife from surface plots at two sites on the Salt Flats during May 19-December 9, 1976. The scraping plots had surface areas of 2 ft^2. The scrapings were designed to determine rates of ground-water evaporation and salt accumulation on the gypsum surface and the sediment-covered salt surface, and the results are summarized in table 7. Site (B-1-17)27ad was near the east edge of the sulfate zone, and on May 19 the gypsum surface was covered with a thin halite coating (675 grams on the plot) that had crystallized when surface brines had evaporated. Site (C-1-18)17bd was near the south end of the racetrack in an area where about 6 inches of sediment had been deposited on the salt crust. On May 19 the sediment was overlain by a thin coating of halite (1,215 grams on the plot) that was the end product of evaporated surface brines.

In the laboratory, the halite gathered from each site was separated from the small amount of insoluble material (carbonate mud and gypsum) that was unavoidably collected with each sample by dissolving the salt in distilled water. The resulting brine was then siphoned off, and the insoluble material was dried and weighed to determine the amount of halite in the original sample. To make

TABLE 7.—*Summary of salt-scraping study and estimated ground-water evaporation at two sites on the Bonneville Salt Flats, May 19-Dec. 9, 1976*

Period	Number of days	Halite accumulation or loss (−) (grams)	Precipitation (in. d)	Evaporation (in. d)	Depth of saturated zone below land surface at beginning of period (ft)
		Site (B-1-17)27ad			
May 19-June 21	34	−66	0.011	(1)	0.21
June 22-July 12	21	103	.000	0.0035	1.04
July 13-Aug. 4	23	−56	.013	(1)	1.23
Aug. 5-30	26	−292	.020	(1)	1.18
Aug. 31-Oct. 20	51	109	.008	(1)	1.06
Oct. 21-Dec. 9	49	175	.001	.0025	1.43
		Site (C-1-18)17bd			
May 19-June 17	30	16	0.012	(1)	1.11
June 18-July 12	25	150	.000	0.0042	1.87
July 13-Aug. 4	23	−287	.013	(1)	1.89
Aug. 5-17	13	−301	.027	(1)	1.74
Aug. 18-Oct. 20	64	107	.010	(1)	1.56
Oct. 21-Dec. 9	49	197	.001	.0028	2.21

[1]Recharge from precipitation and re-solution of the salt crust during this period had too great an effect to estimate a rate of evaporation.

estimates of evaporation, brine from a well at each site was sampled to determine the dissolved solids (mostly sodium chloride) in the shallow ground water.

It was originally thought that evaporation through the surface would exceed recharge from precipitation and that there would be a steady buildup of salt through the summer. Such was not the case. At both sites, there were considerable losses and gains in halite depending mainly on the intensity of the precipitation. At site (C-1-18)17bd, between May 19 and December 9, there was a net loss of 118 grams of halite, or about 10 percent of the original amount. At site (B-1-17)27ad there was a measured loss of 27 grams of halite during the same period, or about 4 percent of the original amount.

Knowing the weight of salt that has accumulated on a known surface area in a specific length of time and knowing the concentration of dissolved solids in the ground water, evaporation can be estimated from the following equation:

$$E = \frac{S(1{,}000 \text{ cm}^3/\text{L})}{TAC}$$

where E = evaporation, in centimeters per day,
S = salt accumulation, in grams,
T = time, in days,
A = area of scraping plot, in square centimeters, and
C = dissolved-solids concentration of ground water, in grams per liter.

Data from table 7 indicate that at site (B-1-17)27ad, 103 grams of halite accumulated on 2 ft^2 during June 22-July 12, 1976. Brine from a well a few feet away contained 295 g/L of dissolved solids. Therefore,

$$E = \frac{(103\text{g})\,(1{,}000 \text{ cm}^3/\text{L})}{(21\text{d})\,(1{,}858 \text{ cm}^2)295 \text{ g/L})}$$

$$= 0.0089 \text{ cm/d or } 0.0035 \text{ in./d.}$$

Reliable estimates of ground-water evaporation were obtained during two periods at each site when precipitation was negligible. At site (B-1-17)27ad, on the sulfate zone where a thin seasonal salt crust had developed, evaporation rates of 3.5×10^{-3} in./d and 2.5×10^{-3} in./d were calculated for the periods of June 22-July 12 and October 21-December 9. At site (C-1-18)17bd, on the sediment covered crust, evaporation rates of 4.2×10^{-3} in./d and 2.8×10^{-3} in./d were calculated for the periods of June 18-July 12 and October 21-December 9.

Evaporation rates were less in the fall than in the summer because of a number of factors including increased depth to water and lower air temperatures. Based on the calculated evaporation rates for the small sites, an evaporation rate of 4×10^{-3} in./d was used to estimate total evaporation from these two types of playa surfaces during the period May-September 1976, and a rate of 3×10^{-3} in./d was used for the period October-December 1976. Total evaporation from these two surface types, which covered 21 mi^2, is thus estimated to have been approximately 1,000 acre-feet during 1976.

No attempt was made to scrape salt from the surface of the carbonate muds because it was felt that evaporation rates would be similar to rates at site (C-1-18)17bd, where the salt crust was covered with a 6-inch layer of sediment that appears to be reworked carbonate mud. Feth and Brown (1962, p. 100 and 101) scraped salt from the surface of the mudflats at Ogden Bay on the Great Salt Lake during the summer of 1954. They estimated that the rate of ground-water evaporation through the surface muds averaged about 3.0×10^{-3} in./d.

The rate of evaporation from the muds undoubtedly varies with depth to water and other factors, such as compaction of the muds by flooding, but the evaporation rate of 3.0×10^{-3} in./d is a fairly accurate estimate for the area. Thus, during the period of May-December 1976, an estimated 2,900 acre-feet of ground water was evaporated from the shallow-brine aquifer through the surface of the 75 mi^2 of carbonate muds in that part of the study area north of Interstate Highway 80.

Withdrawals Through Brine-Collection Ditches

Based on records obtained from a recorder on a flume at a booster pump at site (C-1-17)18dc (fig. 2), an estimated 680 acre-feet of brine—270,000 tons of salt[5]—was withdrawn from the shallow-brine aquifer between June 3 and August 7, 1976, by the ditch system north of Interstate Highway 80 and east of the Bonneville Racetrack. This ditch system has been operated since about 1963 and was the only ditch operated north of the interstate highway since 1966. Records of past withdrawals from this ditch system are incomplete, but data in the files of the Geological Survey indicate that total brine production between July 1966 and December 1972 was about 6,200 acre-feet and averaged about 960 acre-feet per year during the same period (Stephens, 1974, p. 15).

The amount of brine withdrawn from the shallow-brine aquifer by the extensive system of ditches south of the interstate highway, mainly on private property, is unknown. But an estimated 2,000

[5]Estimate based on dissolved-solids concentration of 294,000 mg/L.

acre-feet of brine—870,000 tons of salt[6]—flowed laterally through the shallow-brine aquifer toward the ditches from north of the interstate highway. This estimate was made by applying Darcy's law to transmissivity and density-corrected potentiometric surface data in figures 33 and 37.

TRANSPIRATION BY PHREATOPHYTES

The amount of water withdrawn from the shallow-brine aquifer by the sparse growth of phreatophytes in about 12 mi^2 along the western edge of the playa north of the interstate highway cannot be determined precisely. However, transpiration by the phreatophytes is probably fairly well balanced by recharge from precipitation directly on the area of growth and was on the order of 300 acre-feet during 1976.

LEAKAGE TO ALLUVIAL-FAN AQUIFER

The amount of water that leaked into the alluvial-fan aquifer along the western edge of the Bonneville Salt Flats during 1976 is estimated at 70 acre-feet. Transmissivity data are lacking along the western edge of the playa, and the estimate of westward flow through the aquifer was made along a line about 1 mile west of the racetrack near the edge of the salt crust where the transmissivity was estimated to be about 500 ft^2/d (fig. 33). From the edge of the salt crust to the western edge of the playa, recharge from precipitation seems to be fairly well balanced by losses due to evaporation from the mud surface and transpiration by phreatophytes. Any leakage from the shallow-brine aquifer into the alluvial fan is essentially replaced by water moving laterally through the aquifer from as far away as the ground-water divide shown in figure 37. Thus, the estimate of westward flow along the edge of the salt crust is a fairly accurate estimate of leakage to the alluvial fan. During 1976, the leakage from the shallow-brine aquifer and westward flow through the aquifer from the edge of the salt crust were fairly steady, as the potentiometric surface did not change appreciably.

BRINE CHEMISTRY

The dissolved-solids concentration of water in the shallow-brine aquifer on the Bonneville and Pilot Valley playas varies, but it generally increases from the edges of the playas to the areas overlain by salt crust. (See figs. 43 and 44.) The increase in dissolved-solids concentration toward the center of the playas reflects the natural direc-

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[6]Estimate based on dissolved-solids concentration of 320,000 mg/L.

tion of brine movement through the aquifer toward the natural discharge areas (the salt crusts). However, the natural direction of brine movement on the Salt Flats has been reversed by brine withdrawals from collection ditches and by pumping from the alluvial-fan aquifer. To date (1977), this reversal in the direction of subsurface flow has not caused a similar reversal in the direction of increasing brine salinity because the salinity of the brine in the center of the Bonneville playa has been maintained by re-solution of the salt crust. The salinity of brine along the western edge of the Bonneville playa has remained relatively low, probably because of the abnormally high precipitation and recharge during most of the 1960's and early 1970's. The salinity of brine in the area between the salt crust and western edge of the playa should, however, eventually increase, particularly during extended dry periods when the amount of fresh water recharged to the aquifer in this area will decrease.

To compile figures 43 and 44, it was necessary to estimate dissolved-solids concentration from brine density measured in the field. The curve shown in figure 45, which is based upon dissolved-solids concentration and density determined in the laboratory for 44 samples, allows estimation of dissolved-solids concentration from density within 3 percent.

Selected chemical analyses of brine from the shallow-brine aquifer are listed in table 4. The analyses indicate that the brine (in a gross sense) is relatively uniform, with about 90 percent of the ions (by weight) being sodium and chloride.

The percentages of dissolved potassium chloride and magnesium chloride in brine on the Bonneville Salt Flats are shown in figure 46. The percentages of both generally increase from the edge of the playa toward the central area overlain by salt crust. The general enrichment of potassium and magnesium toward the center of the playa reflects the many years of subsurface drainage, prior to the withdrawals of brine for potash production, toward the salt crust where the water evaporated from the surface and sodium chloride crystallized. As outlined earlier, the potassium and magnesium chlorides are more soluble than the sodium chloride, and most of the potassium and magnesium remained in solution while a large part of the sodium chloride crystallized on the surface as halite.

By extracting brines from the carbonate muds, the percentages of potassium and magesium have decreased in some areas while the concentrations of sodium and chloride have been maintained by re-solution of the salt crust. One such area where potassium has been depleted is in the central part of the area just north of Interstate Highway 80. In this area, the percentage of potassium chloride in brine in the carbonate muds was as low as 0.5 percent in the fall of

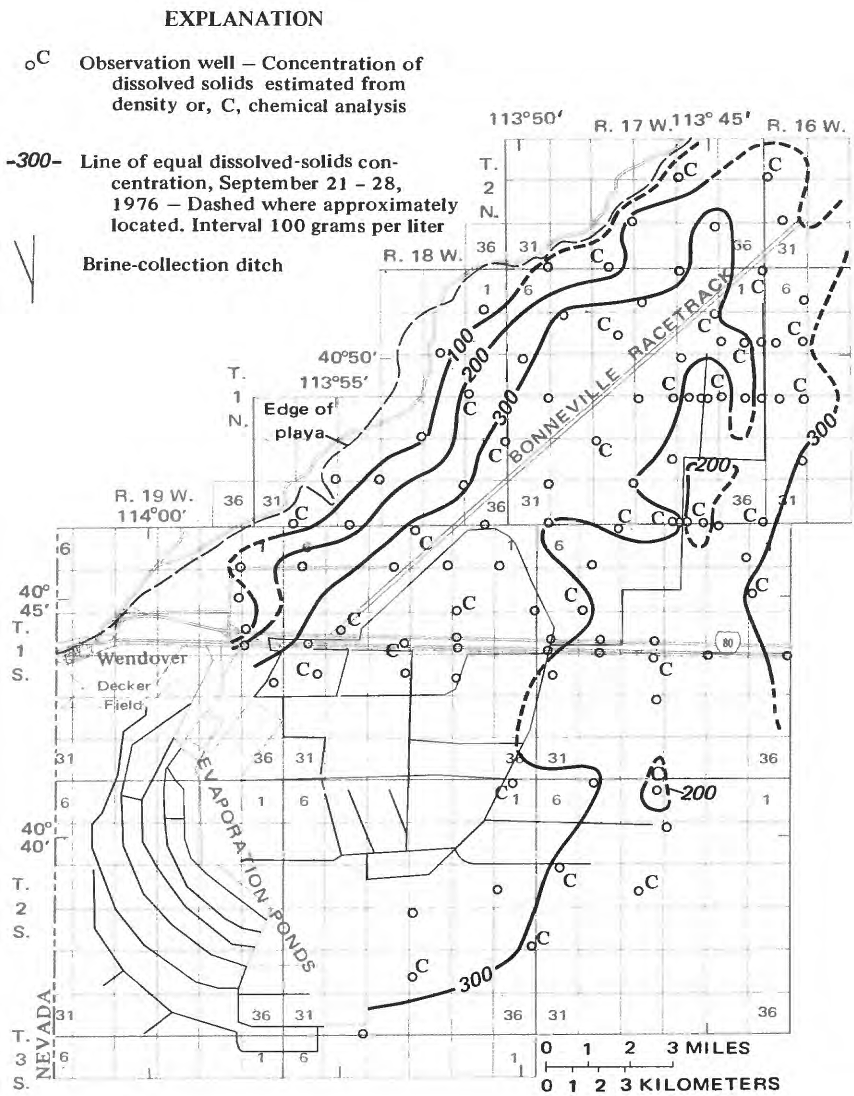

FIGURE 43.—Dissolved-solids concentration of brine in the carbonate muds of the shallow-brine aquifer on the Bonneville Salt Falts, fall of 1976.

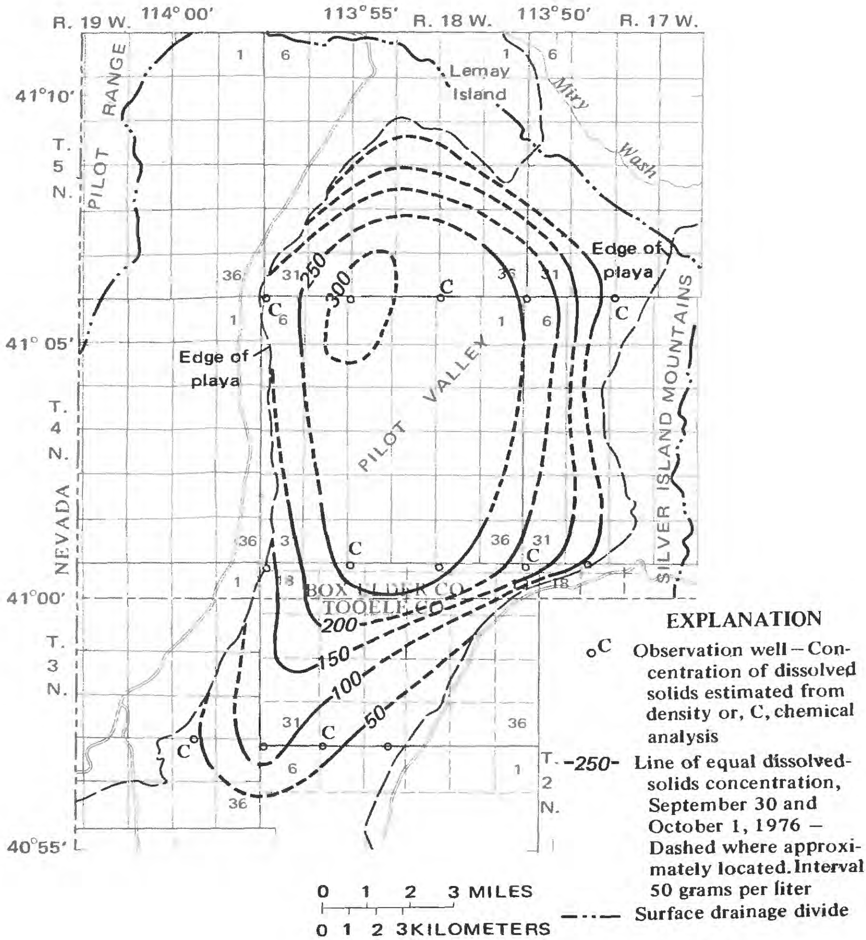

FIGURE 44.—Dissolved-solids concentration of brine in the shallow-brine aquifer in Pilot Valley, fall of 1976

1976. (See well (B-1-18)11ccc-1 in fig. 46.) The data in figure 46 also indicate some depletion of potassium along part of the ditch system east of the racetrack.

If brine were moving vertically from the carbonate muds into the overlying salt crust and then evaporating at the surface, there should also be a relative enrichment in dissolved potassium and magnesium in the brines near the top of the aquifer. This was not the case in the

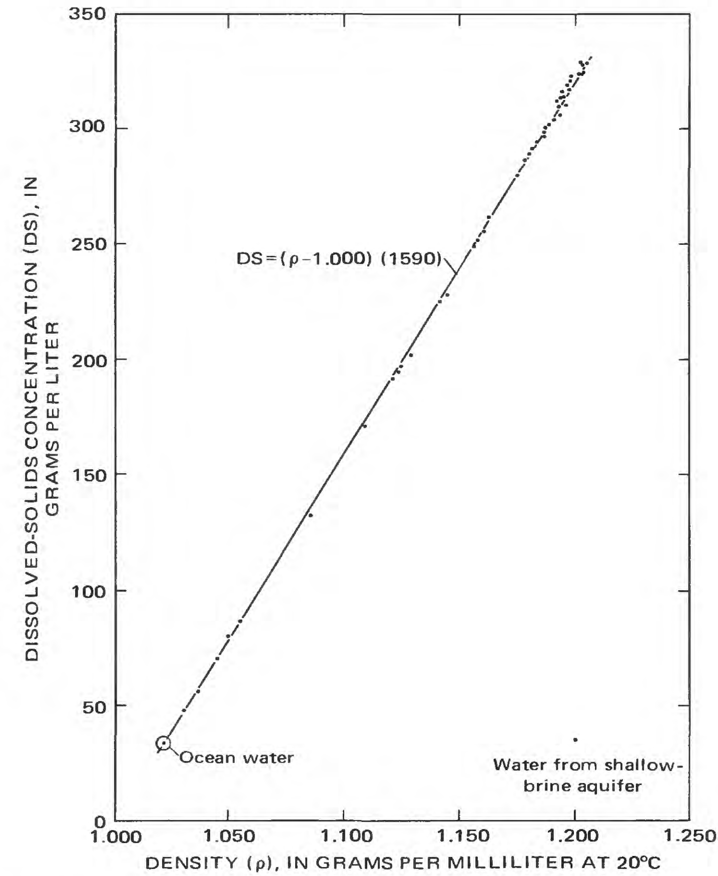

FIGURE 45.—Relation between the density and dissolved-solids concentration of brine in the shallow-brine aquifer on the Bonneville Salt Flats and in Pilot Valley.

fall of 1976. Chemical analyses of brine from five sets of wells were made to test the variability of brine quality with depth in the shallow-brine aquifer. The percentages of potassium chloride and magnesium chloride at four of the sets were smaller near the surface than in the brine in the carbonate muds. These four sets of wells were in areas where a downward component of flow was indicated by the head differences measured in the aquifer (fig. 39). At one set, (B-1-17)28bbb, where there was an upward component of flow, the percentages of potassium chloride and magnesium chloride were the same in brine from both the salt crust and the underlying muds.

It appears that in much of the area covered with salt crust north of Interstate Highway 80, the dissolved potassium and magnesium is slowly being removed from the upper part of the aquifer. One

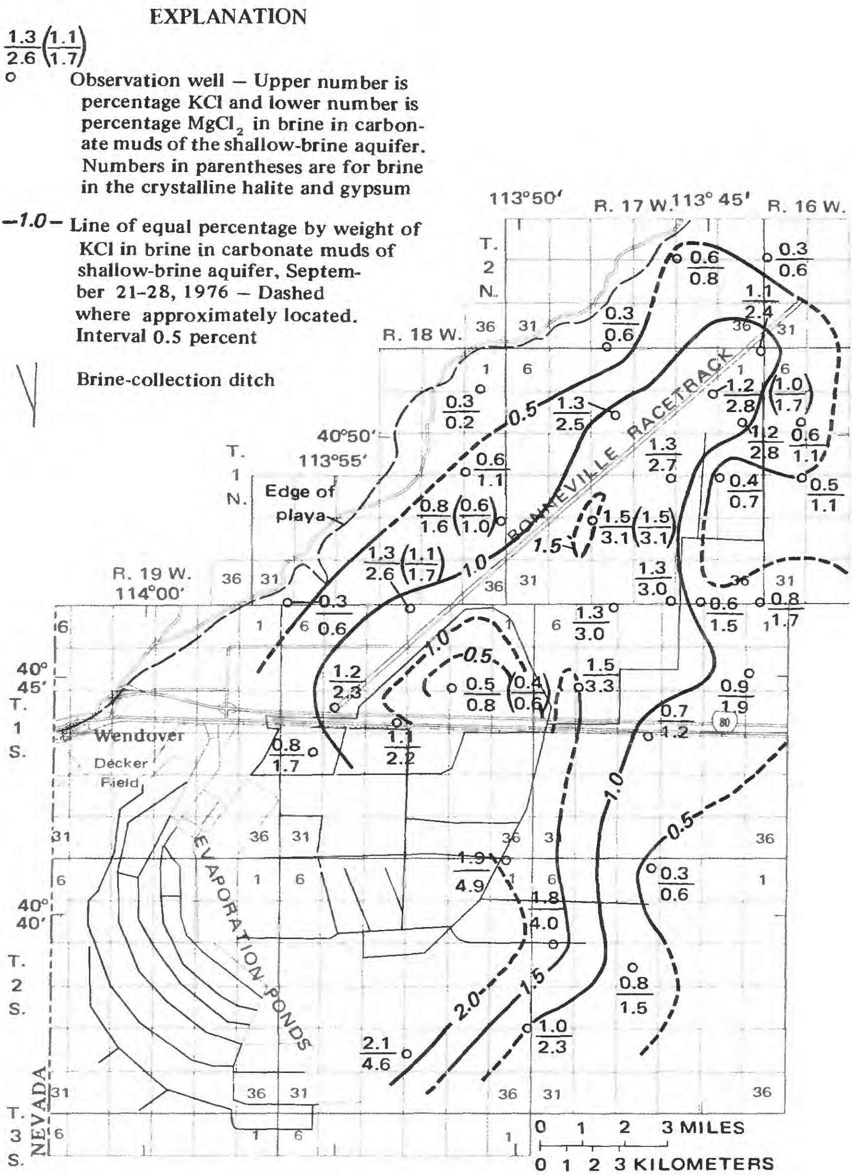

FIGURE 46.—Percentages of potassium chloride and magnesium chloride in brine of the shallow-brine aquifer on the Bonneville Salt Flats, fall of 1976.

mechanism for its removal is recharge from precipitation on the playa surface, which, in conjunction with artificial brine withdrawals, increases the downward flow of brine into the carbonate muds. The new brine created by recharge to, and re-solution of, the salt crust is depleted in dissolved potassium and magnesium because the soluble portion of the salt crust contains only about 0.2 percent potassium and magnesium. This is indicated by the following analysis of the Bonneville salt crust presented by Nolan (1928, p. 35):

Ion	*Percent*
Potassium (K)	0.07
Sodium (Na)	36.85
Calcium (Ca)	1.20
Magnesium (Mg)	.10
Sulfate (SO_4)	2.88
Chloride (Cl)	58.90
	100.00

AREA AFFECTED BY BRINE-COLLECTION DITCHES

Water in the shallow-brine aquifer was moving toward brine-collection ditches from distances of several miles from the ditch system in the fall of 1976 (fig. 37). The position of the major ground-water divide, however, indicates that brine in the shallow-brine aquifer under much of the Bonneville Racetrack was not draining toward brine-collection ditches. This is not to say that halite in the racetrack area is not being affected by the ditch system, because large quantities of redissolved salt crust during most years are moved eastward across the ground-water divide into the area of influence of the ditch system by floods of wind-driven surface brine. The halite that is moved in solution across the divide is subject to direct infiltration into the aquifer. Some of the sodium chloride is also precipitated on the surface southeast of the divide when the surface brine evaporates, and it is subject to later re-solution and infiltration into the aquifer.

The position of the ground-water divide, and thus the area of capture of water by the ditch system, is subject to change and is dependent upon other variables such as the amount of recharge in different areas of the playa and discharge from the ditch system and alluvial-fan wells. Prior to withdrawals from the brine-collection ditches, a ground-water divide probably did not exist across the center of the salt crust, and subsurface drainage was probably like that observed in Pilot Valley in 1976 (fig. 36).

During 1976, brine in the shallow-brine aquifer was moving across boundaries of leased Federal and State lands. But the movement of brine across boundaries of leased areas in some places, particularly east and south of the ditch system, is a natural phenomenon. Natural subsurface flow through the aquifer east and south of the present ditch system was probably much in the same direction as flow during 1976. But withdrawals from the ditch system have caused a steepening of the hydraulic gradient and an increase in the velocity of subsurface flow from the east and south. The ditches are, in effect, capturing northward and westward flowing brine that ordinarily would be evaporated mainly on the surface of the salt crust. The ditch system is also draining brine from the shallow-brine aquifer in a large area of salt crust north of Interstate Highway 80.

The rate at which dissolved solids are moving across boundaries of leased areas depends on the fluid velocity in the aquifer, which in turn is dependent upon a number of variables. The average velocity can be estimated by the following equation (Lohman, 1972, p. 10):

$$v = \frac{KI}{\Theta}$$

where

v = average fluid velocity, in feet per day,
K = hydraulic conductivity, in feet per day,
I = hydraulic gradient, and
Θ = effective porosity, a decimal fraction.

It should be stressed that the solution of the above equation is the average fluid velocity through the aquifer, and it does not necessarily equal the actual velocity between any two points in the aquifer. The velocity between any two points depends upon the flow path followed.

In the fall of 1976, near the southern end of the ditch system that is east of the Bonneville Racetrack, hydraulic gradients were about 6 ft/mi, hydraulic conductivity of the aquifer material averaged about 20 ft/d, and the aquifer had an assumed effective porosity of 0.1; therefore:

$$v = \frac{(20 \text{ ft/d})\ (6 \text{ ft}/5{,}280 \text{ ft})}{0.1}$$

$$= 0.2 \text{ ft/d (rounded).}$$

Estimates of fluid velocity in the remainder of this section assume an effective porosity of 0.1.

About 1 mile east of this ditch sytem, hydraulic gradients in the fall of 1976 averaged about 1 ft/mi, and the hydraulic conductivity of the aquifer material was about 20 ft/d. Thus, the average fluid velocity through the carbonate muds is estimated to have been 0.04 ft/d.

West of this ditch system, in the area of salt crust near the ground-water divide where the hydraulic gradient was only about 0.5 ft/mi and the hydraulic conductivity of the aquifer averaged 150 ft/d, average fluid velocity is estimated to have been 0.1 ft/d.

The greatest fluid velocity during the fall of 1976 was in that part of the shallow-brine aquifer in the central part of the area where brine was flowing south under the interstate highway toward brine-collection ditches. In this area, hydraulic gradients were about 6 ft/mi, hydraulic conductivity was about 300 ft/d, and the average fluid velocity was about 3 ft/d.

The estimates of fluid velocity through the shallow-brine aquifer illustrate the variability in subsurface flow throughout the area, and the variability of the area that can be effectively mined by the ditches in any given period of time. Since the fluid velocity is dependent upon the hydraulic gradient, the estimates are probably maximum values; in some areas the estimates cannot be applied for the entire year of 1976. The estimates are based on hydraulic gradients measured during the end of the 1976 brine-collection season. In some areas, particularly along the ditch system east of the racetrack, hydraulic gradients in the spring of 1976 were much less. In other areas, such as along the interstate highway in the central part of the area, the hydraulic gradient did not change appreciably during 1976 as indicated by the potentiometric surface maps shown in figures 34 and 35.

Velocity of brine that flowed through the carbonate muds 0.5-1 mile east of the ditch system probably averaged on the order of 0.03 ft/d during 1976, and total movement through the year was on the order of 10 feet. In the salt crust area between the ground-water divide and the ditch system north of the interstate highway, fluid movement through the shallow-brine aquifer was on the order of 40 feet during 1976.

MEASURES TO RESOLVE CONFLICTS IN USE OF THE SALT FLATS

One of the objectives of this study was to evaluate possible remedial measures that might be implemented to resolve conflicts between users, if conflicts existed. Previous discussions in this report have made it evident that there are conflicts between the main uses of the area (potash production, the major transportation route of Interstate Highway 80, and racing). The hydrologic environment on the Bonneville Salt Flats has been altered by man's activities; as a result, the delicate surface morphology of the playa is changing. The main concern is with the thinning or re-solution of the salt crust in the area of the Bonneville Racetrack north of the interstate highway. As pointed out earlier, the re-solution of the crust is a natural process that occurs during wet weather cycles, but the re-solution has been accelerated in some areas by man's activities.

Another major concern is with the deposition of sediment on large areas of the salt crust behind manmade drainage barriers (roadfills for the interstate highway and tailings piles along brine-collection ditches). In the manmade ponding area on the south end of the racetrack, the accumulation of sediment and accompanying re-solution of the salt crust has rendered the surface unsuitable for racing. The movement of minerals, both on the surface and by subsurface flow, across lease and property boundaries is also of major concern. To aid in understanding the following discussion, property and lease boundaries on the Salt Flats are shown in figure 47.

No attempt will be made in the following discussion to credit individuals who have proposed remedial measures. Many of the same suggestions have come from different sources, and none of the measures that will be evaluated are the direct outgrowth of this study. Most suggested measures involved one or more of the following actions: (1) construct subsurface barriers to prevent brine in unleased areas from flowing into areas affected by brine-collection ditches, (2) construct new or alter old surface-drainage barriers to control the migration of salt in solution in floods of wind-driven surface brine, (3) cease the withdrawal of brine by brine-collection ditches or move the ditches further from the remaining salt-crust area, and (4) replace the halite removed from the area north of the interstate highway for the production of potash with salt stored in the bottom of the evaporation ponds or with salt from some other source.

It is beyond the scope of this study to evaluate possible remedial measures with respect to their costs, benefits, or social impact. Each will be evaluated solely on the impact it might have on the hydrology and the surface morphology of the playa and in resolving the conflict between uses.

CONSTRUCT SUBSURFACE-DRAINAGE BARRIERS

To prevent the migration of brine by subsurface flow across lease and property boundaries, it has been suggested that impermeable subsurface barriers could be constructed. Construction of a barrier would involve excavating a trench, installing an impermeable lining material such as plastic or concrete, and backfilling. Because the salt crust and underlying carbonate muds are in hydraulic connection, the barrier would have to extend beyond the base of the shallow-brine aquifer to prevent the subsurface flow of brine from the salt crust. In some areas, the fissures of giant polygons may extend to a

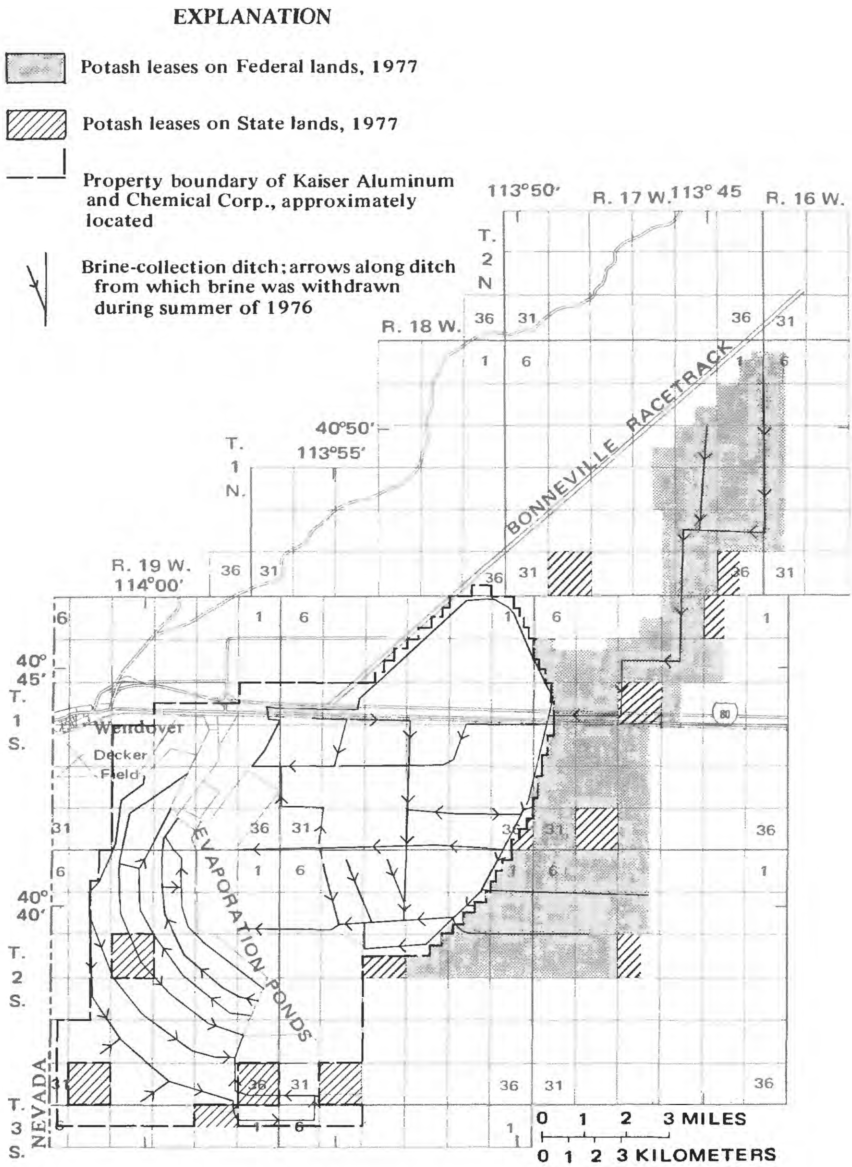

FIGURE 47.—Locations of potash leases on Federal and State lands, property boundary of Kaiser Aluminum and Chemical Corp., and the brine-collection ditches on the Bonneville Salt Flats.

depth of 25 feet or more, and the subsurface barrier would have to extend beyond the zone of fissuring to be effective. Even with a barrier across the aquifer, some leakage would probably occur under the barrier through the unfissured carbonate muds. An extensive test program involving test drilling, excavation, and aquifer tests would be needed along the line of any subsurface barrier to assure that the barrier extended through the shallow aquifer. To isolate unleased lands from the effects of brine-collection ditches, the subsurface barrier would have to be on the order of 50 miles in length.

A subsurface barrier would have no foreseeable adverse effects on the surface morphology of the playa beyond the damage to the surface caused by the initial installation. But a subsurface barrier would not control the migration of dissolved salt across lease and property boundaries during periods of flooding. Some of the wind-driven surface brine would still flow directly into the ditch east of the racetrack, some would recharge the carbonate muds on the leased land, and some would evaporate on the surface on the leased land between the subsurface barrier and ditches. Salt that would crystallize on the surface in the leased areas following the evaporation of the surface brine would be subject to later re-solution, recharge to the aquifer, and removal by the brine-collection ditches. The loss of salt from the south end of the racetrack could be largely eliminated by a subsurface barrier, as there is no surface flow of brine across the interstate highway west of the abandoned arcuate ditch system.

ALTER OR CONSTRUCT NEW SURFACE-DRAINAGE BARRIERS

Surface barriers consisting of something as simple as a small tailings pile or as elaborate as a concrete curb have been suggested to control the migration of surface brine. Surface barriers could control the migration of surface brine to a certain extent, but they would have an adverse effect on the playa surface. Water would tend to pond behind the windward side of the barriers, and the new ponding areas would soon accumulate large quantities of sediment as now exists in the ponding area at the south end of the racetrack.

Surface barriers, if not used in conjunction with subsurface barriers, could also accelerate the re-solution of the salt crust and subsurface flow of brine toward brine-collection ditches. As in the ponding area on the south end of the racetrack, relatively fresh water ponded behind a surface barrier would increase the recharge through the surface. The increased recharge would cause a buildup in head behind the barrier and faster subsurface movement of the newly dissolved salt away from the barrier toward brine-collection ditches.

Altering some existing manmade drainage barriers could diminish the problem of sediment being concentrated in relatively small areas, but in all cases the migration of surface brines across lease and property boundaries would also increase. Elimination of the tailings pile along the abandoned arcuate ditch system north of the interstate highway would undoubtedly diminish the deposition of sediment on the south end of the racetrack and around the northern edge of the ditch; sediment would be allowed to be deposited in an additional 4 mi^2 that is presently (1977) protected from flooding by the tailings pile.

There is only one group of culverts through the roadfill of the interstate highway in the study area, and all the openings are within a few feet of each other inside the abandoned arcuate ditch system. The flow of brine through the culverts is small, as the culverts are several inches above the level of the salt crust on the north side of the roadfill. Additional culverts through the roadfill would probably diminish the buildup of sediment in the ponding areas. But new culverts would also induce additional losses of salt from north of the interstate highway, as salt carried in solution through the culverts would be deposited on the surface or would infiltrate into the shallow-brine aquifer in areas closer to the brine-collection ditches south of the railroad.

ALTER BRINE-COLLECTION DITCH SYSTEM

Moving brine-collection ditches further from the salt crust and eliminating the ditches north of the interstate highway have also been suggested as possible remedial measures. Elimination of brine withdrawals from the ditch system north of the interstate highway would eliminate a yearly loss of about 680 acre-feet of brine and 270,000 tons of salt.

The elimination of brine-collection ditches north of the interstate highway would eventually cause a reversal in the direction of subsurface flow that was observed in 1976 in the area between the salt crust and the ditch. Also, brine that was flowing through the subsurface east of the ditch, and that was being intercepted by the ditch, would eventually be discharged mainly on the surface of the salt crust by evaporation.

Loss of salt from north of the interstate highway could also be decreased by cutting back or eliminating the brine withdrawals from ditches just south of the railroad. Subsurface flow from the area of salt crust north of the interstate highway toward ditches south of the highway was about 2,000 acre-feet in 1976 and represented a loss of 870,000 tons of halite. By eliminating any brine withdrawals from the shallow-brine aquifer within an area of about 1 mile south of the railroad, the hydraulic gradient and rates of salt loss from north of the highway could be lowered considerably.

REPLACING THE SALT

Replacing the salt, which has been removed from north of the interstate highway by the brine-collection ditches, has also been suggested as a remedial measure. An apparent source is salt that is stored in abandoned evaporation ponds on Kaiser's property. Turk (1969, p. 18) reports that when a pond system is filled with salt to a depth of 4-5 feet, leakage from the ponds becomes excessive, and a new pond system must be constructed. Lallman and Wadsworth (1976, p. 9) report that 5-6 inches of halite are deposited annually on the pond floors as the brine is concentrated for the removal of potash, and life expectancy of a pond is 8-10 years. In 1976, brine was being evaporated in the fourth primary pond system constructed since 1939, and construction of the fifth pond system started in the fall of 1976. Total area of the four earliest pond systems is approximately 26 mi^2.

Depressions in the surface of the Bonneville Racetrack were filled with granular salt from the pond system prior to racing in 1976. Transfer of salt by dump truck, at least on a small scale, was successful as the granular salt was later dissolved by rains and became a coherent part of the crust. Adding salt to the racing area would have no foreseeable adverse affect on the salt crust. Problems may arise, however, if rains do not dissolve the granular salt and evaporation does not recrystallize the salt into a coherent crust prior to racing.

It has also been suggested that the best way to replace the salt is by transporting it into the area in solution. Damage to the surface of the crust could occur, however, if brine added to the surface is not near the saturation level with respect to halite. Undersaturated brine distributed over the salt crust would have a tendency to infiltrate into the crust and dissolve enough halite to reach near-saturation level. Much of the redissolved halite would later recrystallize following evaporation, but the overall effect may be a rougher surface.

CONCLUSIONS

Both the Bonneville and Pilot Valley salt crusts are dynamic features and are susceptible to day-to-day climatic changes. Major natural forces acting to change the salt crusts are precipitation, evaporation of both surface and ground water, and wind. Salt-scraping studies on the Bonneville Salt Flats indicate that the amount of halite on the surface is directly related to the amount of recharge to the shallow-brine aquifer through the surface (which causes re-solution of the halite) and the amount of evaporation from the aquifer at the surface (which causes crystallization of halite). Weather cycles may partly explain changes on the Bonneville salt crust. But the activities of man, such as withdrawing brine and constructing surface-drainage barriers, have altered the hydrologic environment and have had a profound effect on the salt crust.

Water-level data indicate that during 1976 brine was moving through the shallow-brine aquifer on the Salt Flats from the area of salt crust toward all areas of manmade discharge (brine-collection ditches east and south of the salt crust and alluvial-fan wells west of the salt crust). In Pilot Valley during 1976, the subsurface movement of brine was in the opposite direction, from the edges of the playa toward the salt crust. Head differences in the shallow-brine aquifer in most areas of the Bonneville salt crust indicated that brine also was moving downward from the salt crust into the underlying carbonate muds.

Comparison of water-level data for 1925 and 1976 indicates that directions of subsurface brine movement in Pilot Valley have not changed appreciably, while on the Salt Flats, the direction of movement has been reversed in some areas because of manmade withdrawals from the shallow-brine aquifer. Comparison of the water-level data also indicates that the potentiometric surface of the shallow-brine aquifer in Pilot Valley was higher in 1976 than in 1925. In those areas on the Salt Flats where comparisons could be made, the potentiometric surface in 1976 was several feet below the level measured in 1925, even though the area experienced a relatively wet weather cycle extending through most of the 1960's and 1970's.

Both the Bonneville and Pilot Valley salt crusts covered less area in 1976 than in 1925. Because of the relatively wet weather through most of the 1960's and 1970's, recharge to the shallow-brine aquifer was above normal, and much of the salt crust in Pilot Valley was in solution in the aquifer during 1976. On the Salt Flats, however, the amount of salt held in solution in the shallow-brine aquifer has declined, as indicated by the decline in the potentiometric surface. Increased recharge from precipitation, and the accompanying resolution of the salt crust, has not been great enough to compensate for the loss through artificial withdrawals.

The reversal in the direction of subsurface brine movement on the Salt Flats to date (1977) has not caused a similar reversal in the direction of increasing brine salinity. The salinity of the shallow brine in the center of the Bonneville playa has been maintained by resolution of the salt crust. Subsurface flow of brine toward brine-collection ditches removed approximately 1.1 million tons of salt from the flats north of the interstate highway during 1976.

Ponding of surface brines behind the roadfill for the interstate highway and tailings piles along ditches have accelerated re-solution of the salt crust in some areas. The manmade ponding areas are also acting as sediment-catchment basins. The accumulation of sediment on the south end of the Bonneville Racetrack is due mainly to the presence of a ponding area on the windward side of the roadfill for the interstate highway and a tailings pile along an abandoned brine-collection ditch.

During 1976, brine was moving slowly through the shallow-brine aquifer on the Salt Flats across lease and property boundaries. In some areas, the subsurface flow has been induced by man's withdrawal of brine; in other areas, the rates of subsurface flow have simply been accelerated by the withdrawals. Estimated velocities of subsurface-brine movement were on the order of 10-40 feet per year in many areas of the Salt Flats during 1976. Velocities were much higher, about 3 ft/d, in the central part of the Salt Flats where brine was flowing south toward brine-collection ditches south of the interstate highway. The area of capture of the brine-collection ditches extended several miles from the ditch system. In some areas the ditches were capturing brine that ordinarily would have flowed through the subsurface toward the salt crust and there evaporated at the surface. Large quantities of redissolved salt crust during most years are also carried across lease boundaries and into the area of capture of the ditches by floods of wind-driven surface brine.

The evaluation of previously suggested remedial measures indicates that a number of steps could be taken to partly alleviate the conflict between uses on the Bonneville Salt Flats. None of the remedial measures that are evaluated, or even a combination of all the measures, would in the near future transform the Salt Flats to its original state prior to man's activities in the area. Changes in the surface of the Bonneville salt crust in the future will continue to be related to unpredictable weather cycles and to man's activities.

Future study or monitoring on the Salt Flats should be keyed to remedial measures that might be implemented to resolve the conflict between uses. Until remedial measures are taken, measurements of water levels and brine density should be made at wells on the Salt Flats, with a predominance of measurements near brine-collection ditches. Water samples for chemical analyses should be collected from wells near brine-collection ditches and boundaries of leased areas to monitor the removal of dissolved potassium and magnesium from the shallow-brine aquifer. In addition, photographs should be taken to document changes in the salt crust.

REFERENCES CITED

Cook, K. L., Halverson, M. D., Stepp, J. C., and Berg, J. W., Jr., 1964, Regional gravity survey of the northern Great Salt Lake Desert and adjacent areas in Utah, Nevada, and Idaho: Geol. Soc. America Bull., v. 75, no. 8, p. 715–740.

Crittenden, M. D., Jr., 1963, New data on the isostatic deformation of Lake Bonneville: U.S. Geol. Survey Prof. Paper 454–E, 31 p.

Eardley, A. J., 1962, Gypsum dunes and evaporite history of the Great Salt Lake Desert: Utah Geol. and Mineralog. Survey Spec. Studies 2, 27 p.

Fennemen, N. M., 1931, Physiography of western United States: New York, McGraw-Hill Book Co., Inc., 534 p.

Feth, J. H., and Brown, R. J., 1962, Method for measuring upward leakage from artesian aquifers using rate of salt-crust accumulation, *in* Geological Survey Research 1962: U.S. Geol. Survey Prof. Paper 450–B, p. 100–101.

Gilbert, G. K., 1890, Lake Bonneville: U.S. Geol. Survey Mon. 1, 438 p.

Groat, C. G., 1970, Geology and hydrology of Troy Playa, San Bernardino County, California, *in* Motts, W. S., ed., Geology and hydrology of selected playas in Western United States: Massachusetts Univ., p. 166–199.

Harbeck, G. E., Jr., 1955, The effect of salinity on evaporation: U.S. Geol. Survey Prof. Paper 272-A, 6 p.

Houlgate, Deke, Engel, George, and Ray, Marla, 1971, The fastest men in the world on wheels: The World Publishing Co., 164.

Hunt, C. B., Robinson, T. W., Bowles, W. A., and Washburn, A. L., 1966, Hydrologic basin, Death Valley, California: U.S. Geol. Survey Prof. Paper 494-B, 138 p.

Kaliser, B. N., 1967, Bonneville Salt Flats hydrogeological study near Wendover, Utah, spring 1967: Utah Geol. and Mineralog. Survey Rept. Inv. 35, p. 6.

Krinsley, D. B., Woo, C. C., and Stoertz, G. E., 1968, Geologic characteristics of seven Australian playas, *in* Neal, J. T., ed., Playa surface morphology, miscellaneous investigations: U.S. Air Force, Off. Aerospace Research, Environmental Paper 283, p. 59–103.

Lallman, M. W., and Wadsworth, G. D., 1976, Kaiser Chemical's Bonneville potash operation: Am. Inst. Mining Engineers Preprint 76–H–302, 19 p.

Lines, G. C., 1978, Ground-water data, Bonneville Salt Flats and Pilot Valley, western Utah: U.S. Geol. Survey open-file report (duplicated as Utah Basic-Data Release 30), 14 p.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geol. Survey Prof. Paper 708, 70 p.

Motts, W. S., 1970, Results of test drilling and winter mapping programs on Coyote Playa, California, *in* Motts, W. S., ed., Geology and hydrology of selected playas in Western United States: Massachusetts Univ., p. 108–136.

Neal, J. T., Langer, A. M., and Kerr, P. F., 1968, Giant desiccation polygons of Great Basin playas: Geol. Soc. America Bull., v. 79, no. 1, p. 69–90.

Neal, J. T., and Motts, W. S., 1967, Recent geomorphic changes in playas of Western United States: Jour. Geology, v. 75, no. 5, p. 511–525.

Nolan, T. B., 1928, Potash brines in the Great Salt Lake Desert, Utah, *in* Loughlin, G. F., and Mansfield, G. R., Contributions to economic geology, Part 1—Metals and nonmetals except fuels: U.S. Geol. Survey Bull. 795, p. 25–44.

Robinson, T. W., 1958, Phreatophytes: U.S. Geol. Survey Water-Supply Paper 1423, 84 p.

Sass, J. H., Lachenbruch, A. H., Monroe, R. J., Green, G. W., and Moses, T. M., Jr., 1971, Heat flow in the Western United States: Jour. Geophys. Research, v. 76, no. 26, p. 6376–6413.

Schaeffer, F. E., and Anderson, W. L., 1960, Geology of the Silver Island Mountains, Box Elder and Tooele Counties, Utah, and Elko County, Nevada: Utah Geol. Soc. Guidebook No. 15, 192 p.

Sharp, R. P., and Carey, D. L., 1976, Sliding stones, Racetrack Playa, California: Geol. Soc. America Bull., v. 87, p. 1704–1717.

Stansbury, Howard, 1852, Exploration and survey of the valley of the Great Salt Lake of Utah including a reconnaissance of a new route through the Rocky Mountains: Philadelphia, Lippincott, Grambo and Co., issued by the U.S. Senate, Spec. Sess., March 1851, 487 p.

Stephens, J. C., 1974, Hydrologic reconnaissance of the northern Great Salt Lake Desert and summary hydrologic reconnaissance of northwestern Utah: Utah Dept. Nat. Resources Tech. Pub. 42, 55 p.

Stephens, J. C., and Hood, J. W., 1973, Hydrologic reconnaissance of Pilot Valley, Utah and Nevada: Utah Dept. Nat. Resources Tech. Pub. 41, 38 p.

Stoertz, G. E., and Ericksen, G. E., 1974, Geology of salars in northern Chile: U.S. Geol. Survey Prof. Paper 811, 65 p.

Stokes, W. L., ed., 1964, Geologic map of Utah: Utah Univ.

Turk, L. J., 1969, Hydrogeology of the Bonneville Salt Flats, Utah: Unpublished Ph.D. dissert., Stanford Univ., 307 p.

———1970, Evaporation of brine; a field study on the Bonneville Salt Flats, Utah: Water Resources Research, v. 6, no. 4, p. 1209–1215.

———1973, Hydrogeology of the Bonneville Salt Flats, Utah: Utah Geol. and Mineral Survey Water-Resources Bull. 19, 81 p.

Turk, L. J., Davis, S. N., and Bingham, C. P., 1973, Hydrogeology of lacustrine sediments, Bonneville Salt Flats, Utah: Economic Geology, v. 68, p. 65–78.

U.S. Environmental Science Services Administration, 1966–71, Climatologic data, Utah, 1966–70: v. 68–72, nos. 1–13.

U.S. National Oceanic and Atmospheric Administration, 1971–77, Climatologic data, Utah, 1971–76: v. 73–78, nos. 1–13.

U.S. Weather Bureau, 1937, Climatic summary of the United States, climatic data from the establishment of stations to 1930, inclusive: Section 20—western Utah, 41 p.

———1957, Climatic summary of the United States, supplement for 1931 through 1952, Utah: Climatography of the United States, no. 11–37, 47 p.

———1961–66, Climatologic data, Utah 1961–65: v. 63–67, nos. 1–13.

———1965, Climatic summary of the United States, supplement for 1951 through 1960, Utah: Climatography of the United States, no. 86–37, 68 p.

Utah Geological and Mineral Survey, 1974, Bonneville Salt Flats: A comparison of salt thickness in July 1960 and October 1970: Utah Geol. and Mineral Survey Rept. Inv. 91, 6 p.

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