Hydrologic Basin Death Valley California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 494-B

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By CHARLES B. HUNT, T. W. ROBINSON, WALTER A. BOWLES, *and*
A. L. WASHBURN

GENERAL GEOLOGY OF DEATH VALLEY, CALIFORNIA

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A description of the hydrology, geochemistry, and patterned ground of the saltpan

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HYDROLOGIC BASIN

By Charles B. Hunt, T. W. Robinson, Walter A. Bowles, and A. L. Washburn

ABSTRACT

The Death Valley hydrologic basin covers about 8,700 square miles, of which about 500 square miles is below sea level. The bottom of the basin—the saltpan in Death Valley, one of the world's great saltpans—covers more than 200 square miles and lies as much as 282 feet below sea level.

Death Valley is the hottest and driest part of the United States. Temperatures greater than 120°F are common during the summer, and a maximum of 134°F has been recorded. Annual rainfall in the valley averages about 1.66 inches; the average precipitation in the entire hydrologic basin probably is about 4–5 inches. The evaporation rate in Death Valley is about 150 inches per year. With increasing altitude the temperature decreases and the rainfall increases. The humidity is low and wind movement moderate most of the time.

The rocks forming the mountains and underlying the valleys of the hydrologic basin are mostly Precambrian and Paleozoic formations. The latter are especially important in the water economy because they are chiefly cavernous carbonate formations that have favored water movement and have affected the quality of the water.

Three principal kinds of valley fill are important to the hydrology: the Tertiary formations, the Quaternary gravels, and the Quaternary playa deposits. The Tertiary rocks are partly volcanic and partly sedimentary rocks derived from the volcanics. They crop out in about 25 percent of the hydrologic basin. In general, the volcanic rocks are porous and favor downward migration of water, whereas the Tertiary sedimentary rocks include thick impermeable shale deposits.

Quaternary deposits most significant to the hydrology are the gravels, the fine-grained alluvial and playa deposits, and the salts.

Gravel deposits form the surface in about 40 percent of the hydrologic basin. They are of three kinds and three ages. The oldest gravel has a desert-pavement surface that favors runoff; the youngest gravel is highly permeable; the gravel of intermediate age is of intermediate permeability. Recharge of ground water in the gravel fans is chiefly through the youngest gravel which occupies the present washes where runoff becomes concentrated.

Fine-grained alluvial deposits form the surface of about 10 percent of the hydrologic basin. They occur as flood-plain deposits along the Amargosa River and Salt Creek and as playa deposits in Death Valley. The flood-plain deposits are most extensive upstream from bedrock dams caused by impermeable rocks upfaulted across stream courses. Such dams are represented by the Salt Creek Hills, at the north end of the saltpan, and by the Confidence Hills near the south end. Upstream from both these structural uplifts, ground water is ponded in fine-grained alluvial and playa deposits.

In the central part of Death Valley, salt deposits form a crust covering most of 200 square miles. These salt deposits and other saliferous surfaces comprise about 10 percent of the hydrologic basin.

Most of the distinctive hydrologic features of the basin are directly the result of the structural geology. Ground water is ponded in the structural basins, and it moves from one basin to another along faults that extend through topographic divides. The relationship of water occurrence to the structural geology is brought out in the descriptions of the occurrences.

Principal parts of the hydrologic basin are the saltpan and the drainage areas tributary to it from the north by way of Salt Creek, from the south by way of the Amargosa River, and from the mountains adjoining the saltpan.

Less than half the saltpan is subject to flooding; the rest is a salt crust 1 or 2 feet higher than the areas that are subject to flooding. The pan is divided into three basins. The lowest part, Badwater Basin, comprises the south half of the saltpan. A buried structural uplift separates this basin from the ones at the north, Middle Basin and Cottonball Basin. These northern basins are a structural unit, but they are divided topographically by alluvial fans that extend panward and form a constriction between them.

An uplift of impermeable beds of the Furnace Creek Formation forms the Salt Creek Hills at the north end of the saltpan and separates it from another broad deep structural basin under Mesquite Flat to the north. Ground water ponded in Mesquite Flat discharges by way of Salt Creek, which has cut a gorge through the hills and drains to the north end of the saltpan. The discharge of Salt Creek varies from an estimated normal minimum of about 0.1 cfs to a normal maximum of about 1.5 cfs.

The Amargosa River, which enters the saltpan from the south, drains an area of about 5,000 square miles; but only short stretches of the river are perennial, and these are at structural dams like the Salt Creek Hills at Salt Creek. The quality of the water in the Amargosa River drainage differs from that in the Salt Creek basin in containing more bicarbonates and less chlorides, and in being high in fluorine and strontium.

Although the mountain areas that are drained directly to the saltpan are as much as 11,000 feet high, springs in the mountains are not numerous and all are small. Practically every spring in the Panamint Range is located at a thrust fault.

Ground water in the Death Valley hydrologic basin probably is augmented by ground water entering the basin along faults from neighboring basins, especially Pahrump Valley by the way of Ash Meadows, but probably also from the basin of the Mojave River and Sarcobatus Flat. That the Pahrump Valley is the source of some of the large springs in the Amargosa Desert is indicated by the fact that the catchment area for the springs, within the hydrologic basin, is far too small to maintain their

flow. Besides, Pahrump Valley has an excess of water that cannot be accounted for simply by evaporation; also, in composition the waters are very much alike.

Springs in Death Valley are of four kinds. The largest springs—the first type—are discharging along high-angle faults. Those along the Furance Creek fault zone are large warm springs. The discharge is excessive for the catchment area of those springs, and an outside source is probable. Chemically, the water is like that in the Amargosa Desert and Pahrump Valley, and a source from that direction seems probable. Such source also could account for the temperature of the water.

A second type of spring occurs in the mountains at thrust faults. These springs are small, but the quality of water from them is excellent.

A third type of spring occurs where ground water is ponded by an impervious structural barrier, like the one at the Salt Creek Hills.

The fourth type of spring occurs around the edge of the saltpan where ground water moving into the pan is ponded in the gravel and sand deposits where they grade to much less pervious silt.

The Death Valley saltpan covers more than 200 square miles, all of it more than 200 feet below sea level and most of it between −270 and −282 feet. The thickness of the salt crust on the saltpan ranges from a few inches to a few feet. Under the crust is silt and clay. At the center of the pan, the salts in the crust and the brines are mostly chlorides. These chlorides are surrounded by a narrow zone in which the salts are chiefly sulfates; these sulfates, in turn, are surrounded by a sandy zone containing carbonate salts and forming the edges of the pan. This zoning reflects the differences in solubility of the salts. Parts of the saltpan are bare mud flats and are subject to seasonal flooding.

Within each salt zone the salts occur in layers having different compositions, and these layers too are orderly with respect to the solubility of the salts. Where deposition is from rising ground water, the upper layers contain the most soluble salts, the chlorides, and the underlying layers contain the least soluble ones, the carbonates. Between these layers is one composed of sulfates. This layering, however, is reversed where there is leaching due to surface water seeping downward into the ground.

The carbonate zone covers about 25 square miles and can be divided into 4 facies that have strikingly different hydrologic environments. The most extensive of these facies consists of sandy playa beds containing acutely terminated crystals of calcite and other carbonate salts. These sandy deposits are protected against flooding by surface or ground water, and they become wet only when rained upon. The sand facies generally includes a calichelike layer of sulfate salts a few inches thick and a few inches below the surface. It consists chiefly of sodium sulfate (thenardite) in Cottonball Basin and of calcium sulfate (gypsum) in Badwater Basin.

Panward from the sand facies is a silt facies of silty sand containing carbonate salts that grade upward into a layer containing small nodules of sulfate salts; this layer, in turn, is capped by a thin blisterlike crust of rock salt. These deposits are wet seasonally, owing to rise of ground water.

A third, but not extensive, facies is represented by marshes that are wet perennially.

Finally, there is a saline facies where the carbonate zone deposits are impregnated and irregularly heaved with rock salt. This facies is, or has recently been, subject to flooding by surface water.

Deposits in the sulfate zone cover 10 square miles. Three facies of these deposits are distinguished: massive deposits of calcium sulfate, mostly gypsum, which are elevated and protected against flooding by surface water or ground water; marsh deposits of calcium sulfate and sodium sulfate that are seasonally or perennially wet; and a saline facies of sulfate impregnated with rock salt because of frequent flooding by ground or surface water. The saline facies of the sulfate zone was not mapped separately from the saline facies of the carbonate zone.

The deposits of massive gypsum, which are 2–5 feet thick, rest on sandy silt. Capping the gypsum is a layer a few inches thick of the hemihydrate, bassanite. Locally, and perhaps seasonally, the caprock is anhydrite.

The marsh deposits consist of cauliflowerlike lumps of gypsum encrusted with gypsum and rock salt. In Cottonball Basin, the marshes include considerable quantities of glauberite and thenardite; in Badwater Basin, they are mostly gypsum.

Deposits in the chloride zone cover about 90 square miles or almost half the saltpan. In these deposits four facies have been distinguished: a smooth facies of silty rock salt, a rough facies of silty rock salt, a massive facies of rock salt, and an eroded facies where the rock salt has been washed by surface water.

Both the smooth silty rock salt and the rough silty rock salt consist of a layer of salt capped by a few inches of silt containing sulfate and other salts. The layer of rock salt ranges from a few inches to about a foot thick in the smooth facies, whereas it is 1–3 feet thick in the rough facies.

The massive rock salt is nearly pure halite, at least 3 feet thick, overlying silt and clay. The eroded rock salt includes deposits of the other three facies which have been sufficiently washed to modify greatly their characteristic appearance. The deposits of eroded rock salt grade into those of the flood plains.

A third of the saltpan, aggregating about 75 square miles, is subject to seasonal flooding. These flood plains are mostly flat expanses of damp or wet sand and silt, in part crusted with salt. Some of the surfaces are eroded on old deposits; others are Recent constructional surfaces. The salt crusts range from delicate efflorescences to firm crusts several inches thick, and in general are thick in the central part of the pan and thin near the edges. The crusts are ephemeral because of seasonal flooding.

Surface water and shallow ground water in Death Valley vary in composition from one part of the pan to another and from time to time at a given place. The variations are due to such factors as (1) differences in source, (2) position in the pan, (3) seasonal changes in temperature, precipitation, and evaporation, (4) whether the water is ground or surface water, and (5) whether it is standing or flowing.

An example of the difference in composition of the water due to difference in source is the contrast between the brine in the north, and in the south of the valley. The ratio of sodium to calcium is very much greater in the north than in the south, so that thenardite (sodium sulfate) is the common sulfate mineral in the north, whereas gypsum (calcium sulfate) is the common sulfate mineral in the south.

In general, salinity of the brines increases panward, is greatest in dry seasons, is greater in ground water than in surface water, and is greater in standing water than in flowing water.

The changes in composition of the brines as they move into the saltpan are mostly those expected from consideration of the solubility of each salt in pure water. There are exceptions, which are probably due to effects such as the decrease in solubility of sodium carbonate and sulfate in the presence of sodium chloride. The general changes in composition of the brines indicate this crystallization sequence: (1) carbonates of calcium, magnesium, and, to a lesser extent, sodium; (2) sulfates of calcium and sodium; (3) chloride of sodium; (4) chlorides of calcium, potassium, and magnesium, and sulfate of magnesium.

The orderly differences in composition of the salts in different parts of the saltpan and the orderly changes in composition of the brines as they move into the pan have been duplicated by artificially evaporating eight brines from Death Valley and analyzing the residues at different stages in the drying process.

The general sequence of fractional crystallization from carbonates to chlorides in the Death Valley brines is very similar to the sequences that have been found in other brines and other salt deposits despite a wide variety in the proportions of anions and cations.

The minerals of the Death Valley saltpan also are zoned in an orderly way with respect to their degree of hydration. This hydration zoning is superimposed on the other zoning and bears little relation to it. The lesser hydrates of carbonate and sulfate minerals and the lesser hydrates of borate minerals occur in two kinds of environments: (1) on high dry surfaces where dehydration would be expected because of the very high ground temperatures, and (2) in wet environments where there is much sodium chloride, as if these salts dehydrate at moderate temperatures in the prseence of sodium chloride or other salts.

These salt formations have given rise to ground patterns similar to those caused by ice in polar, subpolar, and alpine regions. The ground patterns consist of circles, nets, polygons, steps, and stripes. Details of the mechanisms by which such ground patterns develop are not understood, but in cold latitudes frost action is clearly a major factor. In Death Valley, where freezing temperatures are rare, the patterns must be attributed to deposition, solution, and cracking of salts.

Sorted polygons resembling those associated with frost action have developed where there is a layer of rock salt a few inches below the surface. The buried layer of salt, commonly about 6 inches thick, is cracked polygonally, and the positions of the cracks at the surface are marked by shallow troughs in which stones have collected.

Nonsorted polygonal patterns have formed also on the surface of some gypsum deposits where a surface layer of loose granular gypsum 1–6 inches thick is underlain by a firm layer of anhydrite 3–6 inches thick. The plate of anhydrite is broken by polygonal cracks which directly underlie troughs at the surface of the loose gypsum. Other nonsorted polygons in Death Valley, apparently due to desiccation or thermal cracking, are outlined by wedges of salt and are reminiscent of ice-wedge polygons in cold climates.

The gravel fans around the sides of Death Valley are terraced with sorted steps consisting of a lobate downslope border of stones embanking a tread of finer material upslope, very similar to terracettes in cold climates. In Death Valley the fine-grained material of the treads contains as much as 10 times more water-soluble salts (as much as 5 percent by volume) than does the stable ground around the steps, but we cannot be certain to what extent the steps developed because of the salt or the salt accumulated because of the steps. Rows of dowels set across 2 steps show no significant movement in 4 years, despite several soaking rains. The Death Valley forms appear to be fossil features that date from a past climatic condition and that are developing very slowly, if at all, under the present climate.

Other kinds of ground patterns noted in Death Valley and resembling those in cold climates include sorted circles, sorted and nonsorted nets, and sorted stripes.

HYDROLOGY

By Charles B. Hunt and T. W. Robinson

INTRODUCTION

The hydrologic basin draining to Death Valley includes about 9,000 square miles. Although much smaller than the hydrologic basins of Lake Bonneville or Lake Lahontan, it is nevertheless one of the large basins in the Basin and Range province (fig. 1).

About 500 square miles of the basin is below sea level. The bottom of the basin is the saltpan, which covers more than 200 square miles and lies as much as 282 feet below sea level (p. B40). The principal drainage into the saltpan is from the south by way of the Amargosa River, which drains about 6,000 square miles of the hydrologic basin. In addition, there probably is ground-water discharge into the Amargosa River drainage basin from the Mojave River basin which drains another 5,200 square miles and from Pahrump Valley which drains about 1,000 square miles including the west slopes of the well-watered Spring Mountains. The Amargosa River, despite its large drainage area, is dry most of the year where it enters the saltpan. The next largest drainage area is that of Salt Creek, which drains the northwest arm of Death Valley, an area of about 2,200 square miles. The mountains and alluvial fans within these 2 areas that drain directly to the saltpan cover about 1,200 square miles.

Altitudes in the hydrologic basin range from 282 feet below sea level near Badwater to 11,049 feet at the top of Telescope Peak in the Panamint Range. However, only a few square miles on the summit of the Panamint Range is higher than 9,000 feet; most of the mountain summits are about 7,000 feet, and extensive areas of the valley floors are between 1,000 to 3,000 feet in altitude.

Vegetation is sparse in the hydrologic basin and at least 90 percent of it is in the Lower Sonoran zone, characterized by the creosotebush. The summits of most of the mountains reach to the Upper Sonoran zone, but only a few mountains and only very small areas of them, notably the Panamint Range and Grapevine Mountains, reach to higher life zones.

Perennial surface water is restricted to some very short stretches of Salt Creek and the Amargosa River, to source pools at some large springs, and to some marshes around the edge of the saltpan in Death Valley. The saltpan may have surface water for short periods during the winter, when evaporation is reduced, or briefly, following storms. In much of the saltpan the ground is damp most of the year, indicating the presence of ground water.

The scarcity of perennial surface water and sparseness of vegetation reflect the fact that this is the hottest and driest part of the United States.

FIELDWORK

The fieldwork on which this report is based was done in connection with a general geologic study of Death Valley and the adjoining mountains. The saltpan was mapped during 1955–56 and part of 1957. Samples of salts and brines were collected during that study and

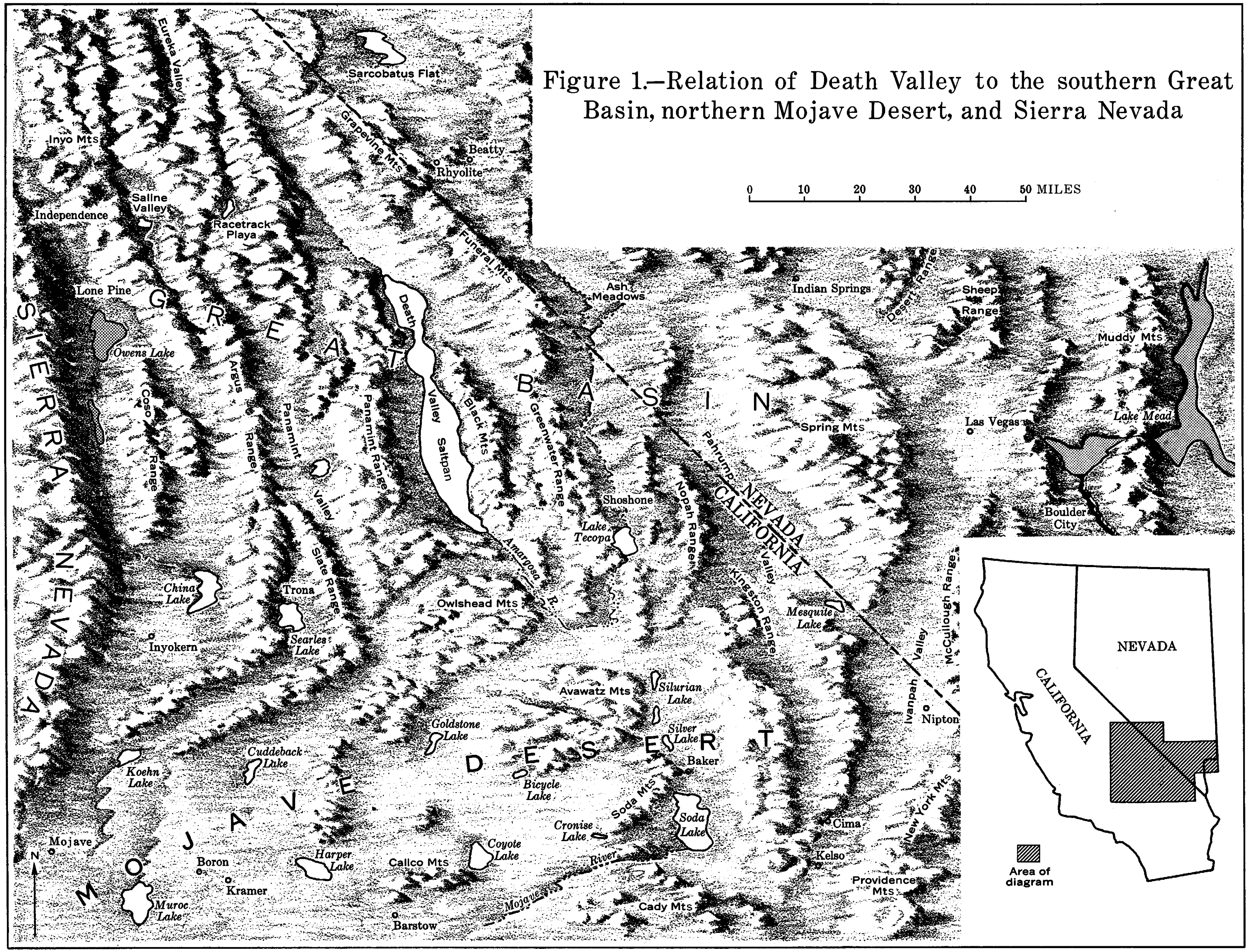

Figure 1.—Relation of Death Valley to the southern Great Basin, northern Mojave Desert, and Sierra Nevada

are the subject of the section on the saltpan. In 1957–58 the gravel fans and the plant stands on the fans and around the edge of the saltpan were mapped (see Hunt, in Hunt and others, 1965).

Most of this fieldwork was done by Charles B. Hunt. T. W. Robinson spent short periods on the project in the winters of 1957, 1958, and 1960 and about 2 months in 1959. Previously he had made field examinations and reported on the hydrology of the springs for the National Park Service and had studied the relations of phreatophytes to ground water in Death Valley.

CLIMATE

The hydrologic basin of Death Valley is the hottest and driest of any in the United States. Temperatures greater than 120°F are not uncommon during the summer months. The highest shade air temperature ever registered in the country by an official Weather Bureau thermometer, 134°F, was recorded at Greenland Ranch (now Furnace Creek Ranch) on July 10, 1913. Over the 47-year period 1912–58, Furnace Creek Ranch also has the distinction of having the lowest average annual rainfall in the United States.

Weather records of the U.S. Weather Bureau in Death Valley extend back to 1912, and some earlier records were obtained in 1891 by the Death Valley expedition (Harrington, 1892). The records are incomplete for studying the hydrology because evaporation records were not kept until 1958 at the instance of this study. An evaporation pan was installed at the National Park Service Headquarters on Cow Creek in the spring of 1958 and the long-range record of evaporation must be estimated from the brief period 1958–61.

Other weather stations in or near the hydrologic basin that help indicate the general climate are at Trona, Barstow, Bagdad, Kingston, Pahrump, Clay City, Lathrop Wells, Beatty, Sarcobatus, and Deep Springs. The annual and monthly average precipitation at these stations is given in table 1.

The conditions of low humidity, high summer temperature, high wind movement during the spring months, high evaporation, and low rainfall typify the climate of Death Valley and the low desert areas of its hydrologic basin. In spite of these extremes, the climate of Death Valley is delightful from about mid-September to about mid-May. This fact is attested to by the thousands of people (397,000 in 1961) who annually visit Death Valley.

RAINFALL

In the 48-year period, 1912–59, the U.S. Weather Bureau at Furnace Creek Ranch recorded the lowest average annual rainfall, 1.66 inches, of any official weather station in the United States. The average monthly rainfall (table 1) ranged from a high of 0.29 inch in February to a low of 0.02 inch in June. There have been periods of more than a year in which less than an inch of rain has fallen, and during 1929 and 1953 no measurable rainfall was recorded at this station. At Bagdad, Calif., which lies about 140 miles to the south, and outside the hydrologic basin, no measurable rainfall was recorded from October 1912 to November 1914.

Rainfall in the hydrologic basin varies considerably not only from year to year but over periods of years. At Beatty, Nev., some 30 miles northwest of Furnace Creek Ranch and Barstow, Calif., 110 miles to the south, the annual range has been from less than 1 inch to more than 10 inches. The long-term average annual figures for these stations are 4.25 and 4.59 inches, respectively. At Furnace Creek Ranch the annual range has been from 0 to 4.5 inches. Moreover, the 48-year period of record, 1912 through 1959, may be divided into alternating wet and dry periods of about equal length, as shown on figure 2. The 12-year period, 1924–36, stands out as the driest, with an average rainfall of only 0.83 inch a year. The following 11-year period, 1936–47, with an average of 2.63 inches a year, is the wettest.

Over a longer period of time the fluctuations have been very much greater. Archeologic evidence (Hunt, A. P., 1960) indicates that during a wet period which immediately preceded the Christian Era, Death Valley held a lake 30 feet deep (p. B48). A number of spring sites now dry were occupied by pre-bow and

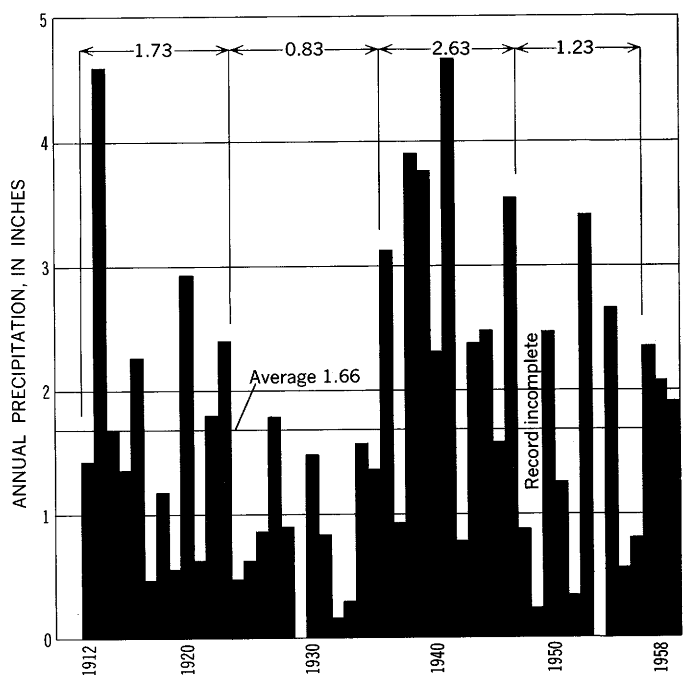

FIGURE 2.—Annual and average precipitation showing wet and dry periods at Furnace Creek Ranch, Death Valley, Calif.

TABLE 1—*Monthly and annual precipitation, years of record, and altitude of 12 weather stations in and around the Death Valley hydrologic basin*

[Data from publications of U.S. Weather Bureau. Precipitation given in inches, altitude in feet above sea level]

Month	Trona	Barstow	Bagdad	Kingston	Pahrump	Clay City	Lathrop Wells	Beatty	Deep Springs	Greenland Ranch (Furnace Creek Ranch, Death Valley)	Cow Creek (Death Valley)	Sarcobatus
January	0.63	0.77	0.17	0.56	0.82	0.16	0.37	0.66	0.64	0.23	0.19	0.41
February	.86	.60	.33	.65	.60	.54	.37	.72	.54	.29	.38	.18
March	.53	.71	.06	.40	.45	.34	.33	.54	.56	.17	.19	.24
April	.18	.17	.24	.23	.30	.15	.29	.43	.92	.11	.20	.36
May	.09	.09	.14	.11	.28	.24	.22	.20	.49	.07	.10	.19
June	.07	.09	.19	.10	.19	.00	.06	.08	.09	.02	.02	.06
July	.04	.19	.29	.27	.21	.00	.15	.22	.31	.08	.12	.61
August	.14	.24	.30	.59	.25	.58	.14	.26	.13	.12	.15	.42
September	.22	.17	.23	.28	.35	.00	.07	.18	.24	.11	.13	.18
October	.19	.35	.15	.18	.25	.52	.17	.30	.19	.10	.16	.20
November	.34	.28	.16	.23	.20	.19	.45	.38	.50	.15	.15	.49
December	.79	.59	.02	.50	.66	.04	.28	.62	.62	.21	.38	.25
Annual	4.16	4.25	2.28	4.10	4.56	2.76	2.90	4.59	5.23	1.66	2.17	3.59
Years of Record	41	46	24	17	10	4	14	36	12	47	24	15
Altitude	1,695	2,142	784	2,475	2,830	2,185	2,665	3,300	5,225	−168	−125	4,020

arrow peoples, but they have not been occupied since the bow and arrow was introduced to Death Valley, about A.D. 500. The archeologic evidence also suggests that some springs have become increasingly saline and have therefore been abandoned. For example, Coyote Hole, which has been little used for the last 500 or 1,000 years, was much used before that time. During the several millennia in the early part of the Recent, the climate is thought to have been as dry and as hot as it is now, but before that, in late Pleistocene time, there were lakes in the valley as deep as 600 feet.

The average yearly precipitation pattern is well illustrated in table 1 by four stations, Trona, Barstow, Greenland Ranch, and Beatty. The records for these stations are sufficiently long, 36 years or more, to provide a firm monthly average. The geographic distribution of the stations to the west, south, in, and east of Death Valley is such as to be indicative of the precipitation over the basin. The precipitation is greatest during the months of December, January, and February, then declines rapidly to its low point in June or July, followed by a slight increase in August. A second low point occurs in September, followed by gradually increasing rainfall during the next 2 months. Except for Bagdad, the stations listed in table 1 show the same general yearly distribution of precipitation. At Bagdad the distribution is the reverse—the high period occurring in July and August and the low period in December.

The record of precipitation at 12 stations in and around the hydrologic basin of Death Valley, ranging in altitude from 168 feet below sea level to 5,225 feet above sea level, is also given in table 1. An analysis of the records indicates that precipitation increases with altitude at a rate of about two-thirds of an inch for each 1,000 feet of altitude to 5,000 feet. This relation is shown graphically on figure 3.

Above 5,000 feet all indications point to a sharp increase of precipitation with altitude. Storage gages in the Spring Mountains to the east in Nevada, and observations of precipitation at Aguereberry Point in the Panamint Range at an altitude of 6,433 feet, point to a precipitation of 15 inches or more at altitudes of 8,000–10,000 feet. This increase of about 10 inches between 5,000 and 10,000 feet indicates a change of 2 inches for each 1,000 feet change in altitude above 5,000 feet. A sketch map showing probable distribution of rainfall in the hydrologic basin is given on figure 4.

A frequency analysis of the record shows an annual precipitation of less than 1 inch during 40 percent of the period, 2 inches or less for 65 percent of the time, and 3 inches or less for 85 percent of the time. The precipitation has exceeded 4 inches only 4 percent of the time, twice in 48 years.

Although the precipitation in the hydrologic basin of Death Valley in any one year, or a short period of years, appears to be erratic, and varies widely with time and place, a study of the long-term records shows the following definite patterns.

1. The precipitation is greatest in winter and least in the summer.
2. It increases with altitude but not at a uniform rate; the average precipitation above 5,000 feet is about three times that below that altitude.

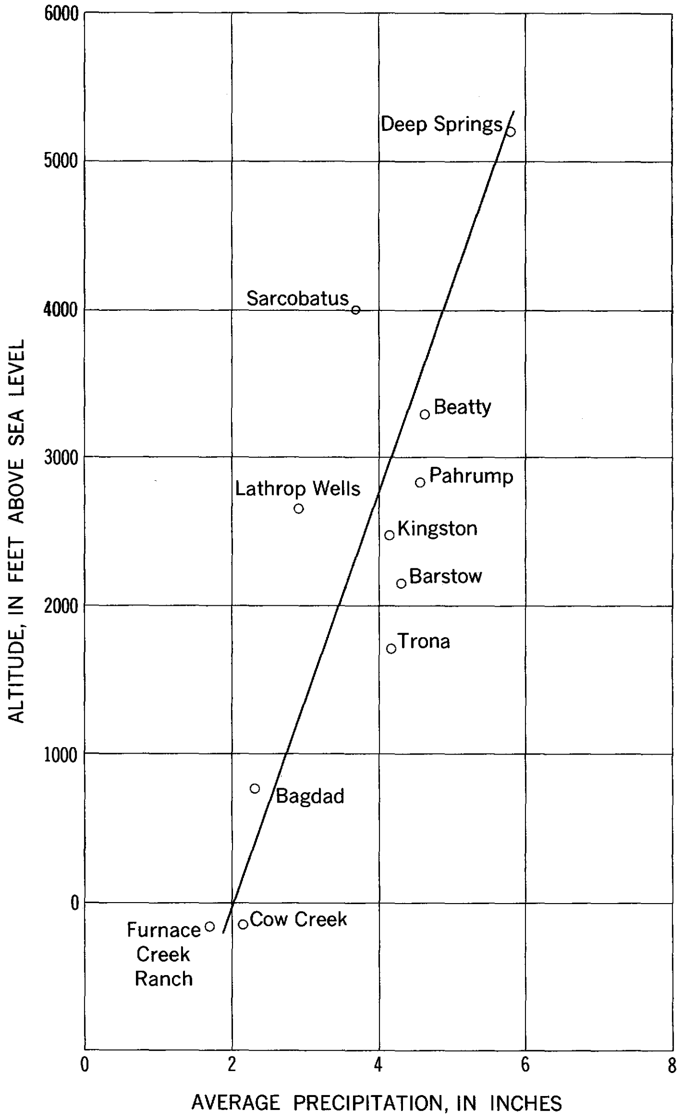

FIGURE 3.—Relation of precipitation to altitude in and around Death Valley.

3. Wet and dry cycles alternate in periods ranging from about 10 to 12 years.

EVAPORATION

Evaporation in the hydrologic basin of Death Valley is the highest in the United States. Pan evaporation over most of the basin is more than 120 inches per year (Kohler and others, 1959). For the purpose of this study a standard Weather Bureau evaporation pan was installed in April 1958 and maintained for 3 years at the weather station at the National Park Service Headquarters on Cow Creek. Evaporation for the first year of record, May 1, 1958, to May 1, 1959, was 155.05 inches. As far as can be ascertained, this is the highest evaporation from a standard pan ever recorded in the United States. Table 2 gives the monthly and average evaporation from the beginning of the record in May 1958 until April 1961, when the station was moved to the new National Park Service Headquarters at the Visitors Center. The monthly evaporation during that time has ranged from a low of 2.72 inches in January 1960 to a high of 22.71 inches in July 1960. During the summers of 1958 and 1959, daily evaporation exceeded 1 inch once each summer, and in the summer of 1960 it exceeded 1 inch four times. The average daily evaporation in June and July was approximately 0.7 inch per day, and in August, 0.65 inch per day. In December and January it was slightly in excess of 0.10 inch per day.

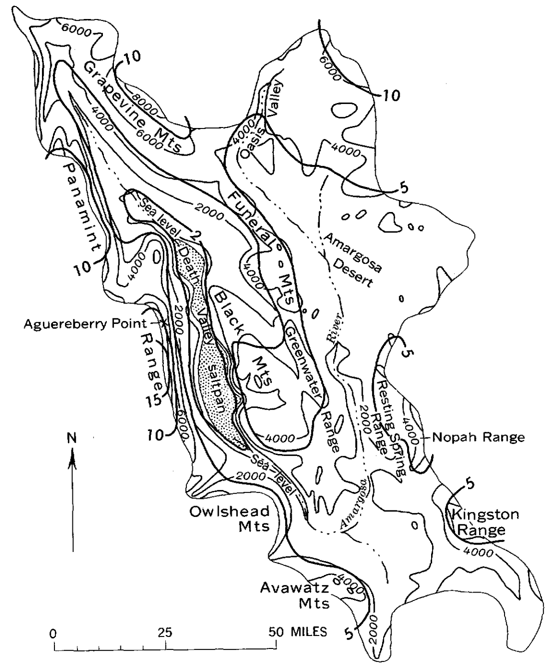

FIGURE 4.—Sketch map showing probable distribution of rainfall in the Death Valley hydrologic basin.

Daily evaporation varies rather widely during winter and summer as the result of the influence of

TABLE 2.—*Monthly and average pan evaporation in inches, at National Park Service Headquarters, Death Valley, Calif.*

[From records of U.S. Weather Bureau]

	1958	1959	1960	1961	Average
January	--------	4. 02	2. 72	2. 88	3. 21
February	--------	5. 66	5. 38	5. 82	5. 62
March	--------	10. 92	9. 90	9. 94	10. 25
April	--------	13. 77	14. 17	14. 31	14. 08
May	17. 98	17. 13	16. 65	(1)	17. 25
June	21. 71	21. 03	21. 36	--------	21. 37
July	22. 44	21. 26	22. 71	--------	22. 14
August	19. 16	19. 84	21. 51	--------	20. 17
September	17. 90	13. 48	14. 69	--------	15. 36
October	11. 09	10. 96	10. 09	--------	10. 71
November	6. 70	4. 97	3. 72	--------	5. 13
December	3. 68	3. 82	4. 31	--------	3. 94
					149. 23

1 Moved to National Park Service Visitors Center at Furnace Creek Ranch.

changes in temperature, wind movement, and humidity. Evaporation is greatest when the temperature and wind movement are high and the humidity low. These conditions prevail most of the time in Death Valley and account for the high evaporation rate.

The aridity of Death Valley is magnified by its high evaporativity. A measure of this is the ratio of yearly evaporation to rainfall which, at the location of the weather station, is about 90 to 1.

As a basis for estimating whether the rate of evaporation was markedly different in different parts of the saltpan and between the saltpan and gravel fans, tubs of water were placed at camps and regular measurements made of the changes in water level. Losses from a tub 2 feet in diameter and 10 inches deep, placed in a shallow pool of water about 100 feet in diameter at Cottonball Marsh, in January 1959 was 99 percent of that of the evaporation pan at the weather station on Cow Creek at the National Park Service Headquarters. Losses from another tub—at a camp at almost 2,000 feet altitude at the mouth of Hanaupah Canyon—in the following February were about the same as the losses at the weather station.

In order to develop some ideas about the relative rates of evaporation from slightly salty water, wet salt, and wet saliferous mud, a pail of each was collected and weighed. The fall in level of the slightly salty water during the first 2 weeks was about 135 percent of the fall in the evaporation pan; the loss totaled just under 12 pounds, equal to about 12 pints. In that same period neither the wet salt nor the wet mud lost as much as a pound. Over a period of 12 weeks the pail of wet salt had lost 3.5 pounds (3.5 pt) of its water, and the salt still retained 50 percent (by weight) of moisture. The wet mud lost 2 pounds, and it retained 19 percent (by weight) of moisture. The loss from the pail of wet salt was equivalent to a depth of 1.2 inches and that from the mud, a depth of 0.70 inch. The loss from the evaporation pan during this 12-week period was 25.4 inches. The loss for the first 8 weeks was nearly the same for both the salt and the mud, being 2.5 and 2 pounds, respectively. Loss from the evaporation pan, located only a few hundered feet distant, during the 8 weeks was 11.9 inches. During the last 4 weeks there was no measureable loss from the mud pail, whereas the rate of loss had decreased slightly for the salt pail amounting to only 1 pound in the 4 weeks. At the same time the rate of loss from the evaporation pan had increases sharply, and during the last 4 weeks it was twice that of the preceding 8 weeks.

The surface of the pail containing the mud was covered with a film of water at the start of the test. This soon disappeared and the mud surface at the end of 12 weeks was considerably drier, exhibiting a thin crust of salt and mud. This crust appeared effective in reducing or preventing evaporation at the end of 8 weeks and very probably much sooner. As a result, it was felt that only the results during the first month of the test should be used in estimating evaporation from the salty mud surfaces of the saltpan. During this period the surface of the mud in the pail was similar to the mud in the saltpan, and the decrease in rate of loss from the pail as the result of "crusting" is believed negligible. The loss during the first month was 1.5 pounds from both the mud and the salt pail. This is equivalent to a depth of 0.50 inch, or for the 33-day period an average of 0.015 inch per day.

That the loss from salty mud surfaces is small is borne out by studies along the east shore of Great Salt Lake, Utah. Using rates of salt accumulation as a measure of evaporation, Feth and Brown 1962 found that evaporation from salty mud surfaces ranged from 0.0015 to 0.006 and averaged 0.003 inch per day during the months of July and August 1954. The rate from the test in Death Valley is about five times that at Great Salt Lake. Differences in climate, such as humidity and wind movement, may account for a part of the difference. Humidity is lower and wind movement higher in Death Valley than at Great Salt Lake. And it is true that the playa is slow to dry after being flooded.

As a result of the experiment it was necessary to drastically revise impressions about the degree of loss of water by evaporation from the salty mud and salt-crusted parts of the saltpan.

TEMPERATURE

A summary of the temperature record at Furnace Creek Ranch is given in table 3; a summary for seven stations in and around the hydrologic basin of Death Valley is given in table 4. The temperature at Furnace Creek Ranch is higher than at any of these other

TABLE 3.—*Monthly temperatures (°F), 1911 through 1952, at Furnace Creek Ranch*

[Data from U.S. Weather Bureau climatic summary]

	Average			Temperature	
	Monthly	Maximum	Minimum	Highest	Lowest
Jan	51.4	64.9	36.9	85	15
Feb	58.1	72.3	43.9	91	27
Mar	65.5	80.4	50.6	100	30
Apr	74.6	89.6	59.5	109	35
May	83.4	99.1	67.7	120	42
June	94.0	110.4	77.6	124	49
July	102.0	116.4	87.6	134	62
Aug	98.9	113.7	84.0	126	65
Sept	88.9	105.5	72.3	120	41
Oct	74.0	90.3	57.7	110	32
Nov	60.6	75.6	46.3	91	24
Dec	52.0	65.8	38.2	86	19
Annual	75.3	90.3	60.2	134	15

stations by about 10°F in nearly every category. Temperatures of more than 110°F, except in the high altitudes, may be expected in the basin during the summer months of May through September.

In the Death Valley, temperatures of 120°F or higher are not uncommon during these months. July, the hottest month, has a long-time average maximum of 116.4°F at Furnace Creek Ranch. The 134°F recorded at the ranch is exceeded by the 136°F observed at Azizia, Tripolitania, in northern Africa, on September 13, 1922, which is generally accepted as the world's highest temperature recorded under standard conditions.

TABLE 4.—*Average, maximum, and minimum temperature (°F) at some weather stations in and around the Death Valley hydrologic basin*

[Data from U.S. Weather Bureau climatic summaries]

	Average			Temperature	
	Annual	Maximum	Minimum	Highest	Lowest
Furnace Creek Ranch	75. 3	90. 3	60. 2	134	15
Trona	64. 9	80. 9	49. 0	115	10
Barstow	63. 6	79. 4	47. 1	114	12
Bagdad	72. 4	83. 6	61. 3	119	10
Lathrop Wells	63. 6	79. 5	47. 5	115	5
Beatty	59. 3	75. 9	42. 5	113	1
Sarcobatus	55. 9	73. 7	37. 9	110	−4

However, Furnace Creek Ranch is probably not the hottest locality in Death Valley. For example, during the summer months at least, temperatures might be higher at Badwater. Maximum and minimum temperature readings at 1-week intervals by the National Park Service from May to October 1934 suggested that this was so. In June 1959, as part of this study, a hygrothermograph was installed in a standard shelter at Badwater and serviced by the National Park Service personnel. The average daily maximums and minimums were higher for the months of July and August than at either of the stations at Furnace Creek Ranch or National Park Service Headquarters, as shown by the following tabulation.

	Badwater	Furnace Creek Ranch	National Park Service Headquarters
July 1959–60			
Average maximum	121. 4	118. 7	119. 8
Average minimum	93. 0	92. 0	92. 0
Average	107. 2	105. 4	105. 9
August 1959–60			
Average maximum	116. 0	115. 0	114. 0
Average minimum	88. 3	87. 0	87. 4
Average	102. 2	101. 0	100. 7

Daily maximums were also higher than at Furnace Creek. In July 1959 the highest temperature recorded at Furnace Creek was 124°F and at National Park Service Headquarters 125°F. At Badwater the temperature exceeded 125°F on 11 days. There were recorded maximums of 126°F on 6 days, 127°F on 3 days, and 128°F and 129°F on 1 day each. In July 1960 the temperature at Furnace Creek exceeded 124°F on 1 day when 129°F was recorded, and at National Park Service Headquarters it exceeded 124°F on 4 days with a maximum of 126°F. At Badwater the temperature exceeded 124°F on 5 days; recorded maximums were 125°F on 1 day, 127°F on 1 day, and 128°F on 3 consecutive days.

Despite these extremes of temperature, the average annual temperature at Furnace Creek Ranch is a pleasant 75.3°F. The average daily range in temperature is about 30°F.

Ground temperatures, even in winter, are higher than air temperatures. In cool weather the ground surface at midday commonly is hotter than the air temperature by about 35°F, and in warm weather the ground may be more than 50°F hotter than the air. Smooth surfaces, like sand dunes or mud flats, are hotter than the roughened salt surfaces. A maximum ground-surface temperature of 190°F was recorded in August 1958 on the surface of the massive gypsum at Tule Spring.

Even where the ground temperatures are greatest, however, the temperature drops rapidly a few inches into the ground; the temperature 1 foot below the surface varies only a little from the seasonal average air temperature, and at about 4 feet the temperature varies only a little from the annual average air temperature. In other words, a few inches below the surface there is little daily range in temperature, although through the year the temperature may range a few tens of degrees. A few feet below the surface the temperature is virtually constant throughout the year.

Where the ground is crusted with salt, the temperature gradient is less steep, partly because the salt is diathermous and partly because it is cavernous.

Some random measurements of ground-surface temperatures are given in tables 5 and 6.

During the course of the fieldwork it was discovered that air temperatures at night, at the level of the saltpan, were substantially lower than air temperatures 1,500–2,000 feet higher on the gravel fans. Minimum temperatures at the saltpan commonly were 10°F lower than at the tops of the fans. This observation led to making a series of temperature readings using maximum-minimum thermometers; some of the results are given in the table below.

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Maximum and minimum air temperatures, November 1958 to March 1959

[Temperatures marked with an asterisk have not been determined]

Reading No.	Location	Altitude (feet)	Minimum (°F)	Maximum (°F)	Date
1	Top of Johnson Canyon fan	2,000	44	65	Nov. 29 to Dec. 2, 1958
	Foot of Johnson Canyon fan	−250	35	72	
2	Top of Johnson Canyon fan	2,000	48	(*)	Dec. 8
	Foot of Johnson Canyon fan	−250	38	(*)	
3	Top of Park Village Ridge	400	48	(*)	Dec. 22
	Foot of Park Village Ridge	−250	42	(*)	
4	On Beatty Junction fan	500	65	(*)	Jan. 12, 1959
	Foot of Beatty Junction fan	−250	62	(*)	
5	On Beatty Junction fan	500	52	71	Jan. 13
	Foot of Beatty Junction fan	−250	50	72	
6	On Beatty Junction fan	500	46	78	Jan. 15
	Foot of Beatty Junction fan	−250	37	83	
7	Travertine Springs	400	42	(*)	Jan. 19
	Saltpan below Travertine Springs	−250	36	(*)	
8	Travertine Springs		49	72	Jan. 20
	Saltpan below Travertine Springs		39	67	
9	Top of Trail Canyon fan	1,000	55	79	Mar. 15
	Foot of Trail Canyon fan	−250	47	90	
10	Capture Canyon fan	500	56	90	Mar. 21
	Foot of Capture Canyon fan	−250	42	90	

This difference in temperature between the top and foot of the fans could not be accounted for by cold-air drainage from the mountains, because thermometers set at canyon mouths also recorded higher minimums than did the thermometers at the saltpan. However, during windy periods, there was little difference between the high and low thermometers. The cooler air over the saltpan apparently is attributable to evapotranspiration of ground water in the area of the saltpan. It was found that the cold air formed nightly as a layer over the saltpan, averaging about 300 feet thick.

The effect of transpiration on air temperatures was noted by placing thermometers under the tamarix growth at Eagle Borax and other thermometers at the same altitude under a creosotebush nearby. *Tamarix*, being a phreatophyte and having a plentiful supply of water at this locality, was presumed to transpire more than the xerophytic creosotebush. Two such readings are as follows:

Under—	Temperature (°F) Min	Max
Creosotebush (xerophyte)	60	100
Tamarix (phreatophyte)	55	(?)
Creosotebush	65	104
Tamarix	61	78

TABLE 5.—*Maximum ground temperatures (°F) on some different kinds of ground, April to November 1957*

[Readings by Natl. Park Service Rangers D. M. Spalding and R. E. Sellers]

Location	*Range of maximum temperature (°F)*
On north slope on gravel ridge above National Park Service residential area; alt 325 ft above sea level; ground bare	110–164
Flat ground in saliferous sandy silt in saltgrass at mouth of Cow Creek; alt 250 ft below sea level	144–180
Flat ground in smooth sandy silt about 500 ft west of the mouth of Cow Creek; alt 260 ft below sea level	126–174

HUMIDITY

The aridity of Death Valley is brought into sharp focus when the humidity there is compared with that at stations in the surrounding desert areas. Table 7 lists the average relative humidity at different times of the day at Independence, Calif., Yuma, Ariz., and Tonopah, Nev., to the west, east, and south of Death Valley. Observations made by the 1891 expedition to Death Valley indicated an average daily relative humidity of 30.6 percent in the morning and 15.6 percent in the evening (Harrington, 1892), considerably lower than at the 3 localities cited. Long-term averages are not available for Death Valley, but a 2-year record of daily maximum and minimum relative humidity is shown in table 8.

TABLE 6.—*Some differences in temperature (°F) at various depths in different kinds of ground during 1956*

	Time and date	Kind of ground	Temperature (°F) Air (waist high)	Surface	Subsurface °F	Depth (in.)
1	Noon, Jan. 11	Sandy ground in stand of mesquite (*Prosopis juliflora*)		73	70	3
					68	6
					54	9
2	Noon, Feb. 23	Silty sand in stand of pickleweed (*Allenrolfea occidentalis*)	82	98	63	12
3	10 a.m., Feb. 27	Damp sandy ground in saltgrass (*Dostichlis stricta*)		84	60	10
4	1 p.m., Feb. 28	Damp sandy ground in stand of mesquite	77	115	65	6
5	Noon, Feb. 29	Silty ground in stand of arrowweed (*Pluchea sericea*)	74	95	68	4
6	2 p.m., Feb. 29	Bare silty ground in chloride zone	77	105	70	5
7	1 p.m., Mar. 1	Silty ground in stand of pickleweed	80	100	68	6
8	Noon, Mar. 6	Bare wet silty ground in flood plains	77	93	77	2
9	2 p.m., Mar. 20	Bare silty ground in chloride zone		122	72	6
10	11 a.m., Mar 21	Saliferous sandy ground in saltgrass	91	129	73	6
11	1:30 p.m., Mar. 21	Fine pebble pavement with stand of desertholly (*Atriplex hymenelytra*)	95	127	90	4
12	11 a.m., Mar. 30	Bare silty ground in flood plain	86	122	80	5
13	1 p.m., Mar. 30	do	93	127	77	8
14	1 p.m., Apr. 9	Sandy ground with stand of mesquite	96	140	86	6

TABLE 7.—*Average relative humidity, in percent, at Independence, Yuma, and Tonopah*

[Data from U.S. Weather Bureau climatic summaries]

Independence, Calif.		*Yuma, Ariz.*		*Tonopah, Nev.*	
5 a.m.	51	6 a.m.	60	5 a.m.	54
Noon	26	Noon	26	--------	--
5 p.m.	28	6 p.m.	27	5 p.m.	36

TABLE 8.—*Monthly relative humidity, in percent, during the period May 1, 1958, to May 1, 1960, at National Park Service Headquarters on Cow Creek, Death Valley, Calif.*

	Average			Highest	Lowest
	Monthly	Maximum	Minimum		
January	27.2	36.9	17.3	72	10
February	25.9	36.0	16.1	74	6
March	14.0	19.0	9.0	38	5
April	12.5	16.3	8.7	32	4
May	14.5	19.9	9.1	68	4
June	11.4	14.7	8.2	22	4
July	11.3	14.2	8.3	27	5
August	16.0	20.8	11.1	64	6
September	15.8	20.7	11.0	68	3
October	15.7	20.6	10.7	67	6
November	20.1	27.1	13.0	69	4
December	26.1	32.8	19.3	68	8
Period	17.5	23.2	11.8	74	3

During this period May 1, 1958, to May 1, 1960, based on 657 days of record at National Park Service Headquarters, Death Valley, the average relative humidity was 17.5 percent. Although the relative humidity reached a low of 3 percent on one occasion and 4 percent on separate occasions during the 2-year period, the driest day occurred on April 8, 1959, when the minimum and maximum relative humidity was 4 and 6 percent, respectively.

The humidity on the east side of the valley, where the instrument is located, is believed to be higher than on the west side. This is due to westerly winds moving water vapor resulting from evaporation and transpiration on the floor of the valley toward its eastern side.

Some measurements at different places during a single day (Nov. 30, 1957) suggest that humidity is greater at the floor of Death Valley than on the adjoining mountains, as follows:

	Location	Air temperature (° F)	Humidity (percent)
7 a.m.	National Park Service Headquarters	41	24
7:45	On massive gypsum at Badwater	37	22
10	At mouth of Hanaupah Canyon; alt 1,600 ft.	58	10
11	In Hanaupah Canyon at head of road; alt 3,600 ft.	48	9½

A traverse across the northern part of the floor of Death Valley, on April 22, 1959, tends to confirm the observations of greater humidity on the floor of the valley than on the sides. Wet- and dry-bulb temperature readings were taken at half-mile intervals along State Route 190, from its junction with the road to Scottys Castle, to Stovepipe Wells Hotel, and thence up the road to Mosaic Canyon. In the lowest part of the valley the highway crosses an area of evapotranspiration discharge. Here there is discharge of ground water by phreatophytes, largely arrowweed and pickleweed, and probably some discharge by evaporation from the land surface. Xerophytic growth, largely creosotebush, occurs on either side of the phreatophytes, and although there is doubtless some evapotranspiration discharge by them, it is generally considered to be only a small fraction of that discharged by phreatophytes.

The relative humidity was greatest near the east edge of the phreatophyte growth. Near the west (windward) edge of the phreatophyte growth the humidity had decreased to nearly that prevailing in the dry xerophytic area to the west, whereas in the xerophytic area to the east of the phreatophyte growth it was from 5 to 12 percent above the humidity on the west side. The slight rise in humidity at Stovepipe Wells Hotel is believed due to irrigation of some shade trees near the buildings. Wind movement was estimated as between 5 and 10 miles per hour. As the prevailing winds are from the west, higher humidities are believed to prevail on the east side of the valley rather than on the west side.

WIND

The winds in Death Valley are variable in direction, but they nearly always have a western component. Strong northerly and southerly winds for short periods are not uncommon, and strong southerly winds may reverse the flow of water on the saltpan. As an example, during the winter of 1959 water that had collected on the floor of Middle Basin was blown back to Cottonball Basin by strong southerly winds.

Sand dunes to the north and east of Stovepipe Wells and along the west side of the valley south of Tule Springs, although testifying to the wind activity, do not necessarily indicate high wind velocities, for fine dune sand may be moved by winds as low as 10 miles per hour.

From the 2 years of record, given in table 9 (p. B12), it may be seen that the months of April, May, and June are the windiest of the year and November and January, the calmest.

ROCK TYPES IN THE DEATH VALLEY HYDROLOGIC BASIN

Almost every type of rock can be found in the Death Valley hydrologic basin, but for discussing their principal hydrologic characteristics they can be grouped into two major kinds: the hard rocks forming the mountains and underlying the basins and the sediments that form deep fill in the basins.

TABLE 9.—*Average monthly and daily, highest and lowest daily, wind movement, in miles, in the period May 1, 1958, to May 1, 1961, at National Park Service Headquarters, Death Valley, Calif.*

	Average		Highest	Lowest
	Monthly	Daily		
January	446	14	124	0
February	1, 269	46	236	0
March	1, 375	44	190	0
April	1, 725	58	335	3
May	1, 661	54	188	3
June	1, 640	55	151	2
July	1, 369	44	132	4
August	1, 485	48	171	2
September	1, 278	43	293	1
October	1, 134	37	236	0
November [1]	602	20	271	0
December [1]	1, 105	37	303	0

[1] Anemometer inoperative in 1958.

The most extensive hard rocks are of Precambrian and Paleozoic age. Of these, the Paleozoic carbonate rocks, many thousands of feet thick, are especially important in the water economy of the region.

In terms of the water economy three principal kinds of valley fill need to be distinguished: the Tertiary formations, the Quaternary gravels, and the Quaternary fine-grained sedimentary deposits. The Tertiary formations crop out in the northern part of the Black Mountains and underlie the Quaternary fill. Quaternary gravels are around the edges of the basins, and impermeable fine-grained Quaternary sedimentary deposits are in the interiors (fig. 5).

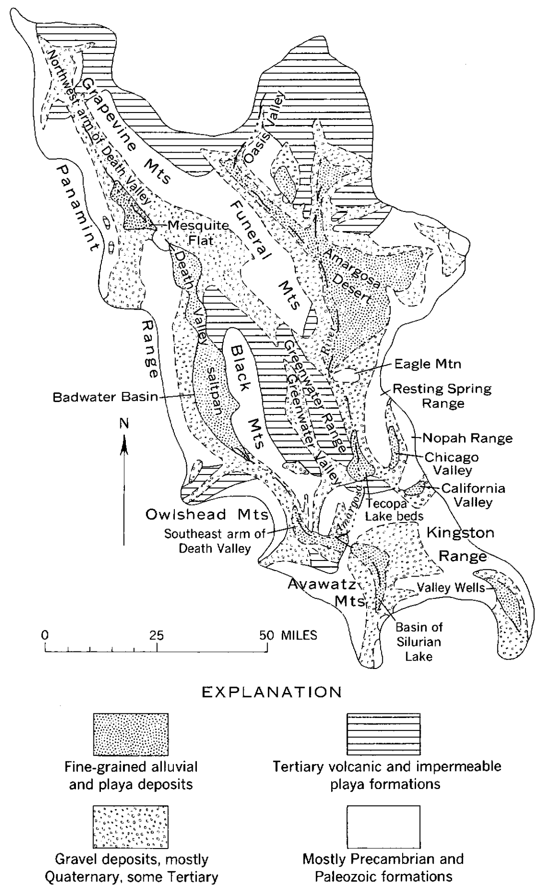

FIGURE 5.—Sketch map of the Death Valley hydrologic basin showing general location and extent of the principal kinds of rocks that are important in the hydrology.

HARD-ROCK FORMATIONS

Hard-rock formations crop out in the mountains, and although these areas comprise only about 20 percent of the hydrologic basin, they probably receive as much rainfall as the other and lower 80 percent. The slopes are steep, the soil cover is thin or lacking, and the rate of runoff is high. The principal rock types and some of the hydrologic properties are indicated in table 10.

The carbonate formations, aggregating more than 15,000 feet thick, are highly important in the water economy of the region—partly because of their extent and thickness, partly because they occur where rainfall and snowfall are greatest, but chiefly because these rocks are much fissured and seem to have provided open, cavernous conduits permitting ground water to move through topographic divides. Where carbonate formations underlie the valleys, ground water may discharge from the fissured carbonate formations into the overlying valley fill; or, the fissured carbonate rocks may drain water from the valley fill.

Roughly, half the area of Precambrian and Paleozoic rocks is bare rock where runoff is rapid. The other half is covered by a few inches or a few feet of highly permeable stony colluvium and soil where the surface water runoff is slowed because of seepage into the ground. Part of the water seeping into the thin colluvium and soil escapes into the fissures which serve as open channels through the parent rock formations.

The Tertiary rocks are partly volcanic and partly sedimentary deposits derived largely from the volcanics. The volcanic rocks include many highly permeable types; the sedimentary rocks are in part impermeable playa deposits. Altogether these rocks crop out in about 25 percent of the hydrologic basin, and they underlie much or all of the Quaternary fill.

The volcanic rocks of the Tertiary are thickest in the northern part of the Black Mountains. A thinner series of volcanic rocks, mostly less than 500 feet thick, overlaps the east foot of the Panamint Range north of Johnson and Trail Canyons. Northward these volcanic rocks intertongue with the Tertiary sedimentary deposits. Volcanic rocks are thick and extensive bordering the Amargosa Desert and also in the Greenwater Range. Together, these volcanic rocks comprise about 10 percent of the hydrologic basin.

TABLE 10.—*Hard-rock formations of pre-Tertiary age and their hydrologic properties in the Death Valley hydrologic basin*

Rock type	Age	Approximate percent of area of basin	Principal area	Hydrologic properties
Granitic (or monzonitic) rocks.	Cretaceous or Tertiary.	2	Panamint Range north of Marble Canyon; south of Tucki Mountain; head of Hanaupah and Starvation Canyons; Owlshead Mountains; Warm Springs and Anvil Spring Canyons; numerous places in Black Mountains; South end of Greenwater Range; Kingston Mountains.	Rock dense and not permeable but broken by numerous widely spaced fissures that provide channels for seepage of ground water. Quality of water good.
Limestone and dolomite formations; mostly dolomite.	Paleozoic.	10	Most of east slope of Panamint Range north of Death Valley Canyon; south half of the Funeral Mountains; part of the Grapevine Mountains; ranges east of the Amargosa River above Tecopa.	Rocks dense and not permeable but broken by closely spaced fissures; some partly closed by secondary carbonate minerals; others opened by solution and cavernous. Water potable but hard.
Quartzite, argillite, diabase, gneiss, schist, and some dolomite and shale.	Early Paleozoic and Precambrian.	10	High part of Panamint Range and the east slope south of Death Valley Canyon; southern part of Black Mountains; north half of Funeral Mountains, Avawatz Mountains; small areas east of the Amargosa River.	Rocks dense but broken by closely spaced joints and fissures. Numerous seeps of good quality water.

The volcanic rocks are highly permeable, because they are porous and fissured. A considerable part of the water falling on this gound must enter it and become part of the ground-water system.

Sedimentary deposits of Tertiary age include both permeable and impermeable rocks. Older formations include a high proportion of permeable sandy and conglomeratic sediments. In Death Valley these rocks form the Kit Fox Hills and underlie the permeable Quaternary fan gravels at shallow depths along the front of the Funeral Mountains. Much of the water entering the ground in these areas probably seeps downward to the water table. Except where slopes are steep, these rather permeable rocks support moderate stands of xerophytic shrubs.

The younger Tertiary sedimentary rocks, such as the Furnace Creek Formation, include a high percentage of fine-grained playa sediments. In Death Valley these rocks are exposed at the north end of the Black Mountains and underlie the gravel on the fans north of Furnace Creek Wash; they also form the Salt Creek Hills. Similar deposits are exposed in Cooper Canyon, the Greenwater Range, and along each side of the Amargosa Desert. Altogether these rocks form about 15 percent of the hydrologic basin. Except at altitudes above about 1,500 feet, their outcrops are without vegetation. Surface-water runoff is retarded by a fluffy surface layer that is easily penetrated by light rains and then dried by evaporation. Such water does not enter the ground-water or surface-water system. Other surfaces are firm and favor runoff. At places, notably in the East Coleman Hills, salines have been removed by solution from the deposits and a miniature karst topography is developed. This solution pitting probably occurred when these areas were flooded by Pleistocene lakes. Ground-water discharge would have been high as the lakes fell, and the solution could have taken place quickly at such times. The channels connecting these solution pits discharge into the present washes, and only a small part of the water entering them is added to the ground-water system.

UNCONSOLIDATED QUATERNARY DEPOSITS

The Quaternary deposits that are significant in the water economy of the region include (1) gravel deposits, (2) fine-grained alluvial and playa deposits, (3) salt deposits and saliferous playa deposits, (4) dune sand, and (5) spring deposits of travertine. The valley fill represented by these deposits comprises more than half the hydrologic basin (fig. 5). Gravel is by far the most extensive of these deposits and comprises about 40 percent of the hydrologic basin. Most of the remainder is represented by fine-grained sediments, much of which is salt crusted.

GRAVEL DEPOSITS

Gravel deposits in the Death Valley hydrologic basin are of three kinds and three ages. The oldest, the Funeral Formation, is well cemented and covered by desert pavement. Gravel of intermediate age is less well cemented, but also is characterized by having desert pavement. The youngest gravels are least well consolidated and are without desert pavement. The older gravels commonly form benches or terraces well above the present drainage; consequently, they receive only the water that falls directly on them. The youngest gravel includes deposits that are subject to flooding, and these are important areas of recharge of ground water (fig. 6).

Fanglomerate belonging to the Funeral Formation is found in the syncline between the Black Mountains and the Funeral Mountains. It also occurs on the Artists Drive fault blocks and at Mormon Point. Such fanglomerates comprise about 5 percent of the hydrologic basin.

The fanglomerate in the Funeral Formation is sufficiently well cemented to stand in cliffs and to be cut by calcite veins. The cement is mostly calcium carbonate and is most abundant downslope from large springs, where there is much ground water, as in the fault blocks west of Nevares Springs and in the trough of the Texas Spring syncline.

The fanglomerate is permeable and has open channels along fissures. Moreover, it overlies impermeable beds, so that the base of the fanglomerate is an important aquifer. Where the aquifer is offset by faults and folds, there are springs.

Little water enters the fanglomerate from the surface, because the surface is smooth desert pavement underlain by a layer of clayey or silty sediments a few inches thick. The combination of these features favors runoff rather than recharge. Ground water at the base of the fanglomerate probably is recharged by ground water discharging from faults and buried gravel deposits on the fans. The quality of the water is good.

Fan gravels, younger than the Funeral Formation and having well-developed desert pavement, are extensive in the hydrologic basin and comprise 10 percent of it. These gravels, only partly cemented, have few fissures and few open channels, but the gravel nevertheless is highly permeable. On the long fans at the east foot of the Panamint Range these gravels probably are hundreds of feet thick.

FIGURE 6.—View of the gravel fans rising from the edge of the saltpan to the foot of the Panamint Range at the mouth of Hanaupah Canyon. The youngest gravels, the light colored areas on the fans, are along the present washes and are important areas of recharge by floods issuing onto the fans from the mountains. The older gravels, stained dark with desert varnish, form terraces and are capped by desert pavement; these gravels favor runoff. The snow-capped peak is Telescope Peak, altitude 11,049 feet, the highest point on the rim of the hydrologic basin. Foreground is 260 feet below sea level. Photograph by Harold E. Maldé.

The surfaces of these deposits, however, are elevated above the present drainage courses and are smooth desert pavement like that on the Funeral Formation; thus the surface water runs off and does not infiltrate. In Death Valley, at low altitudes, the surfaces are without vegetation.

Although little ground water enters the gravels from the surface, they are important aquifers recharged along drainage courses by inflow from the overlying younger gravels and probably also by ground water discharging laterally or upward from underlying fissured hard rocks or Tertiary formations.

Most of the ground water in the gravel deposits is of good quality, except that from under the fans rising eastward and northeastward from Cottonball Basin. This ground is saline, probably chiefly because of salts blown from the saltpan which is to the windward, but partly, perhaps, because the Tertiary formations there are shallow and saliferous.

The youngest gravel deposits, which cover about 25 percent of the hydrologic basin, are highly permeable—much more so than any of the older ones. They consist of loose cobbles and pebbles in present washes. Moreover the deposits are along washes where runoff is collected. Of all the deposits on the gravel fans, these are the principal ones through which ground water is recharged by seepage from surface-water runoff. The greater moisture content in these gravels as compared with the older ones is indicated, too, by the difference in vegetation. The older gravels, at low altitudes, are bare; the young gravels, however, support considerable growths of shrubs, many of which, in terms of this desert environment, are mesophytic.

Some sieve analyses of the surface layers of the gravels indicate a very low percentage of fines. The average of several measurements is—

Percent	*Description*	*Millimeters*
25	Gravel	>4.
25	Very coarse sand	<4 and >1.
15	Coarse sand	<1.0 and >0.42.
30	Fine to medium sand	<0.42 and >0.125.
4	Very fine sand	<0.125 and >0.062.
1	Silt	<0.062.
100		

Water seeping into these gravels probably escapes downward into the older underlying gravels. This form of recharge of ground water probably becomes important at times of flash floods and other torrential runoff.

Except at the foot of the fans around the Death Valley saltpan, the salts in these gravels rarely exceed 0.5 percent, and the quality of the ground water is little affected by passage through them. The deposits below −240 feet, however, contain several percent of salts.

FINE-GRAINED ALLUVIAL AND PLAYA DEPOSITS

Fine-grained alluvium, extensive along the flood plain of the Amargosa River and Salt Creek, covers about 10 percent of the hydrologic basin. The deposits, which are highly permeable, are an important source of ground water discharged into Death Valley.

The alluvium is not evenly distributed along the stream courses, but is most extensive and thickest upstream from bedrock dams caused by impermeable rocks being upfaulted across the stream courses. Such dams are represented by the Salt Creek Hills, by the upfaulted rocks along the Amargosa below Tecopa, and at Eagle Mountain below Death Valley Junction. A fourth bedrock ridge almost dams the tributary drainage from Silurian Lake to the Amargosa River. Upstream from each of these bedrock dams is a broad area of fine-grained alluvial or playa sediments in which ground water is shallow because it is dammed by the rock barrier against which the alluvium overlaps. Substantial stands of phreatophytes in these parts of the flood plains reflect the shallow ground water there.

Alluvial fans derived from the Tertiary formations, like those between Furnace Creek fan and Badwater, are composed of fine-grained compact muds that favor runoff. The amount of moisture entering this ground is below the requirements of even the most xerophytic Death Valley plants, such as desertholly. A fan on Artists Drive, after a 6-hour drizzle on December 15, 1957, was wet only to a depth of 2 inches.

Fine-grained playa sediments more than 1,000 feet thick, with interbeds of rock salt, underlie the saltpan in Death Valley (fig. 7).

In the sandy and silty alluvial and playa ground at the edge of the saltpan, porosity is affected more by the salts than by the size of the clastic grains. When dry, the ground is porous and permits ready circulation of air; but when wet, the salts dissolve, the pores close, and the ground becomes a slime with high water content and low permeability. During dry weather the condition of the ground is that of a porous soil; during wet weather the condition is that of a heavy soil.

SALT DEPOSITS AND SALIFEROUS PLAYA DEPOSITS

Salt deposits and saliferous playa sediments cover more than 200 square miles, all of it more than 200 feet below sea level, in the central part of Death Valley. Other playa flats, mostly saliferous, are located along the stream courses above the bedrock dams. These salt deposits and saliferous playa sediments comprise about 10 percent of the hydrologic basin (p. B40).

Surface water and shallow ground water in Death Valley vary in composition from one part of the pan to another and from time to time at a given place. The variations are due to such factors as source, position

FIGURE 7.—View west across the playa at Cottonball Basin, at the north end of the Death Valley saltpan. Foreground is soda carbonate marsh 250 feet below sea level. Top of Tucki Mountain (skyline) is about 6,500 feet above sea level. Photograph by John R. Stacy.

in the pan, seasonal changes in temperature, precipitation, and evaporation, whether the water is ground or surface water, and whether it is standing or flowing.

An example of the difference in composition of the water due to difference in source is the contrast between the brines in Cottonball Basin at the north and in Badwater Basin at the south. The ratio of sodium to calcium is very much greater in the north than in the south, so that thenardite, sodium sulfate, is the common sulfate mineral in the north, whereas gypsum, calcium sulfate, is the common sulfate mineral in the south.

In general, salinity of the brines increases panward, is greatest in dry seasons, is greater in ground water than in surface water, and is greater in standing water than in flowing water.

DUNE SAND

Dune sand, all of Recent age and most of it deposited during the last 2,000 years (A. P. Hunt, 1960), is extensive in Mesquite Flat northwest of the Salt Creek Hills. Small areas of dunes are on Furnace Creek fan and along the foot of the fans draining from Hanaupah and Starvation Canyons. Other dunes are along the Amargosa River east of Saratoga Springs and in the Amargosa Desert. The dune sand comprises less than 1 percent of the hydrologic basin.

Around the edge of the Death Valley saltpan the dune sand is in the belt of phreatophytes, and most of the dunes have stands of honey mesquite. Ground water is shallow under these dunes and contains as little as 0.5 percent of salts. Except on the Furnace Creek fan, the base of the dunes intersects the capillary fringe. Evaporation of water from the fringe between the dunes leads to an accumulation of salts on that ground, but evaporation is prevented at the dunes. There, ground water is lost by transpiration of the mesquite, but little or none by evaporation.

SPRING DEPOSITS OF TRAVERTINE

Travertine (calcium carbonate) has been deposited in mounds at and near most of the large springs issuing along faults, notably so at Ash Meadows and in Death Valley west of the Funeral Mountains. The deposits are not extensive, but being highly permeable, they favor seepage into the ground near the water sources; this helps to minimize water losses by evaporation.

Related to the mounds are deposits of calcium carbonate caliche in the older gravels at places which were or are near the surfaces. Both the mounds and the caliche layers, however, seem to be in large part relicts of a wetter time than the present.

STRUCTURAL GEOLOGY

The structural geology of the Death Valley region controls many of the distinctive hydrologic features of the basin. Quaternary block faulting resulted in a series of structural basins in the southern Great Basin; those that make up the Death Valley hydrologic basin became filled with sedimentary deposits, so they now are joined and drain to the lowest one which is at the saltpan.

A major hydrologic effect of this structure is that the ground water is ponded in each of the basins, and part of the ponded ground water apparently leaks along faults that extend to lower basins where it reappears as springs (p. B37–B40; see also, Hunt and Robinson, 1960). To a considerable degree, therefore, ground water and surface water move in different directions, and because of the high evaporation rate, the movement of ground water is more important than that of surface water to the water economy of Death Valley.

The principal structural basins and their main hydrologic features are as follows:

1. The basin of the saltpan, which is the lowest and the one that collects all the surface-water and ground-water discharge from the rest of the hydrologic basin.
2. The basin at Mesquite Flat, where ground water is ponded by the uplift at Salt Creek Hills.
3. The basin under the Amargosa Desert, where ground water is ponded by the uplift at the southeast end of the Furnace Creek fault zone.
4. The basin near Tecopa, in which ground water is ponded by a structural uplift on its south side.
5. The basin or basins along the northeast-trending course of the Amargosa River, in which ground water is ponded by the uplift at the Confidence Hills.

The saltpan can be divided into three subbasins. At the south is Badwater Basin, which is topographically the lowest and contains the deepest fill. Gravity surveys indicate that the fill there is about 8,000 feet thick. (See Hunt and others, 1965.) The Amargosa River which enters from the south is dry most of the year; it flows only after local storms. There is no evidence that much ground water moves into the saltpan from under the Amargosa River.

Middle Basin and Cottonball Basin, at the north end of the saltpan, are structurally a unit, but they are separated by the constriction between the fans at the mouth of Furnace Creek Wash and those at the mouth of Tucki Wash and Blackwater Wash. Cottonball Basin lies across the Furnace Creek fault zone and collects the discharge from springs along those faults and the discharge of Salt Creek, whose perennial flow is maintained by the ground water ponded on the northwest side of the uplift at the Salt Creek Hills. The springs along the faults, which are hot springs, seem to be drainage from other and higher basins (p. B37–B40).

The structural basin under Mesquite Flat collects the ground-water and surface-water discharge from the northwest arm of Death Valley and from the neighboring mountains. Ground water there is shallow and is ponded by the uplift of impermeable Tertiary formations in the Salt Creek Hills. This water escapes by overflow along the channel of Salt Creek and probably by underground movement along faults that extend to Cottonball Marsh (p. B37–B38).

Ground water also is shallow in the structural basins under the Amargosa Desert and in the structural basin at Tecopa. Overflow of this ground water southward along the Amargosa River maintains small springs at the uplifts that pond the ground water. These basins also probably lose water by ground water escaping along faults that extend to lower basins. Ground water in the Amargosa Desert may be the source for the water discharging in Death Valley at the springs along the Furnace Creek fault zone. Also, these basins contain large hot springs that must be supplied from outside the hydrologic basin, probably from Pahrump Valley (p. B38–B40).

The structural geology is also important in controlling the occurrence of water in the mountain blocks. In the Panamint Range the formations dip east 25°–60°, and they are broken by a series of faults of the Amargosa thrust system (see Hunt and others, 1965), most of which dip west 10°–45°. The crushed rocks along the faults act as conduits and practically every spring along the east slope of the Panamint Range is along one of these faults.

VEGETATION

About 65 percent of the hydrologic basin is in the Lower Sonoran zone, characterized by open stands of creosotebush. About 20 percent is bare ground, mostly playa or salt flat. About 10 percent of the basin is in the Upper Sonoran and higher life zones, and about half this area supports stands of woodland, the rest is in shrub. About 5 percent of the basin, a total of about 250 square miles, has stands of phreatophytes, plants dependent on ground water (see Hunt, 1965).

Areas with no flowering plants include the saltpan in Death Valley and the floors of other playas where the salinity is excessive, some parts of the gravel fans where desert pavement is well developed, and bare rock areas in the mountains.

Shrubs of the Lower Sonoran zone are mostly creosotebush, but there are stands of desertholly, cattle spinach, burroweed, and encelia. Trees are lacking. Density of growth of the shrubs ranges from a very few per acre to a maximum of about 300 or 400 per acre; the average density probably is about 50–75 per acre.

Little is known about water utilization by xerophytes, but probably they use little water that would not otherwise be lost by evaporation. For example, most of the water that falls on the gravel fans, which comprise 40 percent of the hydrologic basin, would be lost by evaporation. Except where runoff is collected in washes, most water that falls on the fans is held in the pores of the surface and near-surface layers; there is not enough excess water to run downward through this ground to the water table. During a dry period following a rain this water is withdrawn back to the surface by evaporation. That the desert plants use this water is shown by the fact that some species, such as desertholly, flower after rains and do not wait for the spring season. Such species are dormant during dry periods. Most of the water used by the xerophytes is soil water that would be lost by evaporation if not by transpiration.

In the zones above the Lower Sonoran probably somewhat more than half is shrub land—mostly shadscale and sagebush—and less than half of this, which would be less than 5 percent of the hydrologic basin, is woodland. These are areas where the rainfall is greatest and the evaporation is least. The density of shrubs in these zones averages several times that in the Lower Sonoran zone.

Principal areas of phreatophytes, the most significant plants in terms of the hydrology, are around the edge of the Death Valley saltpan, along Salt Creek and in Mesquite Flat, along the flood plain of the Amargosa River, and at small areas near and downstream from springs. The total area in which phreatophytes grow, about 250 square miles, is about equally divided between highly salt-tolerant stands of pickleweed and saltgrass, nonsalt-tolerant mesquite, and stands of arrowweed and (or) four-wing saltbush whose salt tolerance is intermediate. The area of phreatophytes around the saltpan in Death Valley is about 25 square miles. The density of growth of the phreatophytes averages three or four times that for the xerophytes, and the water utilization by individual plants is several times greater for phreatophytes than for xerophytes. As already noted, much of the water utilized by the xerophytes is soil moisture, whereas most of the water used by the phreatophytes is ground water.

PHYSIOGRAPHY AND DRAINAGE

The highest part of the rim of the hydrologic basin is along the west side along the crest of the Panamint Range. At Telescope Peak, 20 miles west of the lowest point in Death Valley, this rim is 11,049 feet (fig. 6). West of this high rim is another closed basin, Panamint Valley, about 1,500 feet higher than Death Valley.

The lowest point on the rim of the basin, only a little more than 900 feet above sea level, is at the south end between Silurian Lake and Soda Lake. Soda Lake, which is only 40 feet lower than the rim, is the sink for the Mojave River, which drains about 5,200 square miles. In pluvial times Soda Lake flooded and overflowed into Death Valley, and at such times the Death Valley hydrologic basin was half again as large as it is now.

Between this low point and the south end of the Panamint Range, the rim is mostly along the crest of low mountains 2,500–3,500 feet in altitude, south of which are numerous small shallow basins.

The east and north rims of the hydrologic basin alternately follow the crests of low mountains and low divides between adjoining basins. Five structural basins along the east side of the Death Valley hydrologic basin are alined northwest—Ivanpah Valley, Mesquite Valley, Pahrump Valley, the Amargosa Desert at the head of the Amargosa River, and Sarcobatus Flat. Of these basins, only the Amargosa Desert is within the Death Valley hydrologic basin, but Sarcobatus Flat and Pahrump Valley may contribute ground water to the hydrologic basin. The warm springs at Ash Meadows, for example, in all likelihood are supplied by water escaping along faults from Pahrump Valley. Other springs like those at Beatty at the head of the Amargosa River and those along the lower part of the river probably are also supplied by ground water from outside the hydrologic basin.

THE SALTPAN

The saltpan on the floor of Death Valley (see p. B40) is the sink for the drainage system in the hydrologic basin. Although the saltpan covers about 200 square miles, only 75 square miles of it is true flood plain; the remainder of the pan has a thick crust of salts and is 1 or 2 feet higher than the areas that are flooded. Most of the flood plain is mud flat, and most of the time it is damp rather than wet. In wet periods there is running water along the main channels, and water collects in ponds on the flats (fig. 7).

During much of the year a little surface water collects at the northeast corner of Cottonball Basin at about −264 feet. This water is fed by springs along that edge of the saltpan, but flow does not extend to the central part of the basin; it is ponded by a crust of salt that has formed on the flat broad channel. During the first 5 years of our survey this northeast arm of Cottonball Basin did not discharge to the main channel of Salt Creek, but in 1961 a flood down the east distributary of Salt Creek caused the pond to overflow and discharge to the main channel.

A long straight channel connects the center of Cottonball Basin with Middle Basin (−277.5 ft), and much of the year this channel has a stream of running water 1–2 inches deep and 2–3 feet wide. The flow is considerably greater in times of flood, but rarely more than 2–3 cfs (cubic feet per second); between floods the channel has no surface water, but for long periods the bottom remains damp and soft.

Water is ponded regularly in the central part of Middle Basin because the channel leading from there to Badwater Basin (−282 ft) is 1½ feet higher than the central part of Middle Basin. At no time during the period 1955–61 was the ponded water sufficiently deep to overflow into Badwater Basin. The flood plains in Middle Basin cover about 1,000 acres and to overflow into Badwater Basin would require about that many acre-feet of water. The largest flood we observed along Salt Creek above Middle Basin discharged 3.0 cfs, which is only 6 acre-feet per day.

The Amargosa River enters the saltpan at 240 feet below sea level in a channel 5 feet deep and 25–50 feet wide. In 5 miles northward the fall is 20 feet, and in places the channel is 10 feet deep and only 25 feet wide. The bottom contains small perennial pools, but little surface water flows except during wet periods.

From opposite Mormon Point at −260 feet the channel of the river heads north and falls 20 feet in 10 miles. The river is in several channels which are braided; each is 2 or 3 feet deep and 25–40 feet wide. Water discharging from the Amargosa River collects in a pond located in the middle of the saltpan between Tule Spring and Badwater. In the winters of 1957–58, 1958–59, and 1960–61, this pond was 1 foot deep, covered as much as 3 square miles, and lasted several months each winter. No such pond formed during the other years of our study except for a few days following rains.

Floodwaters reach the low part of Badwater Basin along the east side of the saltpan too, but this part of the flood plain is without distinct channels. Most of the time this ground is damp without being wet; surface water flows across it only following hard rains or floods from the Black Mountains.

Eastward tilting of Badwater Basin during the last 2,000 years has crowded the saltpan against the foot of the Black Mountains. The hydrologic effect of this has been chiefly on the quality of the water; the chlorides are crowded eastward against the foot of the Black Mountains, and all the springs and marshes along that side of the saltpan are highly saline. Ground water under the west edge of the saltpan is of good quality.

SALT CREEK DRAINAGE BASIN

The Salt Creek Hills, an uplift of the impermeable beds of the Furnace Creek Formation, form a structural barrier across Salt Creek at the north end of the saltpan. Salt Creek crosses the uplift in a gorge cut in the Furnace Creek Formation. In the structural basin at Mesquite Flat, upstream from this gorge, ground water is ponded by the uplift. Mesquite Flat, an area of about 50 square miles and without surface water, slopes about 14 feet per mile towards the Salt Creek Hills. The water table intersects this surface near the hills, and this discharge of ground water supplies the perennial flow of Salt Creek through the gorge to the saltpan.

Salt Creek drains the northwest arm of Death Valley, an area of about 1,600 square miles, most of which is mountainous (fig. 1). The mountains are composed largely of Paleozoic carbonate rocks and are without perennial streams. The water collected under Mesquite Flat is derived from many sources in the bordering mountains, rather than from a few or single source. Although Mesquite Flat is without perennial surface water, the ground water is shallow and the flat has an extensive growth of phreatophytes.

Some analyses of the water (location of samples shown on pl. 3) from the perennial stretch of Salt Creek (tables 11 and 12) show that the salinity increases toward the saltpan and that the salinity is greater in dry years, when discharge is reduced, than in wet years.

AMARGOSA RIVER

The Amargosa River, an intermittent stream draining about 6,000 square miles, discharges into the south end of the Death Valley saltpan at an altitude of 240 feet

TABLE 11.—*Chemical analyses, in percent, of water from Salt Creek showing carbonate and silica content*

[Collected by T. W. Robinson, Apr. 10, 1957, and analyzed by U.S. Geol. Survey. See also table 12]

	A	B		A	B
SiO_2	0.004	0.004	Cl	0.919	0.757
Ca	.0227	.0178	B	.004	.003
Mg	.044	.037	Total dissolved solids (ppm)	1.420	1.180
Na	-------	------	pH	7.9	8.4
K	-------	------			
HCO_3	.078	.063			
CO_3	0	.005			
SO_4	.389	.328			

A. From a 1-ft dug pit on west side of Salt Creek, 600 ft upstream from W1-56s.
B. Salt Creek at W1-56s.

TABLE 12.—*Partial and semiquantitative analyses, in percent, of water from Salt Creek where it enters the saltpan*

[Analyses and analytical methods given on p. B90. Data on surface-water samples W1–W4 are also given in table 50]

	W7–59g	W6–59g	W1s	W1–56s	W2s	W2–56s	W3s	W3–56s	W4–56s
Ca	------	------	------	0.02	------	0.01	------	0.05	0.06
Mg	------	------	------	.02	------	.03	------	.05	.1
K	------	------	0.06	.03	0.04	.07	0.14	.16	.35
Na	------	------	.5	.51	.48	1.44	1.7	3.50	4.41
SO_4	0.10	0.08	.4	.25	.20	.50	.70	1.4	2.2
Cl	.24	.30	.7	.74	.40	2.0	1.0	4.9	5.85
B	------	------	------	.0005	------	.002	------	.005	.02
Sr	------	------	------	.003	------	.004	------	.01	.01
Total dissolved solids	.6	.8	1.8	1.5	1.6	4.	5.3	10.	13.
pH	------	------	7.8	------	8.4	------	8.4	------	7.0

W7–59g. Ground water, McLean Spring; water 2 ft below surface. Carbonate in residue 0.005.
W6–59g. Ground water, 1 ft below surface; at pit in stand of tules 0.5 mile southeast of McLean Spring. Carbonate in residue 0.01.
W1s. Surface water, Salt Creek, at bridge 1,000 ft southeast of McLean Spring.
W1–56s. Surface water, Salt Creek, at lower end of gorge in SE¼ sec. 5, T. 16 S., R. 46 E.
W2s. 1957 duplicate of W1–56s.
W2–56s. Surface water, Salt Creek, in pickleweed at edge of saltpan; N½ sec. 10, T. 16 S., R. 46 E.
W3s. Surface water, location ¼ mile downstream from W2–56s.
W3–56s. Surface water, Salt Creek, southernmost pool in east distributary, at south edge of rough silty rock salt; SE¼ sec. 14, T. 16 S., R. 46 E.
W4–56s. Surface water, Salt Creek, southernmost pool in west distributary, at south edge of rough silty rock salt; SW¼ sec. 14, T. 16 S., R. 46 E.

below sea level. Only short stretches of the Amargosa River are perennial. During the wet winter of 1957–58 and spring of 1958 the river flowed continuously from the spring zone at Eagle Mountain to the saltpan; but at other times during the period of this study the flow was intermittent, and most of the time most of the river was a dry wash.

The lower 10 miles of the river course is partly blocked and confined by the structural uplift at the Confidence Hills. Twenty miles above the mouth, the river is at sea level in a broad flat where ground water is shallow, evidently ponded there by the structural barrier at the Confidence Hills. Perennial springs, known as Valley Springs, represent the spilling over of the ponded ground water, a relationship not unlike that at Salt Creek in the Salt Creek Hills.

From Valley Springs upstream for about 30 miles, the valley of the Amargosa River is wide and open. There are a few springs along this stretch and a particularly large one at Saratoga Springs, an analysis of which is given in table 13; but there is little surface water except following storms or during protracted wet periods.

This stretch of the river receives water from two sources. The main stem of the river upstream from here is in a gorge through the structural uplift below Tecopa. A tributary from the southeast, partly dammed by the structural barrier represented by the Salt Spring Hills, drains an extensive area south of the Kingston Range. A southerly arm of this tributary heads at the low rim separating the Death Valley hydrologic basin from that of the Mojave River at Silver and Soda Lakes. When those lakes have been flooded, as they were during the Pleistocene, they have overflowed to the Amargosa. This tributary probably receives some ground water discharge from the Mojave River drainage (p. B27).

Below Tecopa for about 10 miles the Amargosa River is in a gorge through a structural uplift, and through most of this stretch the flow is perennial. Ground water evidently is ponded in the lake beds at Tecopa upstream from the uplift, and overflow of this ponded ground water produces the perennial flow of the river. This discharge is no more than a few cubic feet per second and probably represents most of the contribution of water discharged from the upper stretches of the Amargosa River.

Several important springs in the stretch of river above Tecopa include the warm springs at Tecopa and Shoshone and the springs at Tule Holes and Resting Spring, the latter a well-known stopping place on the emigrant trail from Salt Lake City to Los Angeles.

At Eagle Mountain the underflow of the Amargosa River again is ponded by a structural barrier across the valley. Upstream from the Eagle Mountain barrier is a stretch 50 miles long, which drains 700 square miles known as the Amargosa Desert. This stretch of the river generally is dry, but in the south half, upstream from the barrier, ground water is shallow. Some ground water from this part of the Amargosa Desert may leak northwestward along faults in the Furnace Creek fault zone to feed some of the large springs in Death Valley (p. B38). This ponded water is derived from three sources. One source is the set of large springs at Ash Meadows; a second source is the high water table draining southward past Lathrop Wells; the third source is the set of springs in Oasis Valley at the head of the Amargosa River. Except for short stretches below the large springs, there rarely is surface water in the Amargosa Desert.

Table 13 gives some analyses of water from the numerous springs along the Amargosa River from the head of the river down to Valley Springs. It will be noted that many of the springs are warm water, and all of them are high in bicarbonates and comparatively low in chlorides. They all are high in sodium, fluorine, and strontium; they differ chiefly in the proportions of calcium, magnesium, and potassium.

Table 14 compares water from the Amargosa River with that of Salt Creek at the opposite end of the saltpan. Salt Creek is high in chlorides. The surface flow of the Amargosa River, though, becomes increasingly high in chlorides as the river approaches the saltpan, as brought out by table 15 which shows the proportion of chloride and sulfate at 5 localities along the lower 80 miles of the river. This sampling was

TABLE 13.—*Complete analyses of ground water and surface water along Amargosa River drainage*

[Chemical components in parts per million. Analyses by U.S. Geol. Survey, except samples 1-5 which are from Thompson, 1929, p. 588]

	Laboratory No.																Samples				
	1149	1151	1150	1156	1155	2163	1154	3057	2164	3059 [1]	3060 [2]	3056	+3646	3062 [3]	1107	1106	2	1	3	4	5
Silica (SiO_2)	65	55	52	68	42	48	82	125	88	32	28	34	24	26	100	44	70	90	52	74	48
Aluminum (Al)	.0	.0	.0	.4	.3	.1	.2	1.2	.1	.0	.2	.2	.4	.5	.00	.00	----	----	----	----	----
Iron (Fe)	.00	.00	.22	.12	.10	.06	.14	.64	.01	.11	.21	.11	.50	.45	.0	.03	.17	.38	.29	.05	.19
Manganese (Mn)	.00	.00	.00	.00	.00	.00	.00	.34	.00	.00	.00	.00	.00	.00	.00	.00	----	----	----	----	----
Arsenic (As)	----	----	----	----	----	----	----	.00	----	.00	.0	.04	.40	.02	----	----	----	----	----	----	----
Strontium (Sr)	----	----	----	----	----	.0	----	1.4	.0	1.8	1.8	.2	----	.8	----	----	----	----	----	----	----
Calcium (Ca)	18	21	8.0	14	42	14	70	64	16	45	40	2.0	2.0	24	5.6	33	31	41	96	71	256
Magnesium (Mg)	.0	2.9	1.0	1.9	6.8	1.5	3.9	54	4.4	18	26	1.0	.5	29	1.9	34	36	9.0	16	56	120
Sodium (Na)	167	58	62	106	84	106	62	1,020	55	98	125	330	374	344	756	970	} 994	545	55	90	1,559
Potassium (K)	7.4	3.0	2.0	5.8	1.2	4.4	9.0	68	8.8	8.8	16	11	12	40	16	30					
Bicarbonate (HCO_3)	256	147	131	194	232	160	142	1,690	161	314	362	546	594	542	724	420	410	175	155	186	313
Carbonate (CO_3)	0	0	0	0	0	0	0	0	0	0	10	28	41	33	8	0	22	22	30	5.8	0
Sulfate (SO_4)	121	27	22	69	40	103	107	530	36	110	122	154	180	277	518	1,040	1,039	675	137	393	901
Chloride (Cl)	45	24	16	27	52	20	61	150	7.5	25	40	49	53	123	400	680	637	261	61	23	2,295
Fluoride (F)	5.0	.7	.5	4.0	----	2.0	1.4	8.0	2.0	1.4	2	6.4	7.2	2.8	2.7	2.2	----	----	----	----	----
Nitrate (NO_3)	.3	12	6.7	.8	8.0	6.3	17	1.1	4.1	.3	.0	.0	.00	.0	.7	4.7	1.7	29	5.7	.23	1.8
Orthophosphate (PO_4)	.0	.0	.2	.0	.0	.10	.0	512	.05	.08	.07	.42	.59	.22	.6	.2	----	----	----	----	----
Boron (B)	----	----	----	----	----	----	----	1.2	----	.51	.68	1.5	1.1	2.1	----	----	----	----	----	----	----
Dissolved solids (residue at 180° C.)	535	266	224	368	376	382	489	3,070	299	468	566	854	965	1,140	2,190	3,080	3,098	1,804	535	860	5,385
Hardness as $CaCO_3$	45	64	24	43	133	41	190	382	58	186	207	9	7	179	22	222	225	139	306	407	1,130
Specific conductance (μmhos at 25° C.)	821	399	319	552	623	568	700	4,740	372	780	937	1,410	1,560	1,860	3,330	4,640	----	----	----	----	----
pH	7.9	7.7	7.9	8.2	8.2	8.2	7.9	8.0	8.1	7.7	8.5	8.7	8.9	8.8	8.3	8.1	----	----	----	----	----
Beta-gamma activity ($\mu\mu$c/l)	<27	<17	17	<17	<17	<19	<23	95±13	<14	16±3.5	8.5±3.5	19	22±3	27±6.9	<85	<140	----	----	----	----	----
Radium (Ra) ($\mu\mu$c/l)	.6	<.1	<.1	<.1	<.1	<.1	<.1	0.1±0.1	<.1	0.1±0.1	<.1	<.1	<.1	0.1±0.1	.2	<.1	----	----	----	----	----
Uranium (U) (μg/l)	10	2.4	5.0	4.5	8.2	1.8	4.7	4.8±0.5	1.6	2.6±0.3	4.5±0.4	4.6±0.5	6.7±0.7	11±1.1	5.2	16	----	----	----	----	----
Discharge, gpm estimated	20	10+	<5	100+	20	----	600	----	----	1,000	----	----	----	2,245	200	25	----	----	----	----	----
Temperature (° F)	100	----	60	76	45	----	74	55	----	83	50	70	----	40	108	----	----	----	----	----	----

[1] Molybdenum (Mo) <0.02. [2] Molybdenum (Mo)8. [3] Molybdenum (Mo)23.

NOTE.—Description of locality as follows:

1149. Amargosa Hot Springs; about 6 miles north of Beatty, Nev.
1151. Crystal Spring about 5 miles north of Beatty, Nev.
1150. Indian Springs, about 3 miles north of Beatty, Nev.
1156. Municipal spring 2 miles east of Beatty, Nev.
1155. Red Fox mine north of Rhyolite, Nev.
2163. Lathrop Wells, Nev., well 560 ft. deep.
1154. About 14 miles west of Lathrop Wells, Nev., NE¼ sec. 36, T. 16 S., R. 48 E. Well 165 ft. deep.
3057. Franklin well, 10 miles north of Death Valley Junction, Calif.
2164. Ash Meadow Ranch, Nev.
3059. Big Spring Ash Meadows, Nev.
3060. Carson Slough, SE¼ sec. 5, T. 18 S., R. 50 E.
3056. Death Valley Junction, Calif., well.
3646. Highway Dept., Death Valley Junction, Calif.
3062. Amargosa River, NW¼ sec. 18, T. 24. N., R. 6 E.
1107. Tecopa Hot Springs, 2 miles north of Tecopa, Calif.
1106. Saratoga Springs, Calif.
2. Saratoga Springs, Calif.
1. Owls Holes, sec. 23, T. 18 N., R. 3 E.
3. Cave Springs near center, T. 17 N., R. 5 E.
4. Sheep Creek Spring, sec. 5, T. 17 N., R. 6 E.
5. Salt Springs in bed of south branch of Amargosa River, approximately in sec. 30, T. 18 N., R. 7 E.

TABLE 14.—*Proportions, in percent, of carbonate, sulfate, and chloride in water from Amargosa River and Salt Creek*

	Amargosa River at Valley Springs [1]	*Salt Creek*
CO_3 and HCO_3	37.5	5.4
SO_4	17.0	28.5
Cl	45.5	66.0

[1] Computed from Mendenhall (1909a, p. 46).

TABLE 15.—*Changes in proportions of sulfate and chloride and total dissolved solids at 5 localities along the Amargosa River between Eagle Mountain and the saltpan in Death Valley, a distance of about 80 miles*

[Samples collected during a wet season (winter 1957–58) when there was continuous flow along this stretch of the river]

	Location of sample	Total dissolved solids (ppm)	Proportion of— Cl	SO4
1	South foot of Eagle Mountain	1,000	30	70
2	Highway crossing, 15 miles below Tecopa	2,300	41	59
3	Sea level, 12 miles below Saratoga Spring	4,500	53	47
4	Edge of saltpan, near north foot of Shoreline Butte	7,500	57	43
5	In the saltpan opposite Coyote Hole, 5 miles below No. 4	[1] 23,000	70	30

[1] During a dry season when the river was not flowing continuously between these locations, a sample from here contained 110,000 ppm total dissolved solids, and the proportion Cl/SO_4 was 78/22.

done during a wet season (winter 1957–58) when there was continuous flow along this stretch of the river.

MOUNTAINS DRAINING DIRECTLY TO THE SALTPAN

PANAMINT RANGE

The east slope of the Panamint Range drains to the Death Valley saltpan in a series of mountain valleys, each of which discharges onto the apex of a gravel fan 4–6 miles long and 1,000–1,500 feet high. This total drainage area is about 450 square miles, of which a third is the highly permeable ground of the gravel fans. About half the mountainous area is more than 4,500 feet in altitude; the summit, which is 11,049 feet in altitude is 12 miles west of the saltpan.

The rocks in the mountains are not permeable, but the fractures breaking them provide channels for collection and movement of ground water. Practically all the springs that issue from the bedrock formations in the mountains are along faults.

From Tucki Mountain south to Death Valley Canyon the mountains are composed in large part of Paleozoic carbonate formations. South of Death Valley Canyon the mountains are mostly Precambrian and Cambrian quartzite and argillite with little carbonate; at the head of Hanaupah and Starvation Canyons are extensive areas of quartz monzonite. Most of the springs, and all the big ones, issue from the noncarbonate rocks. The spring waters are high in sulfates and comparatively low in chlorides and carbonates (table 16).

TABLE 16.—*Total dissolved solids and percent of principal anions, in parts per million, in water at springs in the Panamint Range*

[Semiquantitative analyses of residues, by Geochemical Exploration Laboratory, U.S. Geol. Survey]

	Location	Sample No.	Total dissolved solids	Cl	SO4	CO3
1	Galena Canyon Spring.	(W–1–59)	500	75	205	60
2	Johnson Canyon Spring.	(W–2–59)	600	15	240	108
3	Spring in south fork of Starvation Canyon.	(W–3–59)	265	10	95	------
4	Quartzite Spring	(W–4–59)	1,000	40	250	46
5	Panamint Burro Spring.	(W–9–59)	1,500	40	600	20
6	Hanaupah Canyon Spring.	(W–5–59)	100	4.5	16	------
7	Chuckwalla Spring.	(W–10–59)	1,200	30	170	110
8	Emigrant Spring	(W–8–59)	200	------	95	------

None of the mountain valleys has a perennial stream. Surface water discharging from the mountains onto the gravel fans seeps into the gravel. Even floods from torrential storms in the mountains rarely cross the permeable gravel fans. In brief, surface runoff from the mountains discharges into the fans as ground water, and probably there is considerable additional groundwater discharge into the gravels along the bottom of the fill in the mountain valleys.

The water table in the gravel is deep. At the foot of the fans the water table is shallow. This zone of shallow ground water has some springs and some marshes. The marshes at the foot of Tucki Wash and east of Tucki Mountain cover about 2–3 square miles. Marshes along the west side of Badwater Basin aggregate about one quarter of a square mile.

In the zone of shallow ground water at the edge of the saltpan the salinity of the water increases greatly in short distances panward from the foot of the gravel fans. (See table 17.) At Salt Well (W25–56g, and W74g) the salinity is about 0.6 percent; in a mile to the northeast the salinity increases to 4.0 percent.

At Gravel Well the dissolved solids total 0.13 percent; 1,000 feet east of the well the dissolved solids total 0.54 percent (W12–59g); and 2,000 feet farther east the dissolved solids total 2.5–4 percent (W26–56g and W93g, table 18).

At Shortys Well the dissolved solids total 0.07 percent; 1,000 feet panward the dissolved solids total 0.3 percent (W101g and W11–59g, table 17).

These changes in salinity are reflected in orderly changes in the phreatophytes growing along this edge of the saltpan. Mesquite grows in that part of the zone of shallow ground water where the salinity does not exceed 0.5 percent; panward from this is a belt of

TABLE 17.—*Semiquantitative partial analyses, in percent, of water entering Death Valley saltpan from the Panamint Mountains*

[See also table 52]

	W25–56g	W74g	W12–59g	W26–56g	W93g	W96g	W97g	W98g	W100g	W101g	W11–59g	W13–59g	W102g	W15–56g	W42g
Ca	0.006	0.04	------	0.02	0.15	0.012	0.003	0.01	0.17	0.007	------	------	0.001	<0.01	0.003
Mg	.001	.008	------	.02	.03	.004	.001	.002	.07	.002	------	------	.001	.005	.002
K	.0006	.01	------	.02	.05	.09	------	<.01	.08	.01	------	------	------	.01	.02
Na	.23	.14	------	.9	1.1	1.5	------	.09	1.4	.01	------	------	------	.34	.27
SO_4	.02	.1	0.2	.1	.2	.5	.2	.2	.4	.06	0.03	0.02	.04	.10	.30
Cl	------	.2	.2	1.4	2.8	2	.01	.01	2.8	.02	.09	.02	.1	.52	.50
B	.0003	<.001	------	.0005	<.001	<.001	<.001	<.001	.003	.001	------	------	.001	.003	.001
Sr	.001	.001	------	.01	.01	<.001	<.001	<.001	.007	<.001	------	------	.001	.001	<.001
Total dissolved solids	.6	.56	.54	2.5	4.2	10.	.03	.54	6.6	.07	.3	.2	.2	1	.9
pH	6.5	6.8	------	7.0	6.8	6.8	7.9	6.9	7.0	6.9	------	------	6.8	6.3	6.8

W25–56g. Ground water, at Salt Well, 9 ft below surface. NW¼ sec. 12, T. 22 N., R. 1 E.
W74g. 1957 duplicate of W25–56g.
W12–59g. Ground water, auger hole 1,025 ft east of Gravel well at edge of pickleweed and mesquite; water 6 ft below surface.
W26–56g. Ground water in marsh ½ mile east of Gravel Well. Vegetation: pickleweed, saltgrass, rush.
W93g. 1957 duplicate of W26–56g. Although 1957 was a wet year compared with 1956, there was less water in this marsh in 1957 than in 1956.
W96g. Ground water, 4 ft below surface; in silt facies of carbonate zone. 2,000 ft east of road; 3 miles south of Bennetts Well.
W97g. Ground water, Bennetts Well. Water table reported 15 ft below surface.
W98g. Ground water, spring at Eagle Borax 100 ft east of old crystallizing vat.
W100g. Ground water, 44 in. below surface of gypsum east of Eagle Borax.
W101g. Ground water, Shortys Well. Water table 10 ft below surface at well.
W11–59g. Ground water, auger hole 1,050 ft east of Shortys Well; water 8.3 ft below surface.
W13–59g. Ground water, auger hole 725 ft west of Tule Spring at edge of mesquite and arrowweed.
W102g. Ground water, Tule Spring.
W15–56g. Ground water at warm spring temp. (88°F) along fault at east foot of Tucki Mtn. about 1,500 ft southwest of SW. cor. sec. 33, T. 16 S., R. 46 E. Discharge estimated at 2 gpm.
W42g. 1957 duplicate of W15–56g.

arrowweed which tolerates salinities as much as 3 percent; the most salt-tolerant species is pickleweed which grows with its roots in ground water containing as much as 6 percent dissolved solids (fig. 8). (See Hunt, 1965.)

The salinity of the ground water is least in the fans at the foot of Hanaupah and Starvation Canyons. Isochlors connecting lines of equal salinity are bulged panward at the foot of the fans (see W97g, W98g, W101g, W102g, table 17), probably because these canyons rise in the highest part of the Panamints and their discharge of ground water is greater than that from the other canyons.

BLACK MOUNTAINS

The west front of the Black Mountains drains to the Death Valley saltpan in a series of cascading gorges. The mountain summit, which is 5,000–6,000 feet above sea level, is only 3 miles from the saltpan. Much of the east slope of the Black Mountains also drains to the saltpan by Furnace Creek Wash. The total drainage area is about 200 square miles.

The south half of the Black Mountains is composed of Precambrian crystalline rocks; the north half consists of Tertiary volcanic rocks and sediments derived from them (fig. 5). There are no perennial streams on the Black Mountains and only a few perennial springs, all of them small.

On the west slope little or no water gets into the ground because the ground slopes are steep and the ground is nearly impermeable.

At the foot of the mountains each gorge discharges onto a small but steep alluvial fan, and much of the runoff discharged onto the fans continues to the saltpan. Ground water is shallow at the foot of several of the fans and in the coves between them. There are some marshes at these places, like the one at Badwater, and these support a sparse growth of pickleweed associated with some saltgrass and rush. The total area of these marshes, about one-quarter square mile, is about the same as on the west side of Badwater Basin along the foot of the large fans sloping from the Panamint Mountains.

The salinity of these marshes varies, depending on the season and discharge; it reaches a maximum of about 6 percent. The average is much higher than along the west side of Badwater Basin. The discharge at these marshes is small, and much of the surface water discharged is lost by evaporation.

Chemical analyses of water from the spring at Badwater are given in table 18; some semiquantitative partial analyses of water from other springs along the west foot of the Black Mountains are given in table 19.

TABLE 18.—*Chemical analyses, in percent of water from Badwater showing carbonate and silica content*

	A	B	C	D
SiO_2	0.005	0.003	0.012	0.001
Ca	.150	.095	.063	.100
Mg	.020	.009	.013	.012
Na	--------	{.857}	--------	--------
K	--------		--------	--------
HCO_3	.020	.016	.010	.015
CO_3	.002	0	0	.002
SO_4	.592	.307	.243	.379
Cl	2.570	1.280	.753	1.569
pH	8.3	7.2	7.5	--------
Residue on evaporation at 180°F	--------	2.560	--------	3.197

A. West side pool at Badwater. Collected by T. W. Robinson, Apr. 11, 1957; analyzed by U.S. Geol. Survey.
B. East edge of pool at Badwater; pickleweed growing there. Collector, date, and analyst as in sample A.
C. Pool at Badwater; collected Nov. 11, 1955, by T. W. Robinson; analyzed by U.S. Geol. Survey.
D. Pool at Badwater, west side; collected by W. F. White, Jr., Nov. 19, 1938; analyzed by U.S. Geol. Survey.

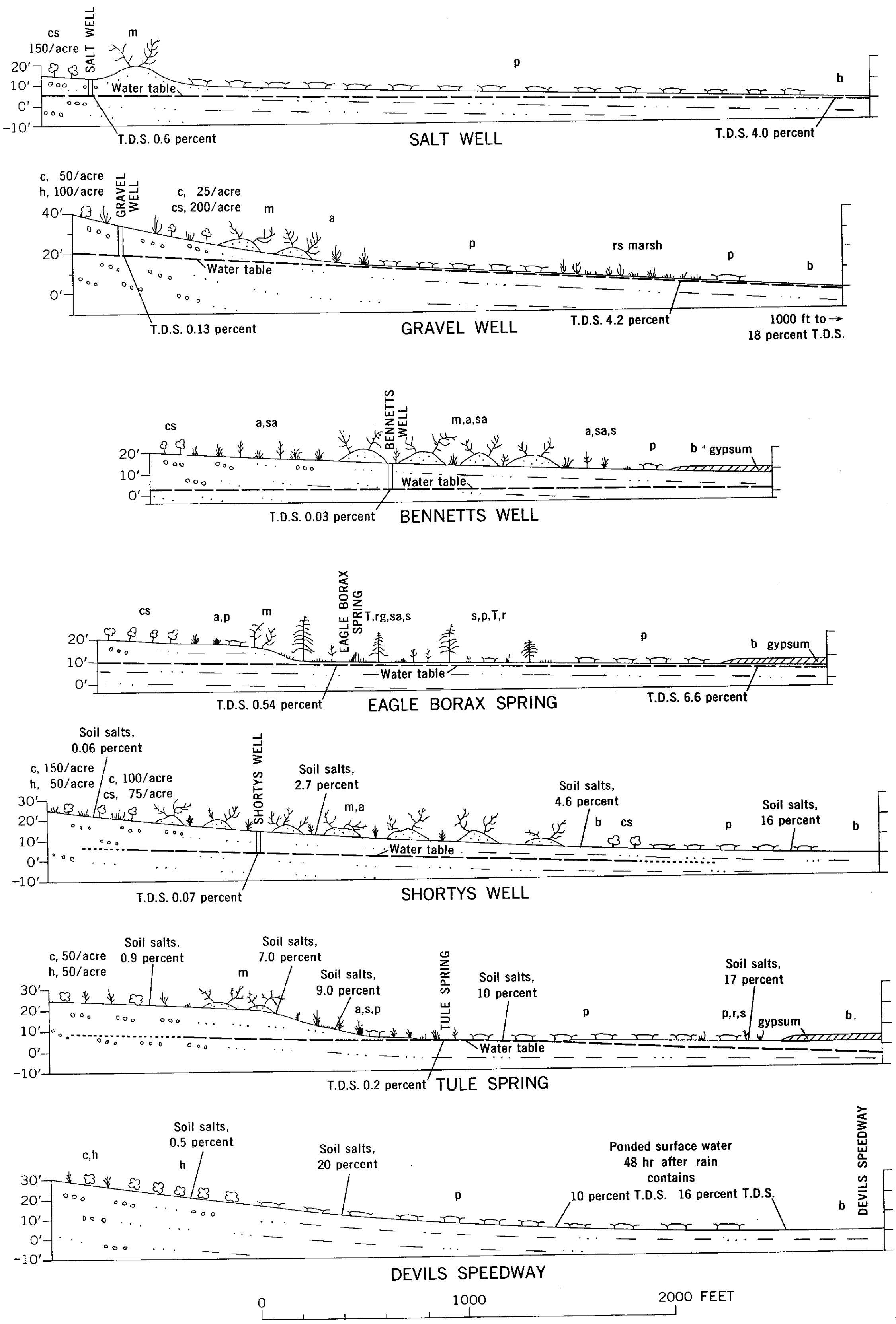

FIGURE 8.—Sections at seven localities along the west side of Badwater Basin illustrating the steep slope of the water table along the edge of the saltpan, the increase in salinity panward, and the orderly zoning of phreatophytes reflecting the increase in salinity. T.D.S., total dissolved solids in ground water, except at Devils Speedway where water is ponded surface water; soil salts, water soluble, are given in percent by volume.

EXPLANATION

a, arrowweed
b, bare ground
c, creosotebush
cs, cattle spinach
h, desertholly
m, honey mesquite
p, pickleweed
r, rush
rg, giant grass weed
s, saltgrass
sa, sacaton grass
t, tamarisk

The east slope of the Black Mountains, part of which drains to Furnace Creek, has less runoff than does the west slope because the slopes are gentler and the runoff must cross a wide area of permeable alluvial gravel. The discharge from this area to Furnace Creek probably is mostly ground-water discharge into the Texas Spring syncline.

TABLE 19.—*Semiquantitative partial analyses, in percent of water entering Death Valley saltpan from the Black Mountains*

[Analysts and analytical methods given on p. B90. See also table 52]

	W59g	W21–56g	W22–56g	W60g	W61g	W23–56g	W65g
Ca	0.11	>0.04	>0.04	0.04	0.16	0.1	0.03
Mg	.01	.006	.008	.04	.03	.01	.01
K	.08	.06	.05	.1	.17	.09	.02
Na	.96	1.24	1.4	1.5	2.4	3.6	.54
SO_4	.20	.37	.22	.20	.6	.4	.3
Cl	1.60	2.28	2.32	1.6	1.7	5.8	1.1
B	.001	.002	.001	.001	.002	.0005	<.001
Sr	.01	.02	.01	.01	.028	.01	.006
Total dissolved solids	3.2	4	4	4.8	7.8	10	1.8

W59g. Ground water, 15 in. below surface; in marsh at toe of fan; second cove south of Badwater.
W21–56g. Seep with water bugs, algae, and larvae at toe of fan next north of Coffin Canyon fan.
W22–56g. Ground water at marsh in cove north of Coffin Canyon. Vegetation: pickleweed, rush, saltgrass.
W60g. 1957 duplicate of W22–56g.
W61g. 1957 duplicate of W23–56g.
W23–56g. Ground water in marsh at north base of Mormon Point; south edge of marsh, by highway.
W65g. Ground water, in pool at Coyote Hole. SE¼ sec. 15, T. 22 N., R. 2 E. Vegetation: saltgrass, rush, reed grass.

FUNERAL MOUNTAINS

The Funeral Mountains are mostly between 3,000 and 4,000 feet in altitude, though some peaks reach to 5,000 feet. The west slope of the mountains drains directly to the Death Valley saltpan; the east slope drains to the Amargosa Desert. The mountainous area draining to the saltpan covers about 200 square miles; this water discharges onto an area of about 60 square miles of alluvial gravels in long fans sloping to Cottonball Basin.

Total runoff from the Funeral Mountains probably is about the same as from the Black Mountains, for the amount of precipitation and the slopes and ground permeabilities in the two mountains are comparable. There are no perennial streams.

When surface water discharges from the Funeral Mountains, it seeps into the ground when it reaches the fans. These fans are as long as those sloping from the Panamint Range, but the gravel deposits are only a thin veneer on faulted Tertiary formations in the Furnace Creek fault zone. No doubt some ground water enters the Tertiary formations along permeable beds or faults, but much of the ground water probably is perched at the contact between the gravel and underlying Tertiary formations. The marshes at the foot of these fans are more extensive than those at the foot of the fans sloping from the more extensive, higher, and better watered Panamints. The marshes around the northeast and east sides of Cottonball Basin aggregate about half a square mile. The great discharge of water into the saltpan from the Funeral Mountains, apparently greater than that from the Panamints, further strengthens the suggestion (p. B38) that much of the water in these fans discharges from faults of the Furnace Creek fault zone and has a source other than on the Funeral Mountains (see tables 20 and 25).

TABLE 20.—*Discharge at some springs on the fans sloping from the Funeral Mountains including underflow in Furnace Creek Wash.*

[Data from Pistrang and Kunkel, 1958]

Spring	Altitude (feet)	Date measured	Flow (cfs)	Temperature (°F)
Cow Springs	200	Mar. 5, 1957	0.04	81
Salt Springs	0	Dec. 1, 1956	.01	73
Water tunnel at Furnace Creek Inn; mostly underflow from Furnace Creek Wash(?).	50	Mar. 1. 1957	.33	91.5
Texas Spring	380	Jan. 22, 1957	.50	91
Undeveloped spring	160	Feb. 28, 1957	.01	80
Do	400	(?)	.01	(?)
Do	320	Dec. 17, 1956	.01	72
Travertine Springs	400	Jan. 19, 1957	.68	92
Do	400	do		92
Do	330	do	.23	89
Do	320	Dec. 16, 1956	.5	91.5
Do	320	Dec. 13, 1956	.001	89
Do	320	do	.01	94
Do	320	Nov. 28, 1956		95.5
Do	330	do	.6	94
Do	330	do		85
Sump in Furnace Creek Wash, underflow(?).	280	do	1.26	92
Buried tile in Furnace Creek Wash, underflow(?).	250	do	.45	(?)
Park Service trench in Furnace Creek Wash, underflow(?).	250	June 20, 1956	.24	
Undeveloped spring in T. 28 N., R. 1 E.	380	Mar. 5, 1957	.01	78
Nevares Springs:				
Northern part	937	Dec. 14, 1956	.60	104
Second sta	896	do	.05	102
Southern part	720	do	.07	78

Table 21 gives some chemical analyses of water from these springs. The composition is strikingly different from that of other springs around the saltpan in having a high proportion of bicarbonate.

Table 22 gives some semiquantitative chemical analyses of water discharging into the saltpan from the foot of the fans sloping from the Funeral Mountains. These seeps and marshes differ from those around other parts of the saltpan in depositing large amounts of sodium carbonate. As elsewhere around the saltpan, the salinity increases greatly in short distances panward from the foot of the fans.

BASINS THAT PROBABLY DISCHARGE SOME GROUND WATER TO DEATH VALLEY

The area of surface-water recharge in the Death Valley hydrologic basin is, as noted above, 8,700 square miles, but ground water probably enters the basin from three neighboring drainage basins—that of the Mojave River, Pahrump Valley (p. B28), and Sarcobatus Flat. Very possibly the water discharging into Death Valley is supplied in large part by ground water from outside the hydrologic basin.

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TABLE 21.—*Complete analyses of water samples from Death Valley*

[Texas Spring analysis by California Dept. of Water Resources. All other analyses by U.S. Geol. Survey. Chemical components in parts per million]

	[1] 3054	[2] 3052	3049	[3] 3055	1109	[4] 3048	3647	2	3051	[5] 1	[6] 3065	[7] 3050	[8] 3058	3053
Silica (SiO_2)	97	29	63	17	32	28	30	25	36	43	30	16	26	39
Aluminum (Al)	.6	.3	.1	.3	.2	.0	.1	------	.0	------	.2	.7	9.3	.2
Iron (Fe)	.74	.14	.23	.00	.00	.03	01	------	.03	------	.01	1.2	16	.09
Manganese (Mn)	1.0	.14	.00	.00	.00	.00	.00	------	.00	------	.00	.00	.04	.00
Arsenic (As)	.04	.04	.00	.00	------	.00	.00	------	.00	------	.00	.04	.00	.00
Strontium (Sr)	11	6.0	2.6	4.4	------	1.0	------	------	.8	------	1.4	2.0	15	1.4
Calcium (Ca)	129	343	34	138	43	43	46	35	37	26	37	9.6	833	46
Magnesium (Mg)	164	71	37	85	21	20	21	20	20	22	29	24	95	19
Sodium (Na)	2,780	4,480	970	20,600	145	155	144	155	159	145	248	2,850	8,050	39
Potassium (K)	219	250	42	1,710	11	11	12	12	12	11	16	107	334	1.2
Bicarbonate (HCO_3)	768	773	1,050	466	350	344	364	348	348	321	430	796	114	140
Carbonate (CO_3)	0	0	22	0	0	0	0	0	0	------	0	62	0	0
Sulfate (SO_4)	1,730	1,600	744	10,000	174	186	164	160	186	158	302	1,480	2,760	87
Chloride (Cl)	3,430	6,290	530	26,000	36	37	37	43	38	39	68	2,840	11,400	54
Fluoride (F)	2.4	3.1	5.9	4.8	2.8	2.8	3.2	2.0	3.6	3.0	4.0	6.9	9.8	.7
Nitrate (NO_3)	8.0	3.0	1.8	58	.0	.0	.00	0	.4	0	.0	6.0	.0	.2
Orthophosphate (PO_4)	.35	.17	.00	.00	.0	.00	.00	------	.00	------	.08	.57	.00	.00
Boron (B)	8.0	30	5.6	96	------	.82	.90	1.0	1.0	0	1.6	22	344	.26
Dissolved solids (residue at 180° C)	8,860	13,700	3,080	58,300	620	648	647	716	635	------	915	7,900	21,300	391
Hardness as $CaCO_3$	996	1,150	237	694	194	190	202	------	174	------	212	122	2,470	193
Specific conductance (μmhos at 25° C)	13,400	20,900	4,510	71,300	988	986	1,020	------	991	------	1,470	12,000	35,000	579
pH	7.6	7.0	8.4	7.8	7.9	7.6	8.0	7.9	7.9	8.05	8.2	8.6	7.5	7.5
Beta-gamma activity ($\mu\mu$ c/l)	350	470	89	2,100	30	28	24±4	------	24	------	29±4	150	<130	<2.6
Radium (Ra) ($\mu\mu$ c/l)	.3	1.0	2.3	0.2	5.7	3.4	2.4±0.5	------	<0.1	------	0.1±0.1	0.1	0.2±0.1	0.1
Uranium (U) (μg/l)	2.8±0.3	3.7±0.4	0.4±0.1	13±1.3	1.5	1.3±0.10	1.9±0.2	------	2.7±0.3	------	3.1±0.3	9.3±0.90	2.8±0.3	0.7±0.1
Discharge gpm estimated	2/3	2	25	1/2	350	40	------	------	2,200	------	------	1/2	1	------
Temperature (° F)	51	90	68	61	102	103	85	91	90	90	56	54	53	77

[1] Zinc (Zn) 0.0; Bromine (Br) 5.0; Iodine (I) 0.0.
[2] Zinc (Zn) 0.0; Bromine (Br) 4.8; Iodine (I) 0.00.
[3] Zinc (Zn) 0.0; Bromine (Br) 4.8; Iodine (I) 0.00.
[4] Molybdenum (Mo) <0.02.
[5] Lithium 0.13.
[6] Molybdenum (Mo) <.02.
[7] Molybdenum (Mo) 0.2; Iodine (I) 0.00; Bromine (Br) 0.00.
[8] Zinc (Zn) 0; Molybdenum (Mo) ±0.02; Bromine (Br) 0.<; Iodine (I) 0.0.

NOTE.—Description of locality as follows:

3054. McLean Spring area; pit 3 ft deep in alluvium; center, N½ sec. 6, T. 16 S., R. 46 E. 1.
3052. Warm Spring at Westside Borax camp.
3049. Keane Wonder mine.
3055. Spring 1 mile southeast of Northside Borax Camp.
1109. Nevares Springs.
3048. Nevares Springs.
3647. Nevares Springs.
2. Texas Spring.
3051. Travertine Spring.
1. Travertine Spring.
3065. Cow Creek Springs.
3050. Marsh at mouth of Cow Creek.
3058. Spring at Badwater.
3053. Bennetts Well.

TABLE 22.—*Semiquantitative partial analyses, in percent of water at seeps and in marshes at foot of fans sloping from the Funeral Mountains*

[Analysts and analytical methods given on page B 90. See also table 50]

	W5–56g	W6g	W7g	W17g	W19g	W27g	W28g
Ca	0.12	0.008	0.003	<0.001	0.001	0.003	0.005
Mg	.01	.002	.001	<.001	.001	<.001	.005
K	.20	.15	.04	.06	--------	.01	.24
Na	4.2	1.6	.40	.84	--------	1.3	9.6
SO_4	1.8	.9	.5	.20	.02	1.0	2.6
Cl	5.64	.01	.02	1.20	.02	.5	11.0
B	.02	.002	.001	.004	<.001	.003	.0260
Sr	.01	.001	<.001	<.001	.001	.003	.0010
Total dissolved solids	12	5.0	1.3	2.4	.15	3.5	26
pH	--------	7.7	8.1	8.5	7.5	8.0	6.5

W5–56g. Ground water at seep, NE ¼ sec. 18, T. 28 N., R. 1 E.
W6g. Ground water in gravel 16 in. below bed of channel 150 ft east of W5s.
W7g. Ground water in gravel 3 ft below surface; by old road at boundary between xerophyte and phreatophyte zones. SE ¼ sec. 20, T. 28 N., R. 1 E.
W17g. Ground water, 1 ft below surface, near W6–56g.
W19g. Ground water 20 in. below surface; at boundary between xerophyte and phreatophyte zones. NW¼ sec. 4, T. 27 N., R. 1 E.
W27g. Spring at west edge of hill at Harmony Borax Mill; along fault scarp south of W26g. W¼ sec. 9, T. 27, N., R. 1 E.
W28g. Ground water, 12 in. below surface; marsh gas. In distributary north of W25s and W26g at same escarpment as W26g. NW¼ sec. 9, T. 27 N., R. 1 E.

MOJAVE RIVER BASIN

The low part of the south rim of the Death Valley hydrologic basin adjoins the drainage basin of the Mojave River. The divide separating the basins crosses a valley 8 miles wide between the playas at Silver Lake and Silurian Lake a few miles north of Baker. South of Silver Lake playa is the much more extensive playa of Soda Lake which is the sink for the Mojave River. The 2 playas are about 40 feet below the divide forming the south rim of the Death Valley Basin. When flooded to that depth in Pleistocene time, they overflowed northward into Death Valley.

There has been no surface water discharge from the playas of Silver Lake and Soda Lake during historic time, although there may have been some during the Recent pluvial period.

Ground water probably discharges from the Mojave River basin to Death Valley at present, as noted by Thompson (1929, p. 561). Figure 9 illustrates the northward slope of the water table at Soda Lake and Silver Lake playas. The fact that Silver Lake playa is occasionally flooded, yet has no accumulation of salts on it, also suggests ground-water drainage from it—probably northward to Silurian Lake and Amargosa River (Thompson, 1929, p. 561–562). The water from Salt Spring (table 13, No. 5) is similar to that at Soda Lake, but very different from that at Silver Lake (table 23).

Proportions of major cations and major anions in water from Salt Spring and Silver Lake are shown below.

	Salt Spring	Silver Lake	Soda Lake
Ca	10	1.5	13
Mg	5	1.5	11
Na+K	35	97	76
HCO_3	9	58	15
SO_4	26	19	10
Cl	65	23	75

The area drained by the Mojave River is composed mostly of crystalline rocks, and the quality of the water in general is good. The absence of salt beds on the playas has been attributed partly to the good quality of the water and partly to ground-water drainage from the playas (Muessig and others, 1957). Why the water at Silver Lake is so different from that at Soda Lake, however, is not known; this difference seems to contradict the thought that ground water from Soda Lake drains northward to Silver Lake.

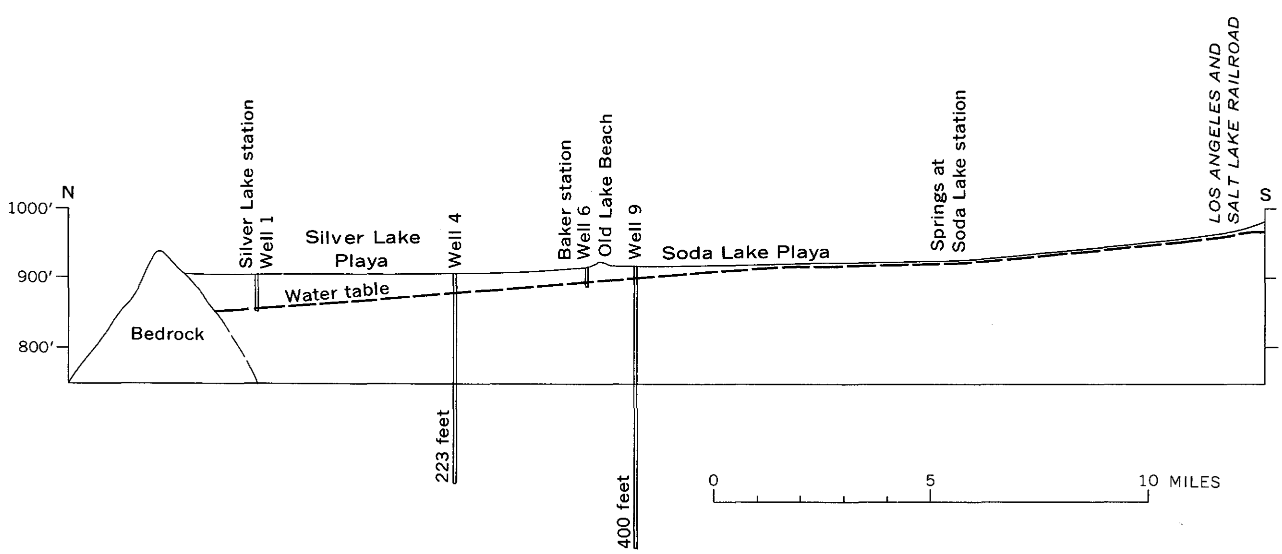

FIGURE 9.—Profile of the surface and water table northward from Soda Lake to Silver Lake. Silver Lake playa is flooded occasionally, but no salts have accumulated on it. Presumably ground water drains from under the playa, probably northward to Silurian Lake and the Amargosa River. From Thompson, 1929, fig. 16, p. 562.

TABLE 23.—*Analyses, in parts per million, of ground water at Soda Lake and Silver Lake*

[Analyst, Addie T. Geiger, U.S. Geol. Survey. Data from Thompson, 1929, p. 532]

	Well, 61 ft to water table; near north end of Silver Lake playa	Well at west edge of Baker; 35 ft to water table
SiO_2	61	52
Fe	.15	.32
Ca	6.8	108
Mg	6.6	88
Na+K	458	623
CO_3	35	5.8
HCO_3	567	221
SO_4	186	153
Cl	223	1,097
NO_3	8.6	10
Total dissolved solids at 180°C	1,269	2,298
Total hardness as $CaCO_3$	44	631

PAHRUMP VALLEY

The Pahrump Valley, covering about 250 square miles, receives drainage from the west slope of the Spring Mountains which reach almost to 12,000 feet. The lowest part of Pahrump Valley is a playa known as Stewart Valley, and ground water there is within 10 feet of the surface (Waring, 1920, p. 66). Stewart Valley is only 10 miles southeast of the large springs at Ash Meadows in the Death Valley hydrologic basin, and is 300 feet higher.

Pahrump Valley seems to be the source of the ground-water discharge at the large springs at Ash Meadows and possibly at some of the other large warm ones farther south in the Amargosa River drainage (p. B40). Water in Pahrump Valley is a bicarbonate water very similar to that at Ash Meadows, as brought out by the analyses in table 24 (compare with table 13).

SARCOBATUS FLAT

Sarcobatus Flat, at the north side of the Death Valley hydrologic basin, is the sink for a drainage area of about 750 square miles. The areas tributary to the flat are hilly and rather mountainous. There is no evident source for water in the Sarobatus Flat area except the meager local rainfall, which probably is not sufficient to maintain the numerous large springs in Oasis Valley at the head of the Amargosa River. The quality of water in these springs is rather like that at the springs at Ash Meadows and in ground water elsewhere in the Amargosa Desert. The water probably is discharging from aquifers along faults, but its ultimate source, at this time, can only be guessed.

TABLE 24.—*Complete analyses of ground water from five wells in Pahrump Valley*

[Chemical components, in parts per million]

	348	3212	3213	3211	3207
Silica (SiO_2)	0.16	22	21	38	90
Aluminum (Al)	.0	.1	.1	.0	.3
Iron (Fe)	.00	3.0	.10	.00	.16
Manganese (Mn)	.00	.00	.00	.00	.00
Arsenic (As)	------	.00	.00	.00	.00
Strontium (Sr)	------	.57	.76	.62	2.1
Calcium (Ca)	53	43	46	31	70
Magnesium (Mg)	22	30	26	33	71
Sodium (Na)	7.1	9.2	28	19	79
Potassium (K)	.8	1.2	4.0	4.0	18
Bicarbonate (HCO_3)	224	235	280	230	686
Carbonate (CO_3)	0	0	0	0	0
Sulfate (SO_4)	47	46	36	45	58
Chloride (Cl)	3.0	6.5	12	16	22
Fluoride (F)	.5	.2	.3	.7	1.4
Nitrate (NO_3)	.6	.3	2.4	1.5	22
Orthophosphate (PO_4)	.0	.00	.00	.00	4.4
Boron (B)	------	.03	.14	.06	.29
Dissolved solids (residue at 180° C)	259	269	302	291	747
Hardness as $CaCO_3$	223	231	222	213	466
Specefic conductance (μmhos at 25° C)	428	455	524	483	1,210
pH	7.8	7.7	7.8	7.7	7.6
Beta-gamma activity (μμc/l)	<14	4.5±0.8	13±2	13±2	54±8
Radium (Ra) (μμc/l)	.1	<0.1	0.1±0.1	0.1±0.1	2.9±0.6
Uranium (U) (μg/l)	1.6	2.2±0.2	2.1±0.2	2.8±0.3	3.9±0.4
Discharge gum estimated	------	------	------	200	------
Temperature (° F)	74	67	73	65	62.5

Location of wells:
Lab. No. 348. 7 miles southeast of Pahrump, Nev., NE¼ sec. 16, T. 21 S., R. 54 E.
3212. 4½ miles south of Pahrump, Nev., SW¼ sec. 12, T. 21 S., R. 53 E.
3213. 8 miles north of Pahrump, Nev., NW¼ sec. 9, T. 19 S., R. 53 E.
3211. 6 miles west of Pahrump, Nev., NE¼ sec. 22, T. 20 S., R. 52 E.
3207. 10 miles west of Pahrump in Stewart Valley, Nev., SE¼ sec. 6, T. 20 S., R. 52 E.

OCCURRENCE OF GROUND WATER IN DEATH VALLEY

Ground water occurs throughout Death Valley in varying amounts. In the mountainous areas ground water is not plentiful. Scattered small springs are to be found in places along joints, fissures, faults, and formation contacts. (See table 10.) In contrast, ground water occurs over much of the lower parts of the valley. In this part there are two principal areas of occurrence. One, the Cow Creek-Texas Spring-Furnace Creek Wash area, and the other, the valley floor and adjacent marginal areas. Travertine Springs, in Furnace Creek Wash, with a flow of about 2,000 gpm, is the largest spring; whereas on the valley floor the discharge of most of the springs is small, generally less than 25 gpm.

The largest springs, such as Travertine Springs, are those discharging along high-angle faults, like those along the Furnace Creek fault zone between the Black Mountains and Funeral Mountains. Other smaller springs of this type occur along the frontal faults at the foot of the Black Mountains.

In the mountains, springs discharge at low-angle faults. Most of the springs in the Panamint Range are of this type; so also is the spring at Daylight Pass between the Funeral and Grapevine Mountains. These springs have excellent water, but their discharge is small—mostly no more than a few gallons per minute.

A third kind of spring occurs where ground water is ponded by an impervious structural barrier. The best example of this type is the spring zone that maintains the flow in Salt Creek through the Salt Creek Hills. The hills are an uplift of impervious Tertiary formations, and ground water is ponded in Mesquite Flat upstream from that impervious barrier. The overflow of this ground water maintains the flow in Salt Creek.

Still a fourth type of spring occurs around the edge of the saltpan where ground water is ponded in the coarse gravel and sand where it grades laterally to silt under the saltpan. Much of this water is saline.

In addition to the springs the presence of ground water on the valley floor and marginal area is indicated by a few wells that have been dug or drilled for water supply, by auger holes and pits dug during the course of fieldwork, and by the growth of phreatophytes. Phreatophytes are confined to a zone that lies between the saltpan and the toes of the alluvial fans and aprons. Uphill from the toes of the alluvial fans the depth to water increases so rapidly that in a short distance the water table is beyond the reach of the phreatophytic plants. On the saltpan the salinity of the water is too great for even the most salt-tolerant phreatophytes.

The springs on Cow Creek, in Furnace Creek Wash, and Texas Spring supply the permanent residents in that area, a public campground, the principal resort establishments, and, in addition, furnish sufficient water to irrigate a golf course and a grove of date palms totaling about 40 acres.

Around the edge of the saltpan ground water is at or witbin a few feet of the surface. In some places it occurs under water-table conditions, that is, unconfined. In other places it appears to be partly confined and, consequently, under some artesian head. In such areas the near-surface sediments, largely silts and clays but with some lenses of fine sand, restrict, but do not prevent, movement of water through them.

Evidence that the water is under an artesian pressure is furnished by the changes in rate of discharge through the sediments related to changes in barometric pressure. In this well-known phenomena, water levels in nonflowing artesian wells rise as the barometric pressure falls and fall as the barometric pressure rises. In flowing wells, the discharge increases with falling barometer and decreases with a rising barometer. On three occasions during the winter of 1959–60, increases in discharge were observed during the periods of a falling barometer. In two areas, Harmony Borax and Salt Springs, this was noted as a thin sheet of water with a front advancing downstream in a nearly flat channel. The increase in discharge was small, of the order of 1–2 gpm. It was apparent that the source of water was due to a temporary increase in discharge near the head of the channel.

At Salt Springs, where the ground water is partly confined, small conduits appear to have developed through the fine-grained sediments —silts and clays—that make up the confining bed. The surface expression of these conduits are tubelike openings. The openings range from the size of a pencil to those that may be 2 inches in diameter as shown on figure 10.

The conduits appear to function, in response to changes in barometric pressure, in a manner similar to intermittent flowing artesian wells. The water level in the conduits stands sufficiently near the land surface so that when the barometric pressure falls the water levels rise to the surface and flow out of the tubelike openings. The flow is small and even for the larger openings is of the order of only 1 or 2 gallons per hour.

Figure 10 shows two of the orifices from which there was a very small but definite flow of water as indicated by the wetted area. The ground water in this area is a brine that contains about 58,000 ppm of dissolved solids, largely sodium chloride. These salts, left behind as the brine evaporates, are plainly visible in the surrounding wetted area and are evidence of continued, although not necessarily continuous, discharge of the

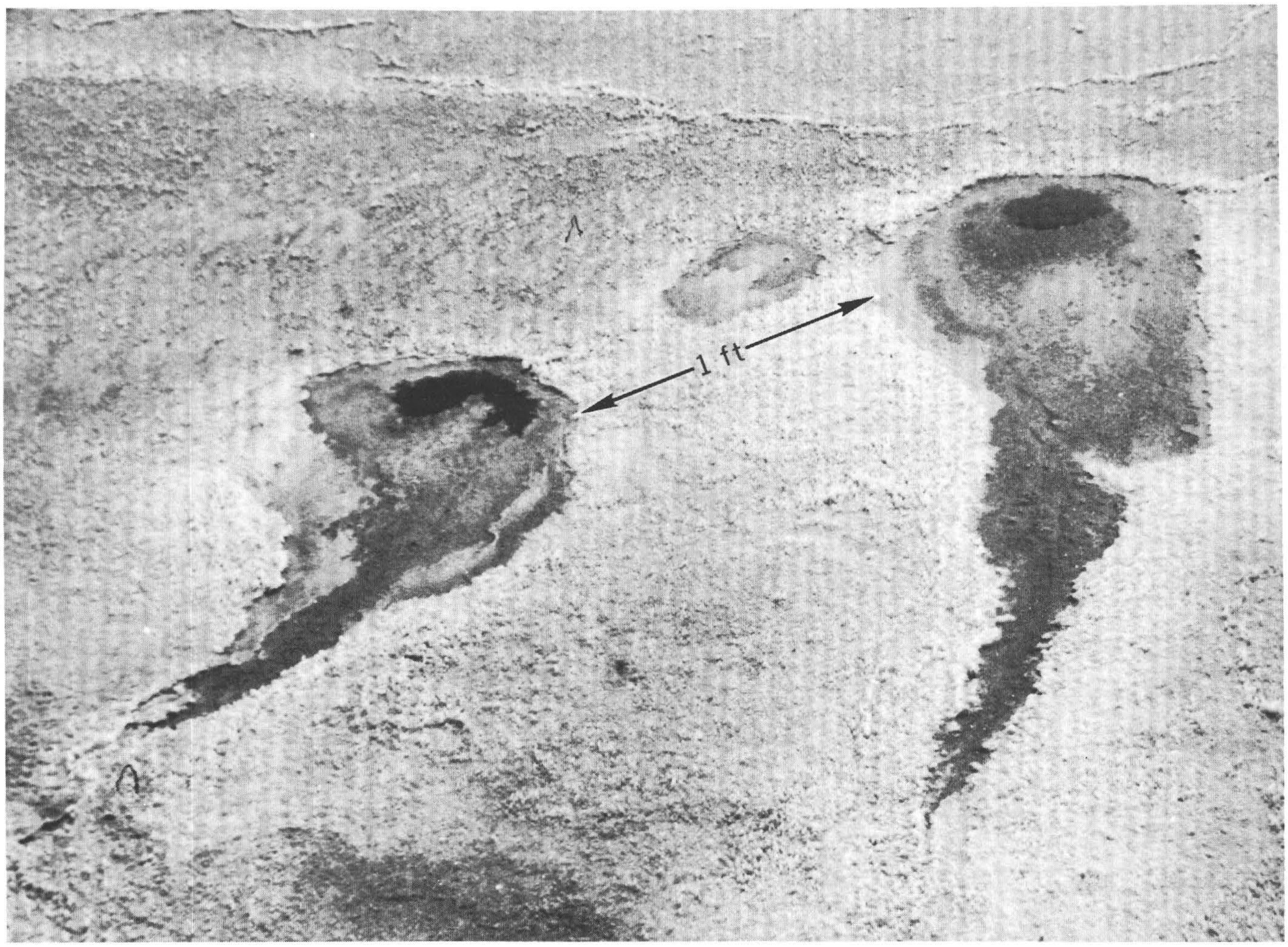

FIGURE 10.—Tubular orifices in the fine sediments at Salt Springs near North Side Borax Camp allow discharge of water to the valley floor. Light areas are accumulations of salts from previous discharges.

brine. Frequently a rim of salt is built up around the orifice, ranging from 1 or 3 to 25 mm in height. Some rims are high enough to prevent flow, and in such orifices the brine stands at or near the top of the salt rim when the barometric pressure is low and recedes as it rises. Earth tides may also be a factor affecting variations in discharge from the springs and tubular openings (Robinson, 1939).

SLOPE AND MOVEMENT

The slope of the water table and the general direction of movement of the ground water, both confined and unconfined, are toward the valley floor. During the course of the study the slope of the ground water was determined at four localities. One was at the east side of the valley and the others on the west side.

At the North Side Borax Camp in the Salt Springs area, the abandoned dug well, used when the camp was active, was cleaned of debris to the water level, which stood 19 feet below the surface. The water level in the well was 3.6 feet higher than at the nearest seep, on the margin of the valley floor 800 feet distant. Thus, the slope of the ground-water surface at this point was about 24 feet to the mile. The elevation of the seep area is about 250 feet below sea level.

The three slope determinations on the west side of the valley were at Tule Spring, at Shortys Well, and at Gravel Well. At Tule Spring a difference in altitude of the water surface in an auger hole 725 feet upgradient from the spring and the water level in the spring pool was 6.1 feet. This is equivalent to a slope of about 44.5 feet to the mile. At Shortys Well the difference in water level between the well and an auger hole 1,080 feet downgradient was 10.75 feet, equivalent to a slope of about 53 feet to the mile. At Gravel Well the difference in an auger hole 1,025 feet downgradient was 9.6 feet, equivalent to a slope of about 50 feet to the mile. Each of the three locations was approximately across the −250 foot contour.

The gradient at these localities is believed to flatten eastward toward the valley floor as shown on figure 8.

The change in facies of the sediments toward the valley floor from coarse to fine, that is, from gravels through sand to silt, results in a decreasing permeability in this direction. The change in permeability restricts the rate of ground-water movement, produces a "ponding" effect that results in a flatter gradient, and forces the ground water nearer to the surface. In places it discharges at the surface to form springs and marshes, such as Tule Spring, Eagle Borax Spring, and the unnamed marsh east of Gravel Well. Over most of the fine-sediment low-permeability zone, the capillary fringe extends to the surface. Phreatophyte growth occurs over the entire zone, ranging in density from sparse, widely separated clumps, to dense thickets.

DISCHARGE ONTO THE VALLEY FLOOR

The water that moves through the coarse gravels and sand reaches the low permeability zone and is discharged in part by upward seepage to the valley floor, by spring flow, by evaporation from the capillary fringe, and, during the growing season, by transpiration of phreatophytes.

The small springs and seeps that occur as the result of these changes in permeability are on or near the perimeter of the valley floor. Most of these discharge areas are below the toes of alluvial fans and aprons where the slope of the land surface is nearly flat. These areas are more prominent and easier to observe during the winter than in the summer. During the summer the high evaporation disposes of the small flow as rapidly as it is discharged at the surface. In winter, the flow is greater than the loss by evaporation, and the water spreads over the surface as a thin sheet or collects in shallow pools. During storm periods when there may be slight precipitation or when the humidity is much higher than normal, these sheets of water and pools increase markedly. This surface-water expression of spring discharge usually starts to form in November or December, reaches a maximum in January or February, and decreases in size until the last of April or first of May when most have entirely disappeared. For some springs the flow is sufficient to balance the higher evaporation loss and the pool remains all summer, although smaller in area. The pool at Badwater is of this type.

The response of spring discharge to changes in the evaporation rate is shown by the discharges of Salt Creek on page B32. The highest discharge occurred during January and February and by April the flow had declined markedly. In the shallow-water-table area above the Salt Creek Hills uplift, water is discharged by evaporation and by transpiration of phreatophytes during the growing season. Both are undoubtedly reflected in the April measurements.

Because of the character of the springs and spring areas where, for the most part, discharge occurred through numerous small scattered orifices, or as slow seepage through the sediments, it was necessary to resort to indirect methods for estimating the spring discharge. The single exception was Salt Creek where there was perennial flow in an established channel. Several measurements of flow of Salt Creek were made during the study.

Estimates of spring flow were made by using the evaporation rate from water surfaces, from salt and mud surfaces, and by applying annual transpiration rates to areas of phreatophytes within the area of spring discharge.

On the basis of the relation of evaporation from the 2-foot diameter tub in a pool at Cottonball Marsh (p. B8) and the evaporation pan at the weather station, evaporation from the water surface at the spring areas was assumed to be the same as the evaporation pan. The pool in which the tub was located—about 100 feet in diameter and containing 2–3 inches of water in the deepest part—was typical of the pools at most of the spring areas during January 1959.

By utilizing the different evaporation rates in January and in April, and the different water-surface areas, it was possible to put limits on the estimate of spring discharge. Thus, during January when the evaporation rate was low, the spring discharge was either going into storage in the pool and increasing its area or the area of the pool had increased to the point where discharge by evaporation balanced inflow. Under these conditions the area of the pool times the average daily rate of evaporation was equal to, or less than, the rate of spring discharge. In April the areas of the pools were much smaller, indicating that evaporation from the pool was greater than inflow. The discharge of the spring was taken as the average of the January and April estimates. Pool areas were obtained by pacing. The evaporation rate used was the average daily pan evaporation for the 10-day period before field examinations of the spring. For January 1959 this was 0.13 inch (0.011 ft) per day and for April 1959, 0.43 inch (0.036 ft) per day.

In addition to the flow into pools, there were generally wetted areas of mud and salt within the spring area from which water was discharged by evaporation. Usually the mud and salt areas were many times the pool areas. Estimates of the discharge from these areas were obtained, similar to that for the pool areas. The areas of mud and salt were obtained by pacing or by outlining them on aerial photographs and planimetering. The average rates of loss obtained from the experiments with buckets of wet salt and wet saliferous mud, described above, were used in computing evaporation from these areas. This averaged 0.015 inch (0.0013 ft) per day over a 33-day period in January and February 1959.

In obtaining the discharge rate for a few of the spring areas, where small channels conducted the flow to a pool, the flow for each channel was estimated and the several flows were totaled. Small flows are difficult to estimate, but by making measurements of width, depth, and velocity, and checking these against volumetric measurements when feasible, it is believed reasonably accurate results were obtained.

At Eagle Borax Spring the estimate of discharge was based on the area of phreatophyte growth in the general spring area and a transpiration rate extrapolated from other nearby areas after allowance was made for differences in temperature and humidity.

DESCRIPTIONS AND DISCHARGES OF SPRINGS AND OF MARSHES

Salt Creek

Seven float measurements of discharge of Salt Creek were made about half a mile below McLean Falls in the canyon, just before it emerges from the Salt Creek Hills. The stream channel here flows on bedrock of fine-grained sandstone, and there is little opportunity for underflow. The channel is from 4 to 6 feet wide, but maximum depths are usually not more than 3 or 4 inches. All the measurements were made at the same location by T. W. Robinson. Depths were measured with a steel tape and velocity by timing floats with a stopwatch. The measurements are believed to be sufficiently accurate to show true variations in flow, and these are attributed to evapotranspiration losses.

Date	*Discharge (gpm)*	*Date*	*Discharge (gpm)*
Apr. 10, 1957	180	Apr. 18, 1959	200
Feb. 4, 1958	625	Feb. 27, 1960	370
Apr. 17, 1958	280	Feb. 25, 1961	350
Jan. 18, 1959	415		

Marsh area at northeast side of Cottonball Basin

This marsh is a large spring area that extends for about 3½ miles along the edge of the salt pan, on the east side of the valley, north of the National Park Service Headquarters. Its southern limit is about 1½ miles north of the road junction leading to the headquarters.

The spring area is characterized by numerous small orifices and seep areas. Many of the orifices have the characteristic tubular shape shown in figure 10. The seeps are present over large mud and salt areas where water is percolating slowly to the surface. Over most of the mud area a thin film of water may be developed on the mud surface simply by puddling with one's feet. There are no large pools of water, the numerous small channels usually continue from the mud flats into the permanent salt crust where the water eventually disappears.

The discharge of the spring area was estimated by noting the number of channels and estimating their flow. To this figure was added the loss by evaporation from the seep areas of mud and salt. The combined flow in some 30 channels was estimated at 150 gpm. The loss from 250 acres of salt and mud flat was estimated as 75 gpm, making the total spring discharge 225 gpm.

Soda carbonate marsh, east side of Cottonball Basin

This marsh is a much smaller spring area than the one just described. However, water was discharged in much the same manner. The flow from 10 small seep areas was estimated as 10 gpm, and loss from about 80 acres of mud and salt flat, partly overgrown with salt grass, as about 20 gpm. Total discharge is 30 gpm.

Marsh near Harmony Borax Mill

This marsh is similar to, but smaller than, the soda carbonate marsh. Water is discharged from four rather widely spaced seep areas. The discharge from them was estimated at about 15 gpm. In addition, the loss in some 10–15 acres of wetted mud and salt flat was estimated as about 5 gpm. Total discharge for the area on this basis is about 20 gpm.

The area next south of the marsh on the north side of the Harmony Borax Hills, where there is discharge of water from springs onto the saltpan, is the alluvial fan of Furnace Creek Wash. However, the source of this water is largely from Travertine Springs in Furnace Creek Wash, discussed on page B35.

From Furnace Creek Wash south to Badwater, a distance of about 17 miles, there is no measurable discharge of water onto the saltpan. From Badwater south to the end of the saltpan there are several springs and marshes.

Badwater

According to Gudde (1949), the name Badwater originated in a notation on the Furnace Creek Atlas sheet, published in 1908, that the water was not drinkable, that is, "bad water." The springs at Badwater are at the lowest altitude—280 feet below sea level—of any in the United States. The lowest land-surface altitude 282 feet below sea level, occurs in the saltpan at 2 points 4 miles west and 3 miles northwest of the springs. The most prominent feature of Badwater is the large pool into which the springs discharge (fig. 11). There are two pools at Badwater, the second and smaller one is about one-tenth of a mile north of the large pool and not so prominent. The total water-surface area of these two pools in January and April 1959 was about half

FIGURE 11.—Badwater. The pool in which the springs discharge overflows during the winter months through the channels (white) that lead toward the saltpan.

an acre. The area in April was only slightly less than in January. The wet salt and mud area was estimated as about equal to the water surface. Because of the small difference in pool area, it seems probable that there may have been some undetected flow away from the springs in January and in April. The report by the park naturalist that the big pool does not go dry during the summer when the evaporation rate is high lends support to this observation. The spring discharge in April, based on evaporation from the pool and salt surfaces, is estimated as 5 gpm. Assuming an equal undetected flow, the spring discharge is estimated as 10 gpm.

Cove 1.6 miles south of Badwater

A small wetted area indicates some ground-water discharge but not sufficient to maintain a pool even in the winter months. Discharge estimated as about 1 gpm.

Alluvial fan 4.3 miles south of Badwater.

Several seeps at the toe of a moderately large alluvial fan discharge onto the saltpan. The seeps are plainly visible along the toe of the fan for a distance of about a quarter of a mile. The seeps here are not sufficiently concentrated nor large enough for the discharge to form a pool.

The seep area extends along the toe of the fan to the next cove south, a distance of about 1 mile. A growth of pickleweed and moist soil marks the extension of the seep area, although there is no visible discharge. At the next cove south, which lies on the north side of the Coffin Canyon alluvial fan, there are 10 pools of water. The combined area of the 3 larger pools noted in April 1959 was estimated as 600 square feet, and for all the pools in February 1960, as 1,500 square feet. There was no flow from the pools during either month. The discharge for the seep area, including the pools, is estimated as between 5 and 10 gpm.

Mormon Point

The discharge of many small seeps maintained a marsh with a water surface that ranged from about $\frac{1}{10}$ to $\frac{3}{4}$ of an acre between January and April 1959. In addition, the wetted area of mud and salt in January was equal to, or greater than, the water-surface area. The flow from the 2 largest seeps was estimated as 1 and 2 gpm, respectively. On the basis of these observations, the discharge of the spring area is estimated as about 5 gpm.

Marsh midway between Mormon Point and Coyote Hole

In January 1959 the water-surface area was estimated as about 1⅔ acres and the wetted area as about the same. By April the water-surface area had shrunk to about one-tenth of an acre, and the wetted area from which there was evapotranspiration had increased to more than 3 acres. Included in the wetted area of 3 acres was about 1 acre of phreatophytic growth, largely desertrush and pickleweed that were probably transpiring some water in April. Over the rest of the wetted area, largely barren, salt and gypsum were being deposited as a result of evaporation. In January 1959 the visible flow from numerous small seeps was estimated as about 5 gpm. The total discharge for the spring area, based on evapotranspiration discharge of 1 acre of phreatophytes and 2 acres of wetted area, is estimated as about 10 gpm.

Coyote Hole

Coyote Hole is the most southerly of the spring areas on the east side of the valley that discharges water onto the saltpan. The marsh is about 2 acres in extent and is nearly covered with a dense growth of phreatophytes. These include giant reedgrass, tules, rushes, saltgrass, and about one dozen clumps of mesquite. In January 1959, water was standing on the phreatophyte growth, and 1 large pool of about 10,000 square feet in area was noted. In April no pools of water were observed, although the marsh was wet and water could be seen in open places in the phreatophyte growth. Green leaves and new growth were observed on the plants, indicating that transpiration was occurring. The discharge of Coyote Hole was estimated on the basis of evapotranspiration from the 2 acres of phreatophytes. The growing season was taken as about 240 days—mid-March to mid-November—based on the weather record at Cow Creek.

Evapotranspiration discharge is estimated as 9 acre-feet per acre for 240 days of growing season. This estimate is based on extrapolation from other areas of like vegetation in the Southwest and from computations and data used to obtain the discharge of Saratoga Springs (Robinson, 1957), some 30 miles to the south and 400 feet higher in elevation. On this basis the evapotranspiration discharge of 18 acre-feet during the 240-day growing season is equivalent to a flow of 17 gpm. It seems probable that the flow of the springs is about 20 gpm.

Springs between Salt Well and Gravel Well

The southern limit of ground-water discharge onto the saltpan on the west side of the valley is at about the latitude of Salt Well. At Salt Well the water level in an abandoned dug well is 8.0 feet below the land surface. East of the road between Salt Well and Gravel Well, a distance of 4 miles, there are small springs with visible discharge. The flow of the springs ranged from less than 1 to about 5 gpm, averaging about 2½ gpm. The combined flow was estimated as 25 gpm.

Marshes east of Gravel Well and Bennetts Well

East of Gravel Well and Bennetts Well there are marsh areas. The areas are not large, the one at Gravel Well being the larger of the two. They are characterized by a hummocky surface on which saltgrass is the dominant vegetation. The discharge of these marshes was difficult to estimate, but the total of the two probably does not exceed 20 gpm.

Eagle Borax Spring

Eagle Borax Spring is the second largest on the west side of the valley. Although the visible discharge is small, variously estimated as between 15 and 25 gpm, the total discharge from the area is many times greater. Employees of the National Park Service report that during some years there is no visible flow during the summer months.

The spring received its name from the old Eagle Borax works, the remains of one of the first companies to attempt borax mining in the valley. In order to obtain water for the refining operations, some developing and excavating was done in the spring area. The only improvement at the time of the study was a crude fence around one spring area to keep out animals, and a half barrel or box sunk into the ground from which water could be dipped.

The spring area supports about 40 acres of moderate to dense growth of different species of phreatophytes. Identified as phreatophytes were the two species of saltcedar, *T. pentandra* and *T. aphylla*, saltgrass, arrowweed, mesquite, pickleweed, tules, and rushes. The tules and rushes grow in wet areas with water at or near the surface. This area was estimated as about 2 acres in extent. Saltgrass, arrowweed, and pickleweed were estimated to cover about one-fifth of the total area. The remainder and most prominent part of the area is a dense growth of saltcedar and mesquite about equally divided. The discharge of the spring was estimated on the basis of the evapotranspiration discharge by the plants for a 240-day growing season.

Use of water for the tules and rushes and for the saltgrass and associated pickleweed and arrowweed was adapted from the values used in estimating the discharge at Saratoga Springs (Robinson, 1957). The use of water for saltcedar was computed by the Blaney and Criddle (1949) method on the basis of use in Safford Valley, Ariz. (Gatewood and others, 1950).

Use for the 240-day growing season on this basis was 13 acre-feet per acre for the rushes and tules, 5.5 acre-feet per acre for the saltgrass and associated pickleweed and arrowweed, 10 acre-feet per acre for the saltcedar, and 5 acre-feet per acre for the mesquite. The use during the growing season on this basis was about 300 acre-feet, equivalent to a flow of 285 gpm. Because of the uncertainties inherent in estimating discharge by transpiration based on data from other areas, the estimated discharge is rounded to 300 gpm.

Tule Spring

Tule Spring, about 3 miles north of Eagle Borax Springs, consists of a pool 20 feet in diameter. The pool is surrounded by a dense growth of arrowweed for a distance of 8–12 feet from the edge of the pool. There is no visible flow from the pool. The discharge was measured by bailing a known quantity of water from the pool and noting the time of recovery. As the result of a bailing test on January 22, 1959, the inflow into the pool was estimated as 20 gallons per hour, or one-third of a gallon per minute. To this should be added a small amount of evaporation and transpiration during the 3-hour recovery period. It seems fairly certain that the spring does not exceed 1 gpm. The discharge from a small marsh area about half a mile east of Tule Spring is estimated as about twice that of the spring. The total discharge of both probably does not exceed 5 gpm.

Cottonball Marsh

Perennial pools of water in Cottonball Marsh contain a considerable population of desert fish of the same species (*Cyprinodon salinus*) that are found in the pools and channel of Salt Creek about 10 miles to the north. Cottonball Marsh is the largest marsh on the floor of Death Valley, covering about 1 square mile of salt-encrusted surface on the west side (north end) of the saltpan. It consists of two areas, the smaller lying sbout half a mile north of the larger. The smaller area covers about 140 acres, whereas the main part of the marsh covers about 500 acres. Although there are scattered clumps of pickleweed and saltgrass in and around the margins, the marsh for the most part is a nearly barren salt- and gypsum-encrusted area, containing a few permanent pools in which the fish live during hot summer months. During the winter months when evaporation is low, the shallow depressions in the salt crush are filled with water, as shown by figure 12. At the time of the photograph, January 1959, it was estimated that about 40 percent of the marsh area was water surface and 60 percent was a wetted crust of salt or gypsum. In April many of the shallow pools were dry, whereas the water-surface area in others had shrunk markedly. The water surface in April 1959 was estimated as between 5 and 10 percent of the marsh area and the wetted crust as about 90 percent. On the basis of these estimates of water surface and wetted areas and rates of evaporation for each, the discharge of Cottonball Marsh is estimated to be about 1.5 cfs (cubic feet per second), or 700 gpm. The marsh has a catchment area inadequate to maintain the water, and probably it is recharged by ground water from Mesquite Flat moving to the marsh along faults.

Discharge of springs in the Furnace Creek fault zone

The Cow Creek-Furnace Creek Wash area on the east side of the valley has the largest spring discharge of any area in Death Valley. The 3 main areas of discharge occur between Cow Creek on the north and Furnace Creek Wash on the south, at altitudes of 400–1,000 feet above sea level. The areas of the springs are, from north to south, Nevares Springs, Texas Spring, and Travertine Springs.

Travertine Springs is adjacent to Furnace Creek Wash on the north. Before the present system of collection ditches and diversion works were constructed, the spring discharged into the gravels of Furnace Creek Wash and moved as underflow down the wash and into its alluvial fan. Here in the lower part of the fan and around the toe of the fan, the water was dissipated by transpiration of phreatophytes (largely mesquite), evaporation from the soil, and possibly some seepage to the channel of Salt Creek.

It is doubtful that much of the water from Texas Spring and Nevares Springs ever reached the floor of the valley. Most of it probably is lost by transpiration and evaporation before reaching the valley floor.

The discharges of the areas of the three springs are taken from earlier reports (Robinson, 1952; Pistrang and Kunkel, 1958). The discharge of the Nevares Springs area, as the total of measurements of 5 different discharge points, was 0.73 cfs (330 gpm) in 1951 and 0.72 cfs (324 gpm) in 1957, indicating virtually no change in the rate of discharge.

The principal discharge point of Texas Spring is from a horizontal tunnel about 300 feet long into the hillside where it apparently intersects the water table. The flow from the tunnel from February 6, 1956, to November 6, 1957, was nearly constant at 0.50 cfs (225 gpm).

The discharge of Travertine Springs includes not only the flow from the main spring area but also underflow in Furnace Creek Wash. A part of this underflow is recovered by means of sand points, sump, trench, and buried tile, which can be measured; a part escapes into the alluvial fan at the mouth of the wash, which cannot be measured. The water that is recovered is diverted for irrigation at Furnace Creek Ranch.

In 1957 the U.S. Borax and Chemical Corp. made periodic measurements of the flow from the main

FIGURE 12.—View of Cottonball Marsh on west side of Cottonball Basin. The marsh, covering about 1 square mile, has a catchment area that is inadequate to maintain the water in the marsh. The water probably is recharged by ground water from Mesquite Flat moving to the marsh along faults.

spring area and of the recovered underflow at four localities in Furnace Creek Wash (Pistrang and Kunkel, 1958, table 4). Based on the measurements made during the last of February and first of March 1957 when the best coverage is afforded and when both loss by transpiration and evaporation would be low, the discharge of the main spring area and recovered underflow is about 4.4 cfs, or nearly 2,000 gpm. These measurements are given in the following tabulation.

	Discharge	
Point of measurement	*Cu ft per sec*	*Gal per min*
Furnace Creek Inn tunnel	0. 45	200
Travertine Springs (main area)	1. 90	855
Sump in Furnace Creek Wash	1. 28	575
Buried tile in Furnace Creek Wash	. 44	200
Trench in Furnace Creek Wash [1]	. 24	110
Undeveloped springs [2]	. 10	40
Total	4. 41	2, 000

[1] Measurement June 20, 1957.
[2] Estimated.

EVAPOTRANSPIRATION DISCHARGE FROM THE VALLEY FLOOR ABOVE THE SALTPAN

In addition to the discharge of ground water from springs, seeps, and marsh areas, there is also discharge by evapotranspiration from areas of shallow ground water. These areas occur for the most part on the perimeter of the valley floor where there is a change from coarse- to fine-grained sediments toward the saltpan. The result is an area of shallow ground water in which the capillary fringe either extends to the land surface or lies within the reach of the most shallow-rooted phreatophyte.

By far the largest of the areas of shallow ground water lies on the west side of the valley between the toes of the alluvial fans and the saltpan. The next area in size lies at the north end of the saltpan north of the channel of Salt Creek. Two smaller areas occur at the south end of the valley along the Amargosa River and on the east side of the saltpan; several occur on the alluvial fan of Furnace Creek Wash. The total area, exclusive of that on the alluvial fan of Furnace Creek Wash, is nearly 19 square miles, or about 12,000 acres.

The alluvial fan of Furnace Creek Wash is excluded from the computation of evapotranspiration discharge for the reason that the water supplying this area of discharge has been determined separately. No doubt some unmeasured underflow from the wash is discharged by evapotranspiration on the fan, but it is not possible to estimate this unmeasured underflow because of probable mingling of it with waters diverted and used for irrigation at Furnace Creek Ranch.

Most of the area of evapotranspiration discharge is either barren or supports a sparse growth of phreatophytes, generally pickleweed. In a few places, however, there is a moderate to dense growth of mesquite, pickleweed, arrowweed, or saltgrass. Scattered clumps of mesquite and four-wing saltbush are not uncommon.

Observations in January 1959 indicated that the transpiration rate by the phreatophytes at that time was low. Arrowweed and other phreatophytes were tested for transpiration by noting the color change in cobalt blue paper—an indication of moisture—placed next to a leaf for 5 minutes. The change in color was slight, indicating a very low rate of transpiration. The tests were made at various hours of the day, all with the same result.

In view of the low rate of transpiration in January and the generally sparse to medium density of the phreatophyte growth, the discharge in January 1959 probably was largely by evaporation from the land surface. Thus, applying the rate of loss determined for mud and salt crust to the 12,000 acres of shallow ground water would give the loss by evaporation. This rate would probably be less where the phreatophyte growth is sufficiently dense to shade the surface or to reduce wind movement at the surface. On the other hand, the slow transpiration rate would tend to increase the rate of loss. The relative magnitude of these rates of loss is not known, but it is believed safe to assume that they are approximately compensating. On this basis the discharge from the 12,000 acres is estimated as nearly 16 acre-feet per day, equivalent to a flow of 8 cfs or 3,600 gpm.

DIVISIONS OF THE VALLEY ACCORDING TO SOURCES OF GROUND WATER

As discussed elsewhere in this report (p. B38–B40), the evidence points to different sources of the ground water that discharge in different parts of the valley. Briefly, these sources and the areas in which they discharge are (1) the desert valleys of Ash Meadows and Amargosa Desert to the east (p. B20 and B28), which discharge into the east side of Cottonball Basin and Furnace Creek Wash area; (2) the Black Mountains (p. B23), which discharge to the east side of Middle Basin and east side of Badwater Basin; (3) the Panamint Range, which discharges into the west side of Badwater Basin and west side of Middle Basin (p. B22–B23); and (4) Mesquite Flat, which discharges to the west side of Cottonball Basin, Cottonball Marsh, and Salt Creek (p. B19).

The discharge of ground water from springs, seeps, marsh, and by evapotranspiration in these four areas is shown separately in table 25.

This estimated discharge would be sufficient to cover the saltpan to a depth of about 0.1 foot per year, if there were no evaporation or other loss.

POSSIBLE SOURCES OF WATER AT COTTONBALL MARSH

Mesquite Flat is 5–10 miles northwest of Cottonball Marsh and is 100 feet higher. It is separated from the marsh and from the rest of Cottonball Basin by the Salt Creek Hills, which represent a structural uplift of impervious upper Tertiary beds belonging to the Furnace Creek Formation. A gorge through the hills enables surface water to discharge from Mesquite Flat to Cottonball Basin, but upstream, ground water is ponded in the structural depression under Mesquite Flat. This ground water reaches the surface and discharges as perennial flow of Salt Creek in the gorge through the Salt Creek Hills. This surface water discharges 3 miles northeast of Cottonball Marsh and does not reach any part of the marsh area.

At the west edge of the Salt Creek Hills a fault trends almost south to Cottonball Marsh from the head of the perennial stretch of Salt Creek. Part of the ground water that is ponded in Mesquite Flat probably

TABLE 25.—*Summary of ground-water discharge in Death Valley, by areas*

Area	Discharge	
	cfs	gpm
1. East side Cottonball Basin and Furnace Creek Wash area:		
Salt Springs	0.50	225
Soda carbonate marsh	.07	30
Marsh north of Harmony Borax Mill hills	.04	20
Nevares Springs	.73	330
Texas Spring	.50	225
Travertine Springs	4.41	2,000
Evaporation from 1,000 acres of mudflats, estimated	.71	320
Unmeasured underflow in Furnace Creek Wash	-------	-------
Total (rounded)	7.0	3,150
2. East side Middle Basin and east side Badwater Basin:		
Badwater	0.02	10
Toe of alluvial fan 4.3 miles south of Badwater	.02	10
Mormon Point	.01	5
Marsh midway between Mormon Point and Coyote Hole	.02	10
Evaporation from 120 acres of mudflats (estimated)	.08	35
Totals (rounded)	0.2	70
Total east side	7.2	3,220
3. West side Badwater Basin and west side Middle Basin:		
Seeps between Salt Well and Gravel Well	0.06	25
Marsh, east of Gravel Well and Bennetts Well	.04	20
Eagle Borax Spring	.67	300
Tule Spring	.01	5
Evaporation from 8,500 acres of mudflats	5.57	2,500
Totals (rounded)	6.4	2,850
4. West side Cottonball Basin and Slat Creek Cottonball Marsh	1.56	700
Salt Creek, average of January and February measurements	1.11	500
Evaporation from 2,400 acres of mudflats	1.56	700
Totals (rounded)	4.2	1,900
Total west side	10.6	4,800
Totals east and west sides (rounded)	17.8	8,000

discharges southward along this fault and related ones to the marsh.

This interpretation not only provides a reasonable source for the otherwise anomalously large quantity of water at the marsh, but it is supported by the similarity in chemical composition of the water at the lower edge of Mesquite Flat and at the marsh, as illustrated on the bar graphs (fig. 13); (see also analyses 3052 and 3054, table 21). The waters at both localities are alike in the proportions of Ca, Mg, Na, K, HCO_3, SO_4, Cl, As, Sr, F, and U. The waters differ in the proportions of boron and radium. The greater boron in the water at the marsh (2 on the bar graphs) than in the water at Mesquite Flat is reasonable if that water has been channeled along a fault through the boron-bearing Furnace Creek Formation.

Where Salt Creek emerges from the Salt Creek Hills and goes into the ground, it contains 1.5 percent dissolved solids (tables 11, 12). The vegetation along this part of the stream course is pickleweed and fourwing saltbush. Half a mile downstream from this locality there is a grove of honey mesquite. It is anomalous to find honey mesquite on the saltpan side of pickleweed and on the panward side of water containing 1.5 percent salts. Elsewhere in Death Valley the mesquite is restricted to areas where the dissolved solids do not exceed 0.5 percent; pickleweed tolerates as much as 6 percent dissolved solids. Probably this grove of mesquite is receiving ground water from a source other than Salt Creek, and possibly this water also is from Mesquite Flat and is channeled along the southeastward-trending fault that crosses the northern part of the Salt Creek Hills.

POSSIBLE SOURCE OF WATER AT SPRINGS ALONG FURNACE CREEK FAULT ZONE

The large springs north of Furnace Creek—Travertine, Texas, and Nevares Springs—issue from northwest-trending faults in the northwest-plunging syncline that separates the uplifts at the Black Mountains and Funeral Mountains. Each spring has built a large mound of travertine. The waters at the three springs are warm and are alike, as brought out in the following analyses (results in ppm).

	1. Travertine Springs	2. Texas Spring	3. Nevares Springs	
			A	B
SiO_2	43	25	32	-------
Ca	26	35	43	42
Mg	22	20	21	22
Na	145	155	145	138
K	11	12	11	12
HCO_3	321	348	350	317
CO_3	-------	0	0	0
SO_4	158	160	174	173
Cl	39	43	36	34
F	3.0	2.0	2.8	2.9
B	0	1.0	-------	1.2
NO_3	0	0	0	1.8
Sums of determined constituents	605	599	637	583
pH	8.05	7.9	7.9	7.9

1. Analysis by U.S. Geol. Survey.
2. Analysis by California Dept. of Water Resources.
3A. Analysis of sample collected by R. C. Scott and analyzed by U.S. Geol. Survey
3B. Analysis by California Dept. of Public Health.

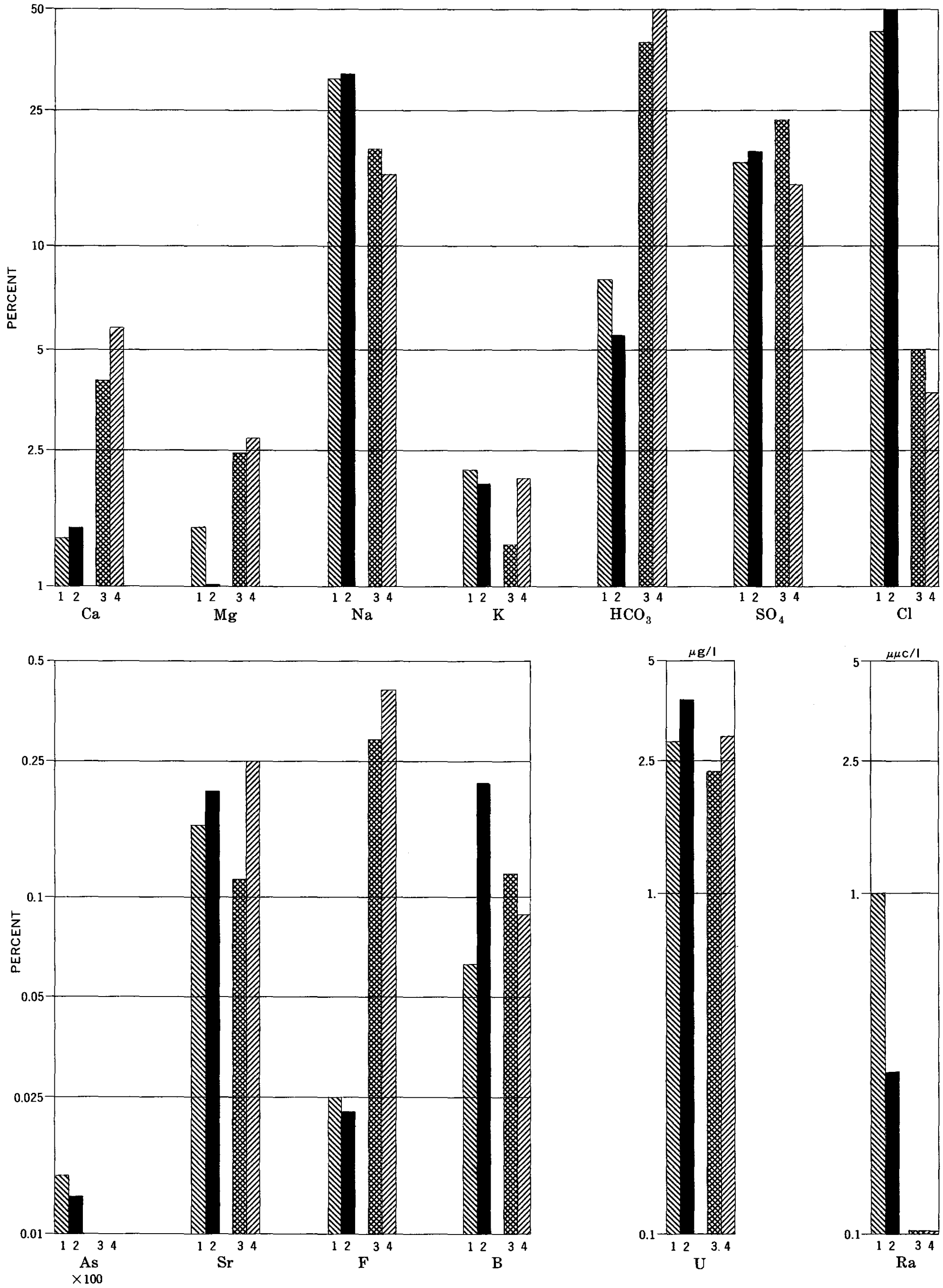

FIGURE 13.—Bar graphs illustrating (a) similarity in chemical composition of water entering Death Valley saltpan at West Side Borax Camp (2) and ground water at lower end of Mesquite Flat west of the saltpan (1); (b) similarity of water entering the saltpan from springs north of Furnace Creek (3) and water at springs in Amargosa Desert east of Death Valley (4); (c) contrast in composition of water entering the saltpan from the west (2) and from the east (3).

The water from the east is a bicarbonate-sulfate water high in calcium and fluoride, whereas water from the west is chloride-sulfate water low in calcium and fluoride but containing some arsenic. The indicated difference in radium content of water from the two directions may not be significant, because graph (3) does not include the anomalously high radium content of Nevares Springs (see table 21). Each bar represents the average of several analyses.

That the water in these springs is moving northwestward down the syncline and along the faults seems probable from the geologic setting. The question is, how far along those structures has the water moved? It has moved deeply enough in those structures to have warmed to about 100°F, but this requires no great depth of circulation. Assuming the thermal gradient in the Death Valley region is about the same as in deep wells in southwestern California, about 35°C per kilometer of depth (Birch and others, 1942, p. 281), the water in these warm springs need have circulated only to a depth of about 1,500 feet. The quantity of water discharged at the springs is anomalously large, considering the size and aridity of the drainage basin in which the springs are located. Moreover, the composition of the water at these springs, a bicarbonate water, differs from the composition of water at the small springs in the mountains which are mostly sulfate waters. The water at the big warm springs chemically is like that at the similar big warm springs in the Amargosa Desert, and their sources probably are related. Bar graphs 3 and 4 of figure 13 show the similarity in composition of water at the springs in Death Valley (3) and in the Amargosa Desert (4). (See also table 13.)

Discharge at the springs at Ash Meadows in the Amargosa Desert is many times greater than the discharge at Travertine, Texas, and Nevares Springs, yet the area draining to Ash Meadows is only about 50 square miles and no part of it is very mountainous. These springs must be supplied by ground water from a remote source and probably from outside the Death Valley hydrologic basin (Loeltz, 1960).

A reasonable source would be the Pahrump Valley, the lowest part of which is a playa, known as Stewart Valley, about 300 feet higher than Ash Meadows. Water in Pahrump Valley is derived from the Spring Mountains, one of the highest mountain ranges in Nevada. That ground water is lost from Pahrump Valley to neighboring basins seems indicated by several facts.

Pahrump Valley has no lake despite its proximity to a major area of recharge. Moreover, during the Recent pluvial period, when Death Valley was flooded by a lake 30 feet deep, Pahrump Valley held no lake, because the playa at Stewart Valley has archeologic sites dating back to the Death Valley II occupation (Hunt, A. P., 1960). Even during that comparatively wet period, Pahrump Valley evidently leaked too much to hold a lake.

Finally, the water discharging at Ash Meadows is chemically like that in Pahrump Valley, and the hydraulic gradient is towards the springs. The intervening ridges of Paleozoic rocks are much faulted. The geologic setting is like that at Cottonball Marsh, and the ground water probably is channeled along faults that extend from Pahrump Valley to Ash Meadows.

Reference has already been made (p. B20) to the structural barrier across the Amargosa Valley at Eagle Mountain and the fact that this barrier has ponded ground water in the valley fill upstream from the barrier. Possibly the water discharging at the springs north of Furnace Creek in Death Valley is drained from this valley fill, the discharge being northwestward along the structures of the Furnace Creek fault zone. However, the composition of the water discharging in Death Valley differs in detail from that in the valley fill above Eagle Mountain (table 13), but it is much like the water at the Ash Meadows Springs, which suggests that the water discharging in Death Valley has had the same history as that discharging at Ash Meadows. Probably the water discharging at the springs in Death Valley, like that at Ash Meadows, is derived directly from Pahrump Valley by movement along faults in the bedrock under the valley fill. The Ash Meadows area is 2,000 feet higher, and the Pahrump Valley is 2,300 feet higher than the springs in Death Valley. This difference in altitude could account for the temperature of the springs.

To recapitulate the possible source of water along Furnace Creek fault zone:

1. The quantity of water discharging from thermal springs into Cottonball Basin from the east and from the west seems excessive to be derived from the limited drainage basins around the points of discharge, and accordingly, sources outside the the basin seem indicated.
2. The composition of water entering Cottonball Basin from the east and from the west is different. The water discharging on the west side is a chloride-sulfate water, whereas that discharging on the east side is, a bicarbonate-sulfate water. The waters differ too, in their content of minor constituents like fluorine and arsenic.
3. The water entering the west side of Cottonball Basin is chemically much like ground water ponded northwest of the basin, and water entering the east side is like water at springs southeast of Death Valley.

The points of discharge are along faults, and probably the water is being drained from other basins. If the underground channels are open conduits, the rate of movement of water along them may be rapid as compared to movement through valley fill.

GEOCHEMISTRY OF THE SALTPAN

By Charles B. Hunt

GENERAL FEATURES

Death Valley contains one of the world's large saltpans, a vast natural evaporating dish covering more than 200 square miles and more than 200 feet below sea level. Salts encrusting the pan, and those in the brines in the underlying clastic sediments, are distributed in zones that are orderly both horizontally and vertically and reflect the relative solubilities of the salts. At the center of the pan the salts both in the crust, which is a few feet thick, and in the brines beneath the crust are mostly chlorides. This zone is ringed by an intermediate zone of sulfate salts, which, in turn, is surrounded by a zone of carbonate salts forming the edges of the pan. Within each zone the salts occur in layers having different compositions; these layers are orderly with respect to the solubilities of the salts and whether deposition was by ground water rising to the surface or by surface water sinking into the bed of the playa. Moreover, the kind and proportion of salts differ in different parts of the saltpan because of differences in the composition of the waters discharging onto the pan.

The chloride zone of the saltpan supports bacteria but few fungi or algae. The sulfate zone supports fungi algae but almost no flowering plants. The carbonate zone around the edge of the saltpan is a belt of phreatophytic shrubs and trees—plants dependent on ground water. The several species of plants in this zone are distributed in an orderly way that reflects differences in the quantity and kind of salts in the ground water. These relationships between the plants and the water supply are described in Hunt (1965).

Although Death Valley trends almost north, the saltpan extends north-northwest diagonally across the valley. The pan is crowded eastward against the Black Mountains in the Badwater Basin and is crowded westward against Tucki Mountain in the Cottonball Basin.

The climate is arid (p. B5), and the chief geologic importance of the present Death Valley climate is that the processes of erosion and weathering are slowed. Much of the salt crust dates from a period wetter than the present. The present climate, although nearly ideal for preserving the salt deposits and other features of antiquity, is not the cause of the saltpan's main features.

Differences in source rocks around the saltpan (p. B11) have affected the composition of waters reaching the pan. For example, around Cottonball Basin, where Tertiary volcanic rocks and sedimentary rocks derived from them are extensive, the ratio of calcium to sodium in ground water and surface water is generally less than 1 to 50, but along the west side of Badwater Basin, where Paleozoic carbonate rocks are extensive, the calcium-sodium ratio generally is more than 1 to 10 and locally exceeds 1 to 2. Also, as might be expected, borates are more plentiful in Cottonball Basin.

The borax deposits in the saltpan figured prominently in the history of mineral development in the United States. The deposits were the principal source of the borax that was transported by the well-advertised 20-mule teams, and the story of that development is one of the colorful chapters in American mining history.

For a modern comprehensive review of various kinds of salt deposits the reader is referred to the excellent volume by Franz Lotze (1957).

FIELDWORK AND ACKNOWLEDGMENTS

The saltpan was mapped (pl. 1) by traverses across the valley at half-mile intervals. The boundaries between the various units and locations of samples were plotted on aerial photographs and transferred to the topographic maps by projection. The saltpan was mapped in 6 months, November 1955 to April 1956, when samples of salts and brines were collected for preliminary study. The second field season, November 1956 to April 1957, was spent in more comprehensive study and more careful sampling of the deposits.

It was found useful to carry a quarter-inch metal rod about 5 feet long to probe the clastic sediments both at the surface and beneath the salt crust. Much could be learned about these sediments from the mud stuck to the rod, and thrusting the rod into the ground provided information about the thickness and number of salt layers in the muds or in the crust. This probing helped select places for augering with heavier equipment.

In February 1956 it was my good fortune to be visited for 2 weeks by Thomas S. Lovering, of the U.S. Geological Survey. His assistance in the geochemical and mineralogical phases of the work can hardly be overestimated. Much of the work that followed and that is reported upon here is the result of his ideas and guidance. In the course of his visit, plans were made for sampling the salts and brines for semiquantitative analysis.

Simple field methods were used for field determinations of the principal anions. Some of the common salts are readily distinguished by their taste, for example, epsomite, sodium chloride, sodium carbonate, and sodium sulfate. In addition to the standard test for carbonates (hydrochloric acid), for chlorides (silver nitrate), and for sulfates (barium chloride), field tests were adapted for roughly estimating quantities of chlorides, boron, and nitrates.

The chloride test involves a measured sample of the brine to which is added potassium chromate indicator. Silver nitrate added dropwise maintains a clouded color until all the chloride has combined with the silver;

thereafter the solution turns reddish. The test provides an estimate in parts per million of the chloride.

The boron test, recommended by Hy Almond, then of the U.S. Geological Survey, consists of applying an iodine stain to a mineral treated with acid and polyvinyl alcohol; borates give a blue stain, and the intensity of the color is roughly proportional to the borate content. Borates also were detected by using turmeric paper.

Frederick N. Ward, of the U.S. Geological Survey, recommended two simple field tests for nitrates. The simpler test involves diphenylamine in concentrated sulfuric acid; a drop of the reagent gives a blue color when added to a test solution or solid, and the intensity of the color is proportional to the amount of nitrate present. However, because of the hazard of using concentrated sulfuric acid in the field, a second test was used. This involves adding a small amount of zinc dust to the material being tested and wetting with a drop or two of sulfanilic acid. A second reagent, 1-naphthylamine dissolved in glacial acetic acid, brings out a pink color that is proportional to the amount of nitrate present in the material being tested.

These "one-drop" field tests proved exceedingly useful. The field kit, including reagents, pH paper, filter paper, small plastic funnel, small test tubes, and a standard test tube tied to a string which could be whirled and used as a centrifuge, weighs less than 2 pounds and fits in a box 4½ by 4½ by 3 inches. This portable equipment made it possible to make thousands of tests on all parts of the floor of Death Valley; the results of these simple determinations guided the mapping and the selection of samples for laboratory analysis (p. B90).

During most of February 1957 the study was further assisted in the field by the Geological Survey's mobile spectrograph and mobile laboratory. Uteana Oda was in charge of the mobile units; he was assisted in the field analytical work by E. F. Cooley. The sampling was done by me with the assistance of James C. Prentice. T. S. Lovering, Hubert W. Lakin, F. W. Ward, and J. Howard McCarthy visited the project at the same time and stayed long enough to help get the sampling and field analytical work under way. In addition to contributing most of the analyses that appear in this report, these individuals contributed many of the ideas—too many for specific acknowledgment.

The chemical analyses that were made in connection with this investigation are semiquantitative. The analyses are given in tables 43–52, and a description of the analytical methods is given on pages B90–B91.

Cuts of the bulk samples that were collected for these chemical analyses were scanned by X-ray by John B. Droste, of the University of Indiana; he has reported the salt minerals that could readily be identified by that method. His data are included with the descriptions of the samples that were analyzed chemically (tables 43–49).

In January 1957 John R. Stacy, of the Geological Survey, visited the project for a week, took photographs of the subjects to be illustrated, and then used selected pictures for making the drawings accompanying this chapter.

GEOLOGIC SETTING

SEDIMENTARY DEPOSITS UNDERLYING THE PAN

Knowledge about the concealed deposits underlying the saltpan is based on logs of borings by the U.S. Geological Survey (fig. 14), some privately drilled holes, and on gravity and aeromagnetic determinations by the U.S. Geological Survey. The gravity determinations by Don R. Mabey (Hunt and others, 1965) indicate that the fill is about 8,000 feet thick under the northern and southern parts of the saltpan, but only about half that thick where the road crosses the valley 8 miles south of Furnace Creek Inn. These estimates include probable Tertiary deposits.

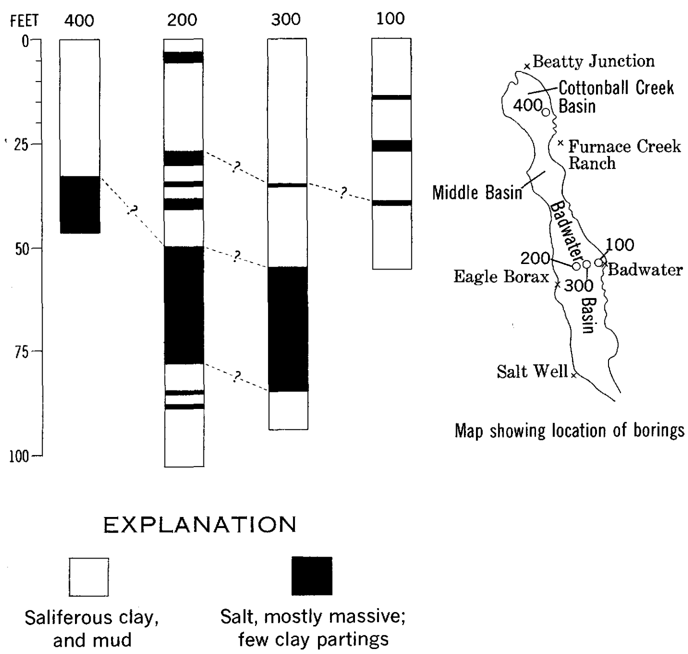

FIGURE 14.—Graphic logs and map showing locations of U.S. Geological Survey borings on the floor of Death Valley. Data from Gale (1914a).

Privately drilled wells 1,000 feet deep near Badwater (Bain, 1914, p. 617) and in the middle of Cottonball Basin encountered very little sand and no gravel, only clay and silt interbedded with salt. (For logs, Hunt and others, 1965). A well near Badwater, in sec. 30, T. 25 N., R. 2 E. (projected), encountered a series of hard salt strata, each from 1 to more than 20 feet thick, alternating with beds of salty mud. The quantity of salt decreases downward. Below the 250-foot level, increasing quantities of sulfate salts were reported; the bottom 150 feet of the hole contains much more clay and less salt. The well in Cottonball Basin encountered a similar section but more sodium sulfate.

A third well, by the road across the valley and 500 feet deep, encountered basaltic gravels at a depth of 130 feet. These gravels and the associated sediments from 130 feet to the bottom of the hole are late Tertiary or early Pleistocene in age, and they form a buried ridge separating Badwater Basin from Middle Basin. Details of the logs of the borings by the Geological Survey are given in table 26; the logs are shown graphically on figure 14. The borings are in areas subject to seasonal flooding and do not show the salt crust on the surface.

TABLE 26.—*Logs of U.S. Geological Survey borings, Death Valley*

[After Gale, 1914a]

	Thickness (ft)	Depth (ft)
Boring 100		
Salt, 1½ in. thick on surface.		
Clay, light-brown; contains crystals	10	10
Clay, light-brown, smooth	4	14
Mud, brown; contains hard salt crystals	1	15
Salt and dark-brown clay	1	16
Clay, dark-brown; contains crystals	4	20
Clay, dark-green; contains crystals	3	23
Mud, soft, black; contains crystals	3	26
Salt, hard strata (required drilling with churn bit)	2	28
Clay, smooth, black	4	32
Clay, black; contains crystals (strata of salt 1–3 in. thick from 32 to 39 ft)	7	39
Clay, light-gray and black, mixed; contains crystals	1	40
Salt, hard (required drilling)	1	41
Clay, light-gray and black; contains many crystals	5	46
Clay, black; contains crystals	5	51
Salt crystals and a little light-colored clay	1	52
Clay, black; contains crystals (salt strata 1–3 in. thick from 52 to 56 ft; very hard salt, from 48 to 49 ft 2 in.)	4	56
Water or brines encountered:		
W.S. 1, salty; strong flow within 1 ft of surface	------	6
W.S. 2, salty; strong flow within 18 in. of surface	------	24
W.S. 3, salty; strong flow within 2 ft of surface	------	29
W.S. 4, salty; seepage water	------	52

TABLE 26.—*Logs of U.S. Geological Survey borings, Death Valley*—Continued

	Thickness (ft)	Depth (ft)
Boring 200		
Salt (6 in. thick on surface).		
Clay, soft, light-brown; contains crystals	3. 5	4. 0
Salt, very hard	2. 0	6. 0
Mud, soft, brown; contains coarse crystals	11. 0	17. 0
Mud, smooth, brown	. 5	17. 5
Salt, in layers 1 in. thick	. 5	18. 0
Mud, soft, brown, smooth	3. 0	21. 0
Mud, light-brown, sticky; contains crystals	3. 0	24. 0
Mud, soft, brown; contains crystals	3. 0	27. 0
Salt, hard	2. 5	29. 5
Clay, tough, brown	. 5	30. 0
Salt, hard, drilled	1. 0	31. 0
Mud, soft, brown; contains crystals	. 3	31. 3
Salt, hard	. 7	32. 0
Clay, dark; contains crystals	4. 5	36. 5
Salt, hard	1. 5	38. 0
Mud, black; contains crystals and hard salt strata 1 in. thick	1. 5	39. 5
Salt, hard, black	2. 0	41. 5
Mud, black; contains crystals	1. 5	43. 0
Salt, hard	. 2	43. 2
Clay, black; contains crystals	2. 3	45. 5
Salt, hard, black	. 5	46. 0
Clay, light-gray and black mixed; contains crystals	5. 0	51. 0
Salt, very hard	1. 5	52. 5
Clay, dark; contains crystals	. 5	53. 0
Salt, hard	. 5	53. 5
Clay, tough, dark	. 5	54. 0
Salt, very hard (hardest yet encountered); black	15. 5	69. 5
Clay, tough, dark-blue; contains crystals	1. 0	70. 5
Salt, very hard, black	5. 0	75. 5
Clay, dark-blue; contains crystals	2. 5	78. 0
Salt, hard, black	1. 0	79. 0
Clay, dark-blue; contains crystals	6. 2	85. 2
Salt, hard	1. 0	86. 2
Clay, dark-blue; contains crystals	3. 8	90. 0
Salt, very hard	1. 5	91. 5
Clay, very tough, dark-blue; contains crystals	4. 0	95. 5
Clay, tough, black; contains crystals	8. 0	103. 5
Water encountered:		
W.S. 1, black salty water; came within 2 ft of the surface	------	32. 00
W.S. 2, salty, nearly clear; came within 1 ft of the surface, strong flow with 8 ft of section pipe on hand pump; well flowed 5 gals in 2 min	------	38. 0
W.S. 3, seepage water in well after standing overnight	------	70. 0

TABLE 26.—*Logs of U.S. Geological Survey borings, Death Valley*—Continued

	Thickness (ft)	Depth (ft)
Boring 300		
Salt, 1½ in. thick, on surface.		
Mud, light-brown; contains coarse salt crystals	1.5	1.5
Salt, layer 2 in. thick, with flow of brine at bottom		
Mud, soft, brown (small flow of warm water at 30 ft)	29.0	30.5
Mud, yielding seepage of water	2.5	33.0
Clay or mud and crystals of salt	1.5	34.5
Salt	.5	35.0
Mud, black, and crystals of salt	1.5	36.5
Salt	.5	37.0
Mud, black, and crystals of salt (water all shut off and auger cut without seepage)	15.0	52.0
Salt	.3	52.3
Clay, black; occasional thin salt layers	3.7	56.0
Salt, crystalline, hard; contains layers of black clay mixed with salt crystals, 1–4 in. thick, at intervals of about 2 ft	8.5	64.5
Mud	.5	65.0
Salt, crystalline; apparently solid	13.0	78.0
Mud	.2	78.2
Salt, crystalline	3.8	82.0
Clay, black	1.0	83.0
Salt, crystalline	2.0	85.0
Clay, black; contains salt crystals (no water encountered in the lower part of the well)	10.5	95.5
Water encountered:		
W.S. 1, surface, salty; strong flow 6 in. from surface to	------	5.0
W.S. 2, warm, salty; came within 1 ft of surface	------	30.0
Boring 400		
Surface, borax soda, and brown mud	0.5	0.5
Mud, light-brown; contains a few flat crystals	7.5	8.0
Mud, tough, brown, smooth	4.0	12.0
Clay, light-brown, smooth	5.0	17.0
Mud, dry, brown, smooth	9.0	26.0
Clay, light-blue; contains crystals	5.5	31.5
Salt, hard	2.0	33.5
Clay, tough, blue; few crystals	1.5	35.0
Salt, hard	12.0	47.0
Water encountered:		
W.S. 1, salty; strong flow within 2 ft of surface	------	32.0
W.S. 2, salty, warm; strong flow within 2 ft of surface	------	38.0

STRUCTURAL GEOLOGY

The floor of Death Valley has been tilted eastward 20 feet in the last 2,000 years, for the shoreline of a shallow lake, believed to date from a Recent pluvial period just before the Christian Era (A. P. Hunt, 1960; Hunt and others, 1965), is at −240 feet along the west side of Badwater Basin and at −260 feet along the east side.

The tilt of the saltpan and crowding of the salt zones in the direction of the tilt is similar to that of the Great Salt Lake Desert where the salt beds and other products of desiccation are crowded against the west edge of the Bonneville flats (Nolan, 1927, p. 40).

Other structural features of the saltpan include some structures that extend northwesterly under the saltpan from the front of the Black Mountains. Two of these apparently caused S-patterns in the drainage on the flat playa. One such S-pattern of drainage is 1–3 miles northwest of Mormon Point; another is 2–3 miles northwest of Copper Canyon.

An en echelon series of fractures in the salt near the north end of the Badwater Basin may also reflect buried faults.

Just north of Furnace Creek fan, northwest-trending folds and faults can be traced into the saltpan as far as the flood plain of Salt Creek. On the saltpan along the projection of these structures, old marshes are marked by accumulations of rock salt and some elevated areas in the otherwise flat playa surface. Also, the drainage is northwesterly in that part of the playa, and the flood plain in the NW¼ sec. 32, T. 28 N., R. 1 E., is 1½ feet higher than the flood plain to the northeast and southwest.

HYDROLOGY

Four drainage systems contribute salts and sediments to the Death Valley saltpan, and during Pleistocene time there were lakes possibly fed by overflow eastward of glacial lakes that lay to the west (Gale, 1914b).

The Amargosa River (p. B19), which drains about 6,000 square miles, discharges into the south end of the Death Valley saltpan; Salt Creek (p. B19), draining 1,600 square miles, discharges into the north end. Streams flowing from the Panamint Range (p. B22) drain 450 square miles, and those from the Black (p. B23) and Funeral Mountains (p. B25) drain 400 square miles; but most of these streams from the bordering mountains must reach the pan by crossing the gravel fans, and, as noted above, practically all their water discharges into the fans and reaches the saltpan as ground water.

In the present climatic regimen ground water probably is more important than surface water as a source of the water on the saltpan. Each winter the ground water rises, and extensive areas become wet even though there may have been little or no rain. The rise evidently reflects decrease in evaporation on the pan rather than an increase in total water being discharged into the valley. The excessive evaporation causes salts to be leached from below and precipitated at the surface—an upside-down soil process. Posts set in the ground serve as wicks (fig. 15), drawing ground moisture into the wood which is shattered by the precipitated salts. Telephone poles on the Bonneville Flats of the Great Salt Lake Desert are similarly shattered (Gilluly and others, 1951, p. 106). Adobe walls in the Southwest locally serve as wicks when salts accumulate and spall the adobe just above ground level (Hayden, 1945).

Around the edge of the saltpan ground water is shallow, and cold springs are numerous (pl. 2). These springs probably are controlled by the change from permeable gravel on the fans through sand to less permeable silt in the playa beds under the saltpan. The impervious barrier of silt causes ponding of the ground water in the gravels. Such springs belong to the border type of Bryan (1919, p. 537).

Near the outer edge of the saltpan, at the boundary with the gravel fans, the water is potable, but panward the salinity increases to 5 or 6 percent at the limit of vegetation (fig. 16) and to still greater salinity in the interior of the pan.

Some warm springs issue from fault zones in the northern part of the valley. One at the west edge of the Cottonball Basin has a temperature of 88° F. Above Furnace Creek Ranch are Texas Spring and Travertine Springs (temp about 95°F). At the foot of the Funeral Mountains is Nevares Springs that has a temperature about 100°F. Although these springs provide potable water, they contain much fluoride.

The hygroscopic property of salt is an important source for moisture that affects the salt growths. During periods when Death Valley is relatively humid but without rain, salt-impregnated areas, such as the clay and silt areas on the flood plains, darken with absorbed moisture and in places become sticky or even slippery. Compositions of the brines are given in tables 50–52 on pages B100–B103.

VEGETATION

The sulfate and chloride zones in the saltpan are without flowering plants (fig. 16). This barren central area is surrounded by a discontinuous belt of phreatophytes which are zoned with respect to the quality of the ground water. Along the panward edge of the belt the plants are salt-tolerant phreatophytes, and rooted in ground water containing as much as 6 percent of salts. The principal plant is pickleweed. Toward the gravel fans the ground water becomes less saline. Where the salinity is between 1 and 2 percent, the principal phreatophyte is arrowweed. Where the salinity is less than 0.5 percent, the principal plant is honey mesquite.

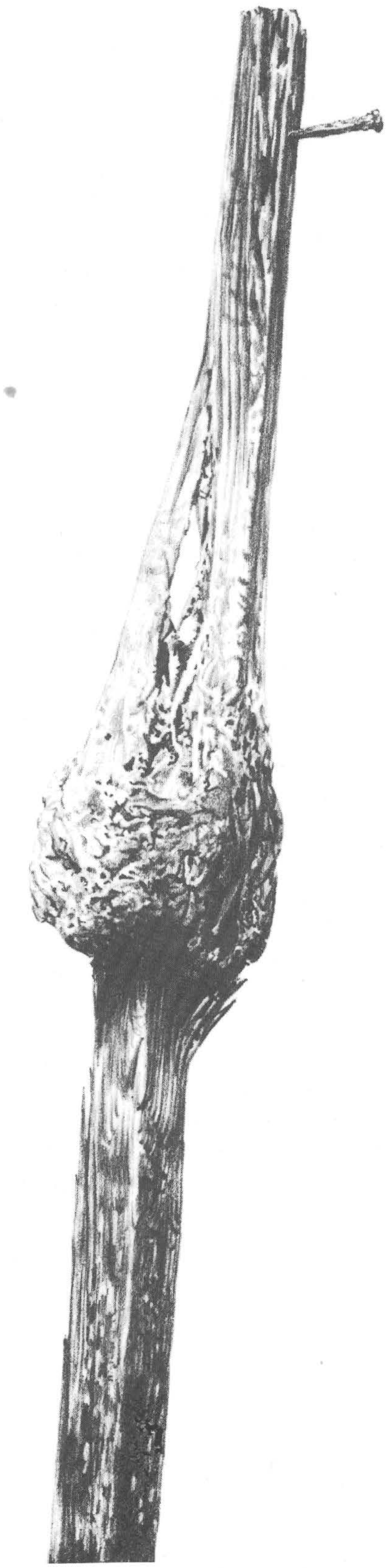

FIGURE 15.—Wood post shattered by salt, an example of evaporation effects on the saltpan. This wood post, 3½ feet long, was set in the flood plain of Salt Creek about 1910; ground level was at the lower edge of the bulge. Water rising in the wood evaporated at ground level and burst the wood with precipitated salts. Drawn by John R. Stacy, from photograph.

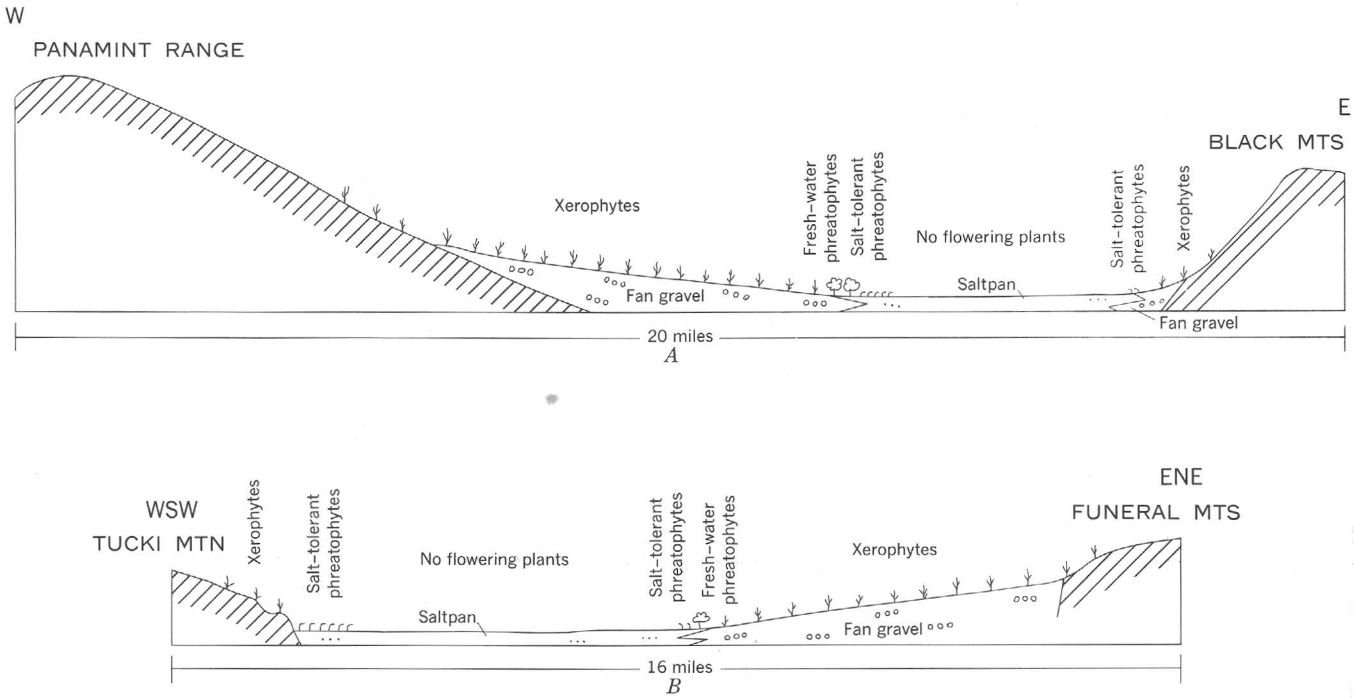

FIGURE 16.—Diagrammatic sections across Death Valley showing the distribution of different kinds of plants in Badwater Basin (*A*) and Cottonball Basin (*B*). Phreatophytes dependent on ground water that is not excessively saline are restricted to the sides of the saltpan where there are extensive gravel fans rising to the mountains. Only salt-tolerant plants grow where the saltpan is crowded against the base of the mountains, as on the east side of Badwater Basin and the west side of Cottonball Basin.

Only xerophytes grow on the gravel fans, where ground water is too deep to be reached by plants.

The phreatophytes dependent on ground water that is not excessively saline are restricted to the sides of the pans where long gravel fans rise to the mountains; they occur only on the west side of the Badwater Basin and the east side of Cottonball Basin. Opposite these sides of the valley, where the saltpan has been crowded against the foot of the Black Mountains and against the foot of Tucki Mountain, the ground water is briny, and only salt-tolerant phreatophytes can grow. This floral distribution reflects the asymmetry in the distribution of brines in the saltpan.

DEVELOPMENT OF THE SALT CRUST

The development of the salt crust on the Death Valley saltpan can be illustrated by the diagrams on figure 17. Evaporation of brine in a dish leads to an increasing concentration of salts in the residual liquid and finally to their crystallization. The least soluble salts are the first to crystallize. These salts are mostly the carbonates, and as the water evaporates, a zone of carbonate salts is deposited around the edge of the dish and across the bottom. The sulfate salts are next to form; then the chlorides form from the last of the liquid (fig. 17*A*).

The Death Valley saltpan consists of concentric zones of such salts, but two complexities must be introduced to continue the analogy on the laboratory scale. In the first place, because the floor of Death Valley has been tilted, the rings are crowded against an edge of the pan, as illustrated on figure 17*B*.

A second difference between Death Valley and an evaporating dish is the recycling of salts in the Death Valley pan by fresh increments of ground water and by floods of surface water. Salts deposited at one stage in the history of the saltpan are reworked, as illustrated diagrammatically on figure 17*C*.

During the early Recent the climate is thought to have been even drier than at present, and the floor of Death Valley probably received even less water than it does today. The evaporation of ground water must have produced a crust of salt like the present one.

Just before the Christian Era, however (Hunt, A. P. 1960), the valley floor was flooded more frequently than it is now; this flooding was sufficient to produce ephemeral ponds, and at one stage it formed a lake about 30 feet deep. This flooding introduced chlorides into the older carbonate and sulfate zones.

The deposit of massive rock salt northwest of Badwater (pl. 1) is interpreted as the final residue of the Recent pluvial lake and ponds. Surrounding this massive rock salt are extensive areas of silty rock salt which probably was deposited where there was ephemeral surface water during Recent pluvial time—where three kinds of hydrologic environments alternated:

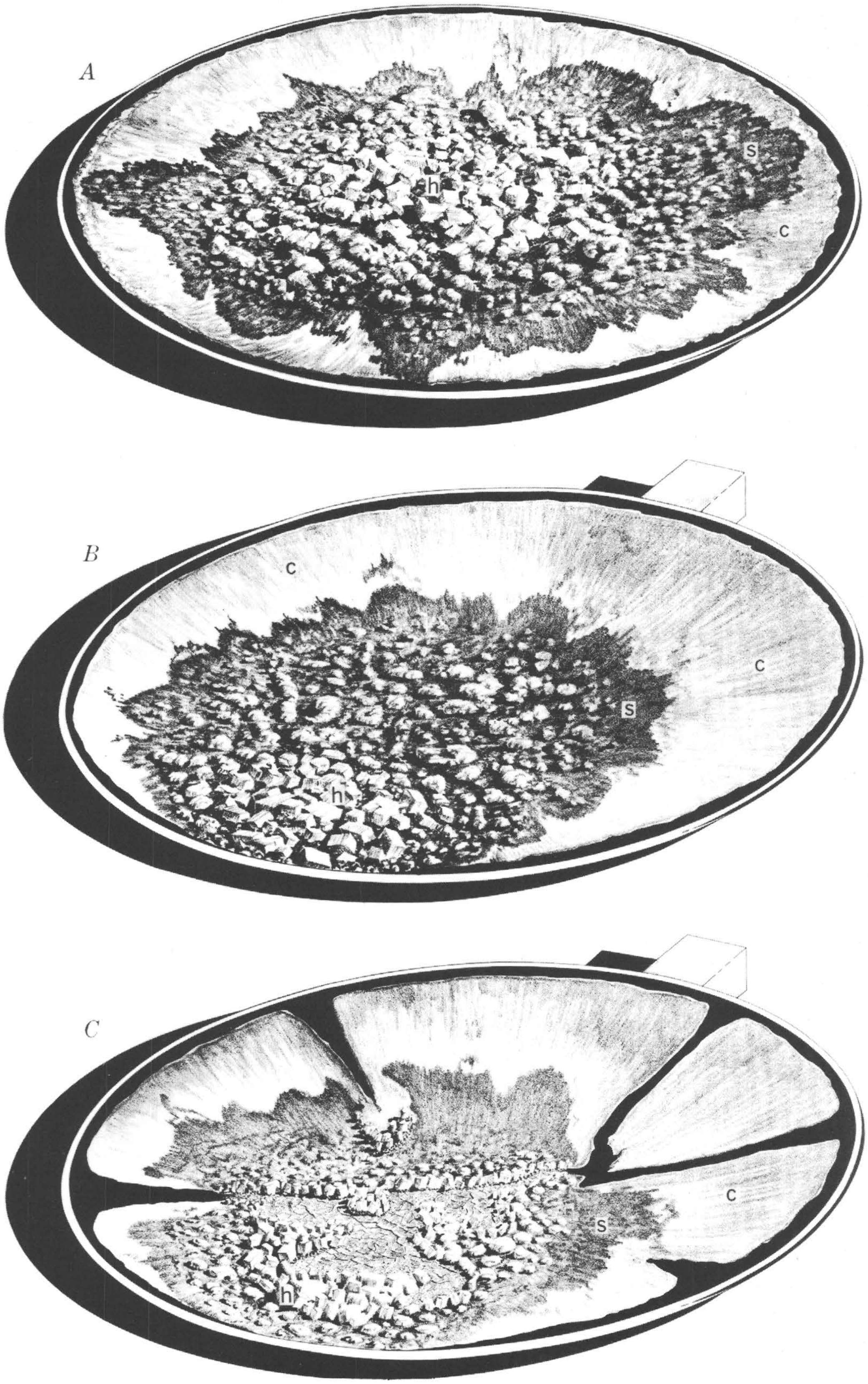

FIGURE 17.—Diagrams illustrating history of the saltpan in Death Valley. Evaporation of a brine in a dish (*A*) deposits salts that are zoned in an orderly way with respect to their solubilities. As evaporation progressed, the saltpan became tilted, as represented by the tilted dish (*B*). New additions of fresh water by rains and floods rework the salts that have already been deposited and introduce the kind of irregularities illustrated in (*C*). c, carbonates; h, rock salt; s, sulfates. Diagrams sketched by John R. Stacy.

flooding by rise of the Recent pluvial ponds, periods of desiccation causing salts to be deposited because of evaporation of ground water, and flooding by streams.

The silty rock salt consists of a smooth facies and a rough facies, and the difference is attributed to frequency of washing by surface water. The smooth facies is located about the mouths of the main streams entering the valley—the Amargosa River, Salt Creek, and Furnace Creek. These areas would be subject to frequent washing by surface water. The rough facies is between these areas and the massive rock salt, where there would be less frequent washing by surface water and more of the effects of evaporation of ground water.

Locally around the edges of the silty salt are deposits of massive gypsum which probably were deposited at springs that fed the ephemeral ponds. The sand and silt in the carbonate zone which surrounds the saltpan date from late Pleistocene time, but the impregnation of sodium chloride in the sand and silt and the layering of other salts occurred during the Recent, probably mostly during Recent pluvial time when the water table stood higher than it does today.

During the last 2,000 years, stands of water on the saltpan have been restricted to those parts of the playa mapped as flood plain.

This history can be summarized as follows:

Stage 1. Late Pleistocene time.
Much more moisture than at present; there were temporary lakes several hundred feet deep. The valley floor probably was a playa most of the time, but it probably was repeatedly flooded.

Stage 2. Early Recent, or altithermal time.
Death Valley drier than now; final desiccation of the Pleistocene lakes probably formed a salt crust zoned like the present one.

Stage 3. Middle Recent, or Recent pluvial time.
Death Valley wetter than now; at one stage was flooded by a lake 30 feet deep. Drying of the ponds and lake produced the chloride zone; springs that fed the pond deposited sulfates. Flooding by the pond inpregnated the carbonate zone with sodium chloride.

Stage 4. Late Recent, the Christian Era, A.D. 1 to present.
The salt crusts were removed from areas subject to flooding, and the salts were redeposited around the edges of the flooded areas. Deposits of salts not flooded have become weathered. Sand dunes formed locally on the edges of the saltpan and on the old lake floor.

SALT DEPOSITS

The salt crust on the floor of Death Valley, which ranges from a few inches to a few feet thick, has formed on silt and clay. At the sides of the valley the silt and clay grades to sand, and this, in turn, grades into gravel at the foot of the fans. In the interior of the valley, below the silt and clay, is another layer of salt about 25 feet thick, and below that is more silt and clay. Deeper wells in the vicinity of the borings indicate that this alternation of salt and clay silt continues to a depth of at least 1,000 feet. Probably the zoning of salts observed at the surface of the pan is duplicated in these buried salt deposits.

The general distribution of the salts and related geologic features are shown on the geologic map (pl. 1) and block diagram (pl. 2). The locations of samples of the salts and brines that have been analyzed chemically are shown on plate 3.

The chloride zone, which occurs in the central part of the saltpan, is the most extensive of the salt zones and covers about half the pan. The discontinuous sulfate zone between the chloride and carbonate zones is the least extensive, and at its maximum is only about half as wide as the carbonate zone that forms the outer edge of the pan.

Differences in the sources of the brines and sediments that are moving onto the saltpan also lead to differences in the composition and mineralogy of the salt deposits. Cottonball Basin, for example, has little calcium in comparison to sodium which is high enough that some of it combines even with the carbonate, giving trona or thermonatrite. In Cottonball Basin the common sulfate mineral is thenardite. In Badwater Basin, on the other hand, there is much calcium, and sulfate deposits in that part of the valley are mostly gypsum. The mineralogy of the borates varies similarly. In Cottonball Basin the common borate minerals are ulexite and probertite, whereas in Badwater Basin, meyerhofferite is common (table 27). Cottonball Basin contains more boron and more strontium than does Badwater Basin. Twenty samples of sediments from the flood plain in Cottonball Basin average 0.66 percent boron and 0.5 percent strontium; a similar number of samples from the flood plain in Badwater Basin averages 0.08 percent boron and 0.15 percent strontium.

TABLE 27.—*Composition and occurrence of minerals referred to in text*

Mineral	Composition [1]	Known or probable occurrence
Halite	$NaCl$	Principal constituent of chloride zone and of salt-impregnated sulfate and carbonate deposits.
Sylvite	KCl	With halite.
Nahcolite	$NaHCO_3$	Not yet identified; might be found in wintertime as an efflorescence on trona or thermonatrite in the carbonate zone in Cottonball Basin.
Trona	$Na_3H(CO_3)_2 \cdot 2H_2O$	Carbonate zone of Cottonball Basin, especially in the marshes.
Thermonatrite	$Na_2CO_3 \cdot H_2O$	Questionably present on flood plain in Badwater Basin; would be expected in marshes of carbonate zone in Cottonball Basin.
Natron	$Na_2CO_3 \cdot 10H_2O$	Not yet identified but may be expected, especially in winter, immediately following rains or periods of high discharge at marshes in carbonate zone in Cottonball Basin.
Pirssonite	$Na_2Ca(CO_3)_2 \cdot 2H_2O$	Not yet identified. May be expected in environments where gaylussite would be dehydrated.
Gaylussite	$Na_2Ca(CO_3)_2 \cdot 5H_2O$	Carbonate zone and flood plain in Badwater Basin.
Calcite	$CaCO_3$	Occurs as clastic grains in the sediments underlying the saltpan and as sharply terminated crystals in the clay fraction of the carbonate zone and in sediments underlying the sulfate zone.
Magnesite	$MgCO_3$	Obtained in artificially evaporated brines from Death Valley; not yet identified in saltpan; may be expected in carbonate zone of Cottonball Basin.
Dolomite	$CaMg(CO_3)_2$	Identified only as a detrital mineral; may be expected in the carbonate zone.
Northupite and (or)	$Na_3MgCl(CO_3)$	An isotropic mineral, having index of refraction in the range of northupite and tychite, has been observed in the saline facies of the sulfate zone in Cottonball Basin.
Tychite	$Na_6Mg_2(SO_4) \cdot (CO_3)_4$.	
Burkeite	$Na_6CO_3(SO_4)_2$	Sulfate zone in Cottonball Basin.
Thenardite	Na_2SO_4	Common in all zones in Cottonball Basin and in sulfate marshes in Middle and Badwater Basins.
Mirabilite	$Na_2SO_4 \cdot 10H_2O$	Occurs on flood plains in Cottonball Basin immediately following winter storms or floods.
Glauberite	$Na_2Ca(SO_4)_2$	Common on flood plains except in central part of Badwater Basin; sulfate zone in Cottonball Basin.
Unidentified	------	Unidentified hydrous sodium calcium sulfate; presence determined by R. C. Erd, of the U.S. Geological Survey who writes: "Wide spread in saline efflorescent deposits in California and Nevada. Typically associated with thenardite, glauberite, and gypsum. Occurs as white fibrous tufts somewhat resembling ulexite. Biaxial negative, $\alpha=1.490$, $\beta=1.498$, $\gamma=1.501$, all ± 0.002; $2V$ approx 60°, $Z>c=3\frac{1}{2}°$. Easily soluble in cold water with separation of crystals of gypsum. Perhaps a new mineral; possibly the double salt $NA_2SO_4 \cdot 2CaSO_4 \cdot 3H_2O$ prepared by Fridman *et al.* (Chem. Abs., v. 50, 16509c)."
Anhydrite	$CaSO_4$	As layer capping massive gypsum 1 mile north of Badwater. Possibly also as dry-period efflorescence on flood plains.
Bassanite	$2CaSO_4 \cdot H_2O$	As layer capping massive gypsum along west side of Badwater Basin and as dry-period efflorescence in flood plains.
Gypsum	$CaSO_4 \cdot 2H_2O$	In sulfate-caliche layer in carbonate zone, particularly in Middle and Badwater Basins; in sulfate marshes and as massive deposits in the sulfate zone.
Hexahydrite	$MgSO_4 \cdot 6H_2O$	Not yet identified but might be expected as dehydration product of epsomite in chloride zone or on flood plains.
Epsomite	$MgSO_4 \cdot 7H_2O$	Not yet identified; probably will be found as efflorescence on flood plains following storms or floods; would dehydrate to hexahydrite during dry periods.
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	Questionably present in efflorescence on flood plain in chloride zone.
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	Questionably present on flood plain in chloride zone.
Barite	$BaSO_4$	Not yet identified but probably will be found in carbonate zone and as clastic grains in sediments underlying the saltpan.
Celestite	$SrSO_4$	Found with massive gypsum.
Schairerite	$Na_3(SO_4)(F,Cl)$	Not yet identified; might be expected in Cottonball Basin or east side of Middle Basin.
Sulfohalite	$Na_6ClF(SO_4)_2$	Do.
Kernite	$Na_2B_4O_7 \cdot 4H_2O$	Possibly present in Middle Basin in surface layer of layered sulfate and chloride salts.
Tincalconite	$Na_2B_4O_7 \cdot 5H_2O$	Probably occurs as a dehydration product of borax.
Borax	$Na_2B_4O_7 \cdot 10H_2O$	Flood plains and marshes in Cottonball Basin.
Inyoite	$Ca_2B_6O_{11} \cdot 13H_2O$	Questionably present (X-ray determination but unsatisfactory) in flood plain in Badwater Basin.
Meyerhofferite	$Ca_2B_6O_{11} \cdot 7H_2O$	Found in all zones in Badwater Basin and in rough silty rock salt in Cottonball Basin.
Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	Questionably present (X-ray determination but unsatisfactory) in flood plain in Badwater Basin.
Ulexite	$NaCaB_5O_9 \cdot H_2O$	Common on flood plain in Cottonball Basin; known as "cottonball."

See footnote at end of table.

TABLE 27.—*Composition and occurrence of minerals referred to in text*—Continued

Mineral	Composition [1]	Known or probable occurrence
Probertite	$NaCaB_5O_9 \cdot 5H_2O$	A fibrous borate with an index of refraction higher than ulexite is found on dry areas of flood plains in Cottonball Basin following long hot dry spells and in the surface layer or the smooth facies of silty rock salt.
Soda niter	$NaNO_3$	Weak but positive chemical tests for nitrates have been obtained in the saltpan, and X-rays suggest the presence of soda niter; more positive tests have been obtained from caliche layers in bordering hills of Tertiary rocks (Noble, 1931; Mansfield and Boardman, 1932; Noble and others, 1922).
Sulfur	S	Not yet identified; would be expected in flood plain deposits where there is reduction of sulfates.

[1] Compositions as given by Palache and others (1951).

The general appearance of the saltpan changes markedly with the seasons. Each of the salt zones becomes coated with a characteristic efflorescence following wet or humid periods, but this efflorescence is blown away soon after the ground is dry. Dust-devils lift columns of fine salt dust hundreds of feet into the air, where it drifts away from the pan mostly to the northeast. After a few windy days the efflorescence has largely disappeared.

Some of the salt minerals occur in large crystals, but most are so fine grained that determinations have had to depend on indices of refraction that could not be related to cleavage or other crystal structure. These petrographic determinations have been supported by a number of X-ray analyses of salt samples.

Table 27 gives the chemical composition and the occurrence of minerals referred to in the text. More than 20 minerals have been identified, and probably another dozen are common. Many were seen that could not be identified. The list no doubt will be considerably extended when mineralogists study these salts intensively. Solubility curves for the principal minerals are given on figure 18.

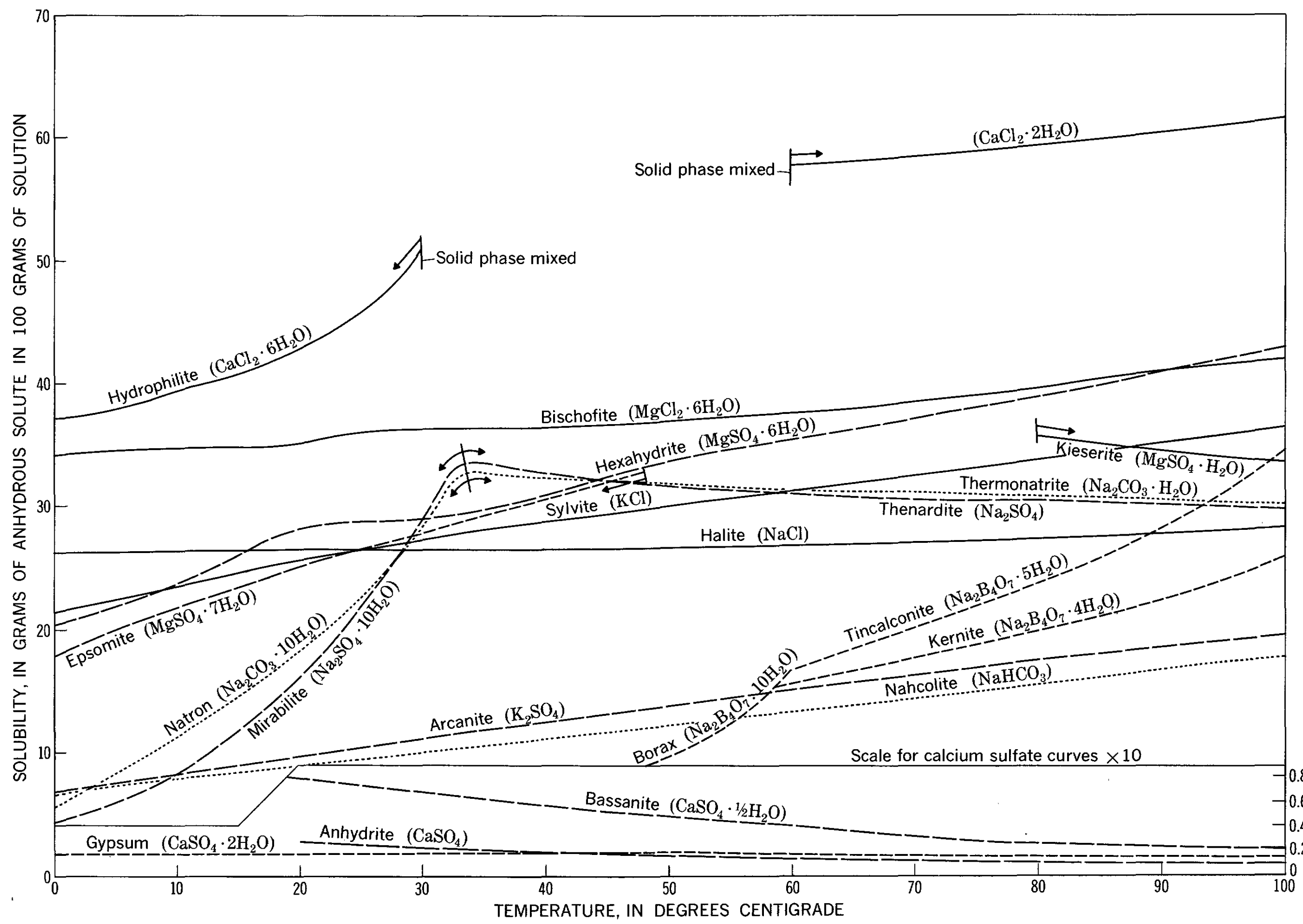

FIGURE 18.—Solubility curves for some Death Valley salts. The graphs show solubility with respect to temperature. Solubility of the calcium and magnesium carbonates (not shown) is less than 0.1 g per 100 ml of solution. Data mostly from Seidell (1940); data on borates from Kemp (1956).

Both the general zoning and the layering of these salts reflect differences in their solubilities. General differences in solubility of different kinds of salts have been summarized concisely by Pauling (1950, p. 346–347), as follows:

Least soluble (less than 0.1 g per 100 ml of water) are the normal carbonates, phosphates, and hydroxides, except those of the alkali metals and ammonium, and except barium hydroxide.

Most soluble are the chlorides, nitrates, bromides, and iodides, and, to somewhat less degree, the sulfates. The solubility of all chlorides, except that of lead, is more than 1 g per 100 ml of water; all sulfates are soluble except barium, strontium, and lead sulfate; the calcium sulfates are sparingly soluble.

The effects of the differences in solubilities are modified by factors such as temperature and the presence of other solutes (for bibliographies and review of investigations relating to solubilities of salts, see Van't Hoff and others, 1912; Clarke, 1924, p. 222–229; Mellor, 1952a, p. 427–436; 1925b, p. 249–397; Seidell, 1940).

Temperature changes within the range encountered on the floor of Death Valley influence the solubility of individual minerals as shown on figure 18. The solubility of some is increased by increases in the temperature of the solution, sylvite for example. Other minerals, notably halite, are nearly as soluble in cold water as they are in warm water. The solubility of a few others decreases as temperatures increase, for example, the solubilities of thenardite and thermonatrite decrease as the temperature increases from about 33° to 100°C. The solubility of carbon dioxide (not shown) also decreases as the temperature increases.

In wintertime on the floor of Death Valley, diurnal changes in ground temperature are mostly between 5° and 20°C, and the equilibria to be expected would be those along the left part of the curves on figure 18. In summertime the ground temperatures are mostly above 50°C and reach as high as 85°C, and the stability fields would be those toward the right side of the curves. A short distance below the surface, however, the annual temperature range and stability fields would be those illustrated in the central part of the figure.

Solubilities very likely are affected not only by the amount of temperature change but also by the rate of the change. For example, the sudden cooling of the ground surface caused by an afternoon shower, especially in the summertime, may alter the mineralogy more than would be expected from just the temperature difference.

The degree to which the presence of one salt affects the solubility of others involves many complexities, and full discussion of that subject is best left to those conversant with the physical chemistry of multiphase solutions. Discussion here is restricted to a few examples of how sodium chloride, the omnipresent solute in Death Valley, affects the solubility of some other salts.

As the content of NaCl increases, the solubility of both Na_2CO_3 and Na_2SO_4 decreases, apparently a common-ion effect. The presence of 10 percent NaCl in a solution reduces the solubility of the carbonate and sulfate by a third or half. Brines as concentrated as 25 percent NaCl may contain small quantities of Na_2SO_4 but no Na_2CO_3, (Seidell, 1940, p. 1202, 1234).

By contrast, some other minerals are more soluble in the presence of NaCl. The solubility of calcite, dolomite, magnesite, and barite is increased (Palache and others, 1951, p. 154, 164, 411; Chilingar, 1956b, p. 2772). The solubility of $CaSO_4$ is affected but slightly by the presence of NaCl: 0.6 gram of $CaSO_4$ is soluble in 100 cc of brines containing 10 percent NaCl; 0.7 gram is soluble in 100 cc of brines containing 15 percent NaCl; 0.6 percent gram is soluble in 100 cc of brines containing 25 percent NaCl (Seidell, 1940, p. 340). Moreover, at ordinary temperatures, $CaSO_4$ crystallizes from a saturated solution of salt in the form of gypsum (Vater, quoted by Clarke, 1924, p. 227), but it crystallizes as anhydrite when a solution of the sulfate in concentrated brine is evaporated at about 30°C (Mellor, 1952a, p. 435).

$SrSO_4$ is only slightly soluble in water (0.0132 g $SrSO_4$ in 100 ml of solution at 20°C), but it is slowly soluble in a warm solution of Na_2CO_3 (Palache and others, 1951, p. 427).

The presence of NaCl in solutions is known to dehydrate many minerals. Crystals of gypsum sinking through a salt solution at 25°C dehydrate to anhydrite (Lindgren, 1928, p. 332, 336). Also, whereas the temperature of dehydration of gypsum to anhydrite is 42°C (Posnjak, 1938), in the presence of a saturated NaCl solution the gypsum breaks down to anhydrite and water below 14°C (MacDonald, 1953, p. 894). At 30° the solubility of gypsum and anhydrite first increases as other salts are increased, and reaches a maximum at about 7 percent NaCl and then decreases. The decrease is more rapid for anhydrite than for gypsum; at about 15 percent, anhydrite becomes the stable phase (Posnjak, 1940).

The transition temperature, or temperature of equilibrium, of pure anhydrous sodium sulfate (thenardite) and the decahydrate is 32°C, but in the presence of sodium chloride this transition temperature drops to 18°C (Wells, 1923, p. 6, 7).

The salt minerals on the Death Valley saltpan also are zoned in an orderly way in their degree of hydration. This hydration zoning is superimposed on the other zoning and bears little relation to it. The lesser hydrates occur on dry surfaces protected against flooding, where dehydration would be expected because of the very high ground temperatures. These lesser hydrates also occur in wet environments where there is much NaCl, indicating dehydration at moderate temperatures in the presence of NaCl.

Probably many of the lesser elements are zoned in an orderly way too, but this part of the problem was touched on only lightly. Random tests for selenium indicate that the concentration is greatest (5–20 ppm) in the chloride zone, intermediate in the sulfate zone, and least in the carbonate zone. An attempt to trace the movement of molybdenum in water entering the saltpan indicates that it becomes concentrated with the sodium carbonate and sodium sulfate (Ward and others, 1960).

The clay mineralogy of samples from the gravel fans and saltpan in Death Valley has been examined by John B. Droste, of Indiana University. He found that the clay minerals in Death Valley are like those in other playas in southern California (Droste, 1958) and that no change has been found in the clay mineral composition of the nonsaline detritus being carried into the basin and the clay mineral composition of the saline muds.

CARBONATE ZONE

The carbonate zone forms a nearly continuous belt of outcrop, in places half a mile wide, around the edge of the saltpan. Its exposed area is about 25 square miles, a tenth of the surface of the pan. In this zone, acutely terminated calcite crystals have grown in the sand and silt. These deposits are a few feet thick where they are exposed around the edge of the saltpan, but panward they thicken and grade into silt and clay and extend under the crusts of other salts (pl. 2).

Four facies of the carbonate zone are distinguished: a sand facies of playa or lake beds, a silt facies of silty sand capped by a blisterlike crust of rock salt, a marsh facies, and a saline facies of deposits impregnated with rock salt deposited by the pond that formed during Recent pluvial time (p. B48). The differences between these facies are due to differences in their hydrologic environments. The sand facies is elevated and protected against flooding by surface water or ground water and becomes wet only when rained upon. The silt facies is low and is wet seasonally by flooding or when ground water rises, whereas the marsh facies is perennially wet. The saline facies is, or has been, subject to flooding by saline surface water.

SAND FACIES

The sandy playa or lake deposits representing the sand facies of the carbonate zone consist chiefly of very fine grained to medium-grained (0.1–0.3 mm) brown sand, most of which is rounded or subrounded quartz. Grains of feldspar are common. In addition there is some mica and a little hornblende. There may also be substantial percentages of volcanic glass or other volcanic rocks and of clastic grains of dolomite or limestone if these were in the source rocks. The sand is 3–10 feet thick along the west side of Badwater Basin and along the east side of Cottonball Basin and 7 feet thick at the foot of Blackwater Wash fan where the jeep trail crosses the valley.

This sand grades to silt and clay at the panward edge of the carbonate zone, and the fine-grained clastic sediments extend under the salt crust of the saltpan. In the interior of the pan the silt and clay is 35–50 feet thick (fig. 14).

A sharp boundary separates the carbonate-bearing sand from the gravel deposits at the foot of the fans. The sand has been eroded from the lower edges of the fans, and now crops out in a small cuesta facing the mountains. It overlaps gravel. Along the west side of Badwater Basin and Middle Basin the cuesta is 2–4 feet high, but it is buried under younger deposits along the east sides of those basins. This may reflect eastward tilting of Badwater Basin. The reverse is true in Cottonball Basin where the sand forms an east-facing cuesta along the east side of that basin and is buried under younger deposits along the west side.

Erosion of the sand from the lower edges of the fans has produced a lacework of rills and washes containing a foot or less of younger deposits. The scale of the geologic map, however, is not adequate to show the many intricacies of this boundary; the irregularities are shown only diagrammatically, although the contact at most places is sharp.

Salts in the upper 2 or 3 feet of the sand commonly are in 3 layers. A surface layer 3–20 inches thick overlies a calichelike hardpan layer a few inches thick, and this, in turn, rests on sand like that in the surface layer but containing a different suite of salts. Semiquantitative chemical analyses of the salts are given in table 43.

The surface layer contains much sodium chloride in addition to carbonates and sulfates, and the surface is heaved into characteristic hummocks 1 or 2 inches high (fig. 19). The salts occur with the sand, and there is little enough of it; the hummocks therefore collapse with a soft crunch when stepped upon. This microrelief is modified each time the ground is rained upon: the salts dissolve and the hummocks partly collapse when wetted, but new ones form when the salts are reprecipitated in new positions. Nevertheless, the seasonal changes in microrelief are slight. Old trails that, for all practical purposes, have been abandoned for 50 years (Hunt, A. P., 1960) still are distinct where they cross the sand facies of the carbonate zone. One example is in the northeast corner of Cottonball Basin, near the North Side Borax Camp, where the old trail takes a shortcut across the two embayments at the edge of the saltpan. About 15 percent of this trail has been destroyed by salt heaving. Another similar example is west of the West Side Highway half a mile south of the road to Trail Canyon.

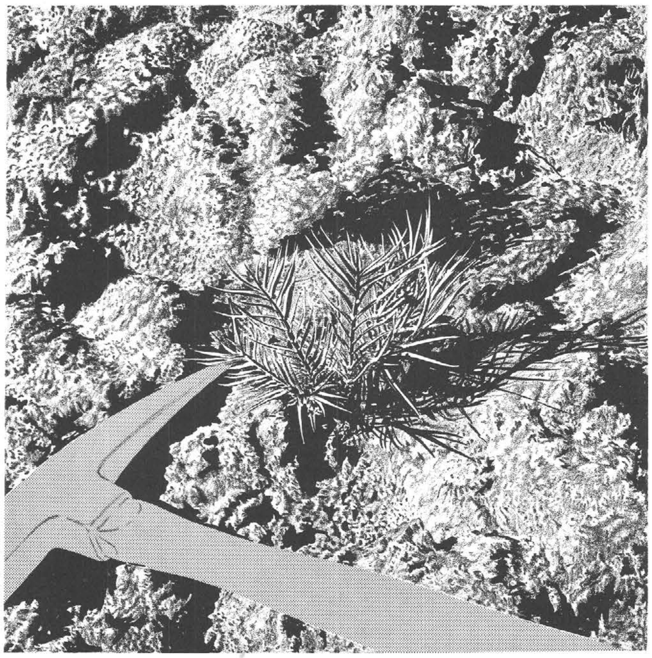

FIGURE 19.—Microrelief of ground surface in the carbonate zone. The ground is sandy and contains carbonates as clastic grains and as secondary salts. The hummocks are the result of slight heaving by interstitial rock salt. The plant is saltgrass. Location, east side Cottonball Basin. Sketch by John R. Stacy, from photograph.

After each wetting the surface becomes coated with a thin (<1 mm) white efflorescence. The efflorescence forms even after the mere dampening that occurs when the humidity is high, but it is soon blown away during dry spells.

The efflorescent salts differ in different parts of the sand facies, and probably at any given locality they vary from time to time, depending on the degree of wetting that preceded their development, Samples collected around the north and east sides of Cottonball Basin in February 1957, after a wet period, contained mostly sodium chloride near Beatty Junction, mostly sodium sulfate between there and Echo Mountain Wash, and mostly sodium carbonate between Echo Mountain Wash and Cow Creek. The efflorescence closely reflects the salts that are in the surface layer. In Badwater Basin the sulfate in the sand is mostly gypsum, only sparingly soluble, and efflorescence on the sand there is less well developed than in Cottonball Basin.

Directly underlying the surface layer at many places is a caliche layer 1–4 inches thick of sulfate salts containing very little clastic sediments. The layer is soft and readily dug at most places; but where rock salt is present, the layer becomes cemented to a tough hardpan.

This sulfate caliche layer is well developed around the north and east sides of Cottonball Basin, less developed on the Furnace Creek fan, and of only local occurrence elsewhere in Middle and Badwater Basins. Where the layer is not well developed, it consists of clastic sediments with 1- to 3-mm nodules of sulfates. The abundance and size of the nodules decrease both downward and panward.

In Cottonball Basin the caliche layer is mostly sodium sulfate (table 43, samples S2, S3, S17, S20; see also table 28). In Middle Basin the layer is mixed sodium and calcium sulfate; in Badwater Basin it is mostly gypsum (table 43, samples 104, S111a, S126). Tables 28, 29, and 30 illustrate some differences in the geochemistry of the different layers.

Table 28 brings out the fact that the caliche layer in the northern part of Cottonball Basin is chiefly sodium sulfate. This caliche is 8 feet above the present water table and 4–5 feet above the capillary fringe. The high chloride content of the sediments underlying the caliche may be due to aluminous or other chlorides.

TABLE 28.—*Proportions of major soluble constituents in different layers of the sand facies of the carbonate zone on the north side of Cottonball Basin*

[The caliche layer, commonly a few inches thick and 1-6 inches below the surface, is largely sodium sulfate, whereas the underlying sediments contain small amounts of sodium and sulfate, but large amounts of calcium, magnesium, carbonate, and chloride (computed from semiquantitative partial analyses as given on table 43. Items marked with an asterisk are considered to be of special interest]

	Sediments under caliche layer			Caliche layer	
	S1	S4	S5	S2	S3
Ca	*14.8	*12.5	*20.0	2.2	0.7
Mg	6.4	8.0	7.6	1.7	.6
K	2.3	1.5	3.2	.5	.3
Na	6.7	8.0	3.2	*34.0	*41.5
CO_3	*14.8	*16.5	*24.6	3.2	.9
SO_4	16.2	39.3	15.2	*49.6	*50.3
Cl	38.8	14.2	26.2	8.8	5.6
Total	100.0	100.0	100.0	100.0	99.9

Table 29 illustrates some contrasts between the sulfate caliche layer in the saltpan and on adjoining hills, specifically between Middle Basin and Artists Drive fan. The proportion of the anions is the same in both places; but on the fan the caliche is calcium sulfate, whereas in the saltpan it is the more soluble sodium sulfate.

Table 30 illustrates the contrast between the gypsiferous caliche and the overlying and underlying carbonate-rich layers in the sand facies of the carbonate zone in Badwater Basin.

TABLE 29.—*Differences in proportions of major soluble constituents in sulfate caliche layer in Middle Basin and on Artists Drive fan*

[The Middle Basin sample is composed largely of sodium sulfate; the caliche on Artists Drive fan is largely calcium sulfate (computed from semiquantitative partial analyses as given on table 43. Items marked with an asterisk are considered to be of special interest]

	Middle Basin	Artists Drive fan		
	S70	S79	S104	S111a
Ca	3. 8	*27. 5	*29. 1	*31. 8
Mg	1. 4	1. 6	2. 1	4. 9
K	. 2	. 3	. 3	. 5
Na	*37. 0	. 9	. 4	. 6
CO_3	. 6	. 6	1. 7	5. 5
SO_4	*52. 5	*65. 7	*65. 0	*55. 5
Cl	4. 5	3. 4	1. 4	1. 2
Total	100. 0	100. 0	100. 0	100. 0

TABLE 30.—*Soluble salts in different layers of the sand facies of the carbonate zone in Badwater Basin*

[The caliche layer is gypsum; the layers above and below are high in carbonates (computed from semiquantitative partial analyses as given on table 43). Items marked with an asterisk are considered to be of special interest]

	Surface layers			Caliche layer		Bottom layer, or layers mixed	
	S127	S141	S148e	S126	S148b	S125	S148a
Ca	*25. 5	*12. 8	*21. 9	*17. 3	*25. 2	*21. 2	*27. 2
Mg	7. 4	4. 2	12. 5	1. 4	2. 6	10. 6	4. 0
K	2. 0	4. 5	1. 9	. 3	. 8	2. 6	1. 4
Na	3. 4	2. 9	10. 1	16. 0	1. 4	10. 1	1. 8
CO_3	*9. 5	*32. 3	*21. 4	. 7	7. 0	*25. 9	*26. 1
SO_4	*37. 1	*42. 5	*23. 4	*39. 6	*61. 0	*18. 6	*34. 0
Cl	15. 1	. 8	8. 8	24. 7	2. 0	11. 0	5. 5
Total	100. 0	100. 0	100. 0	1000. 0	100. 0	100. 0	100. 0

The sediment below the caliche resembles the surface layer in being composed largely of clastic grains, and the texture and composition of the clastic fraction, at any given locality, resemble the surface layer. Sulfate salts occur as widely scattered white nodules, a millimeter or so in diameter. In Cottonball Basin these are largely of sodium sulfate accompanied by sodium-calcium borate; in Badwater Basin they are mostly calcium sulfate with small amounts of calcium borate. Along the east side of Cottonball Basin there is also some trona or thermonatrite and abundant tiny (0.05 mm) euhedral grains of acutely terminated calcite in this substratum of the sand; similar calcite has been observed in the sand in Middle and Badwater Basins.

These sand deposits of the carbonate zone are rarely flooded now and in general are wetted only by the infrequent and slight rains that fall on them. The sand probably dates from late Pleistocene time, but the layering of the salts in the sand is attributed to reworking during Recent time. The caliche layer is many feet higher than the capillary fringe above the present water table, but it probably formed when the capillary fringe was at the surface. The sand was flooded briefly by the small lake that formed during Recent pluvial time, and the sodium chloride in the sand could have been introduced then. During most of that comparatively moist period the ephemeral ponds in Death Valley did not extend to the sand; but the water table was high, and probably the caliche formed in the capillary fringe above that ground water.

Plants on the sand facies of the carbonate zone are phreatophytes and include mesquite, arrowweed, four-wing saltbush, inkweed, sacaton grass, and saltgrass. The water table is within a few feet of the surface, and the ground water contains less than 2.5 percent of dissolved solids. In the stands of mesquite the ground water contains less than 0.5 percent salts.

SILT FACIES WITH SALT CRUST

The silt facies of the carbonate zone consists mostly of silty sand or sandy silt capped by a crust of rock salt in blisterlike growths (fig. 20). The silty sand crops out on the panward side of the sand facies in Badwater Basin and along the north side of Cottonball Basin, and is a fine-grained facies of the sandy playa and lake beds.

Like the sand facies, the silty sand is feldspathic and contains a high percentage of rounded grains of quartz, feldspar, limestone, dolomite, mica, and glassy volcanic rocks. A considerable proportion of the clastic grains are fine sand (0.125–0.25 mm), but with them is silt (<0.06 mm) and some clay.

Salt crusts on the silty sand are restricted to the Badwater Basin and to the north side of Cottonball Basin. In Middle Basin and along the west side of Cottonball Basin there is silty sand along the panward edge of the sand facies of the carbonate zone, but in those areas the water table is deep and does not seasonally wet the ground surface.

In the silt facies the salts are distinctly layered with regard to the solubilities of the salts (fig. 21). At the surface is a chloride layer, below this is a sulfate layer, and below this is a carbonate layer. This layering is interrupted locally by irregular layers of rock salt, with or without gypsum. These layers generally are no more than an inch thick, and they are irregularly distributed in both the sulfate and carbonate layers.

The blisterlike growths at the surface are 1–4 inches high and 10–18 inches wide; their crusts are ¼–1 inch thick. The crust contains gypsum locally, partly dehydrated to bassanite. This dehydration must be a seasonal phenomenon because the blister crust recrystallizes seasonally when the surface is wetted.

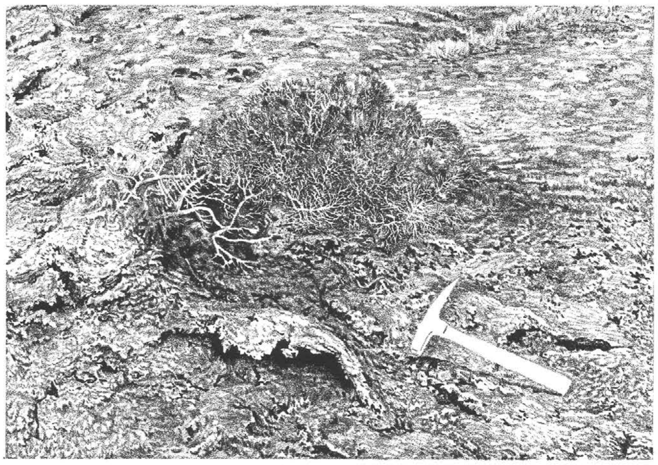

FIGURE 20.—Microrelief of ground surface in the silt facies of the carbonate zone. A salt crust, 1 inch to a few inches thick, occurs in blisterlike growths. The underlying silty sand, which contains carbonate minerals, is seasonally wetted by rise of ground water; the blister-salt crust is ephemeral. The silt facies coincides with the belt of pickleweed (illustrated) whose roots tolerate brines containing as much as 6 percent of salts. Sketch by John R. Stacy, from photograph.

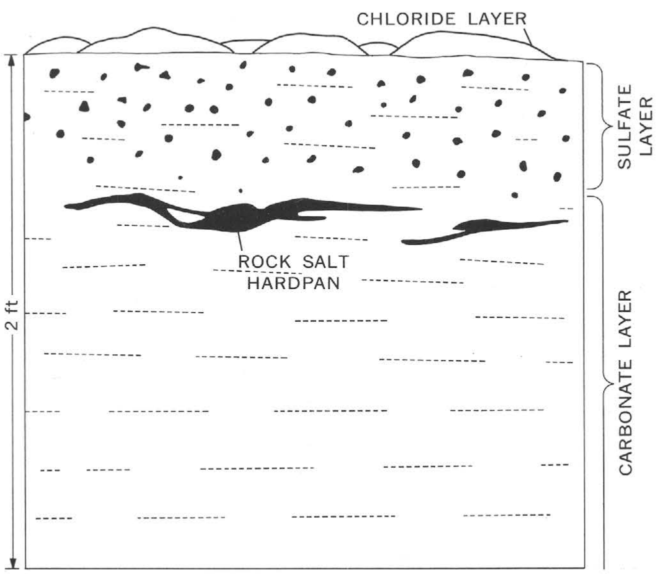

FIGURE 21.—Diagrammatic section illustrating layering of salts at the top of the silt facies of the carbonate zone. On the surface is a blisterlike crust composed mostly of rock salt. A sulfate layer, 1-6 inches below the surface, is silty sand containing small nodules of gypsum. Silty sand below this contains euhedral crystals of acutely terminated calcite. This layering, in the order of solubilities, is interrupted by irregular hardpan layers of rock salt.

The crust contains as much as 80 percent of salts (table 44), but is brown because of admixed clay and silt. On the ground surface under the hollow spaces a thin layer of salts may coat the silty sand. Among the minerals found as efflorescence on the blister crust are thenardite, acutely terminated calcite, ulexite (or the lesser hydrate, probertite), and what probably is epsomite (or hexahydrite), sylvite, and possibly polyhalite, as well as halite and gypsum. Some analyses of the salt crust are given in table 44.

Table 31 illustrates some differences in the composition of the salt crust in different parts of Badwater Basin. Considering the extent of area represented by the samples, the variations are slight, far less than the differences between the crust and the sediments beneath it.

The sulfate layer which underlies the chloride layer and is 1–6 inches below the surface (fig. 21), consists of silty sand containing widely scattered nodules of gypsum 1–3 mm in diameter.

TABLE 31.—*Proportions of major constituents in the blisterlike crust of salt on the silt facies of the carbonate zone and in the sediments underlying the crust*

[The blisterlike crust is mostly sodium chloride; the sediments underlying the crust are high in calcium and magnesium carbonates and sulfates (computed from semiquantitative partial analyses as given on table 44. Items marked with an asterisk are considered to be of special interest]

	Salt crust									Sediments under the crust
	S121	S131b	S133	S134	S135b	S149	S155	S159	S160	S136a
Ca	0.8	1.9	4.9	6.6	8.5	1.4	5.2	6.7	8.6	*17.6
Mg	2.0	1.8	1.4	2.4	4.6	4.5	2.4	2.0	3.1	*13.2
K	2.6	.5	2.5	1.1	1.5	1.3	1.9	.5	.4	4.4
Na	*33.2	*33.6	*30.1	*27.4	*23.5	*28.9	*31.3	*24.8	*29.2	2.3
CO_3	.3	.3	.8	.8	15.1	1.8	1.6	2.6	.5	*35.2
SO_4	7.7	11.9	13.6	10.9	8.5	19.9	12.3	23.6	14.7	*22.0
Cl	*53.4	*50.0	*46.7	*50.8	*38.3	*42.2	*45.3	*39.8	*43.5	5.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

In most places the gypsum in the nodules is massive and earthy, but locally they consist of aggregates of diamond-shaped crystals or fibers (fig. 22). At any given locality the crystal form of the gypsum appears to be uniform, but the forms differ from one locality to another. These crystal forms may be an ephemeral feature subject to seasonal change and may reflect the presence of impurities or seasonal differences in physical environment, such as degree and rate of recent wetting or drying. The hemihydrate, bassanite although common in the chloride layer at the surface, was not observed in this buried layer of nodules where there is little sodium chloride.

The nodules contain traces of borates and nitrates; no nitrates were detected in the salt crust.

Below the sulfate layer is the carbonate layer of silty sand, containing tiny delicate crystals of acutely terminated calcite as illustrated on figure 23. This calcite is abundant, but comprises only a fraction of a percent of the deposit. The high proportion of calcium and carbonate in the deposit (see for example, S136a, table 31) is due chiefly to the clastic limestone and dolomite. The acutely terminated calcite is the characteristic mineral of the carbonate zone, but by no means is it the dominant one. It is in fact a minor one. Its deposition possibly is facilitated by the organic

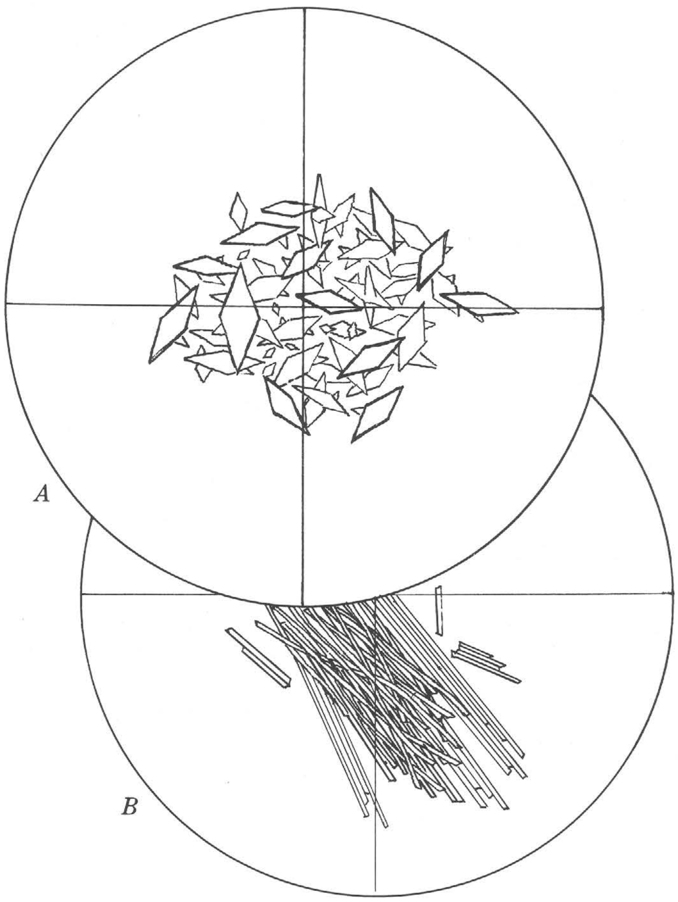

FIGURE 22.—Micrographs of gypsum crystals from the sulfate layer in the silt facies of the carbonate zone. The gypsum occurs in nodules which in part are aggregates of nearly diamond-shaped crystals (*A*) and in part are straight fibers (*B*). Diameter of fields, 0.5 mm.

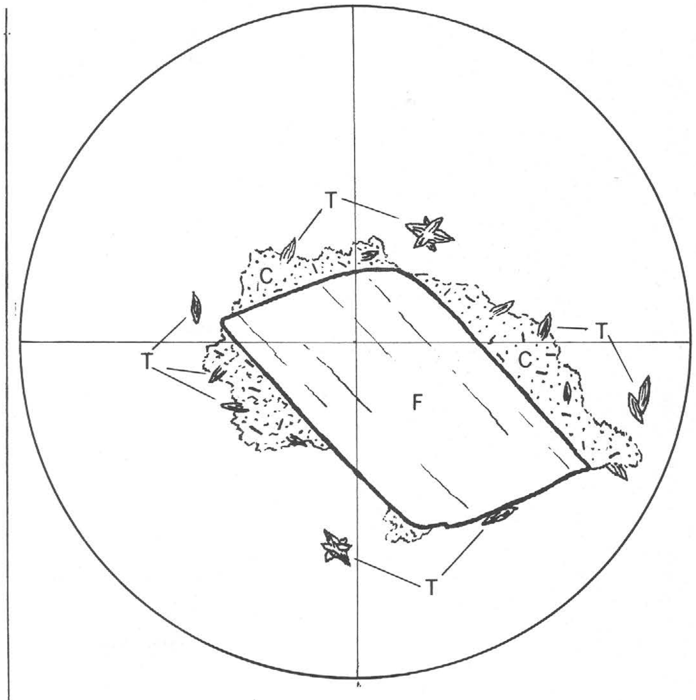

FIGURE 23.—Micrograph of powdered salts showing acutely terminated calcite in silt of the carbonate zone. The euhedral calcite crystals (T) occur singly and in interpenetrating groups in the silty clay (C) that envelopes grains of feldspar (F) and other detrital minerals. Diameter of field, 0.5 mm.

matter available in and about the root systems of the phreatophyte plants.

This threefold layering of the salt-crusted silty sand was encountered in every pit and auger hole along the west side of Badwater Basin. The layering evidently is caused by the seasonal rise of the water table which wets even the surface. The water table rises after rains, but there is also a winter rise due to decrease in evaporation. The layering of the salts with respect to their solubilities indicates that the ground water becomes increasingly briny as it rises through the upper foot or so of this ground. Evaporation in the silty sand must be considerable at least to the depth represented by the base of the sulfate layer. The hard layers of rock salt that interrupt the threefold layering are interpreted to be younger and transient features superimposed on the threefold layering. Perhaps they form where the capillary fringe did not reach the surface during temporary drops in level of the water table.

Along the west side of the Badwater Basin the salt-crusted silty sand coincides with the belt of pickleweed, and the brine in the silty sand in that area contains as much as 6 percent of soluble salts.

MARSH FACIES

Marsh deposits in the carbonate zone are restricted to the east side of Cottonball Basin, where from Cow Creek northward for 2 miles a series of closely spaced carbonate springs discharge even during dry periods. The silty sand around these springs is coated white with an efflorescence, as much as one-fourth inch thick, composed very largely of the carbonate, sulfate, and chloride of sodium (fig. 24). The pH where the springs emerge commonly is 8; it increases to 9 and even 10 in the marsh, but decreases to neutral westward in the chloride zone.

Analyses of the water discharged by the springs are given in table 50. They show that the calcium/sodium ratio is unusually low, about 1 to 100 (see also fig. 40).

At these marshes, sodium carbonate and sodium sulfate have crystallized before the sodium chloride, as indicated by the fact that the chloride continues to move panward in the brines (fig. 40), and the crystals of the chloride grow on the outside of the aggregates of the sulfate and carbonate (fig. 24). Presumably this is because the solubility of the carbonate and sulfate both are reduced in the presence of sodium chloride (p. B51); in solutions that are not mixed and at temperatures like

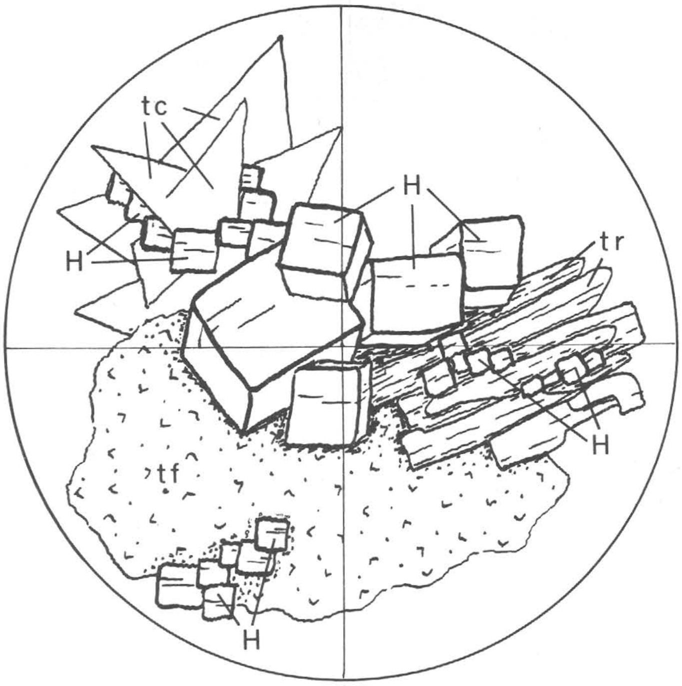

FIGURE 24.—Micrograph of powdered salts from efflorescence in marshes in the carbonate zone. The chief salts are sodium carbonate, trona or thermonatrite (tr); a coarsely crystalline (tc) and finely crystalline (tf) form of sodium sulfate, thenardite; and sodium chloride, halite (H). The halite is the last to crystallize and grows over and around the other minerals. The finely crystalline thenardite, which probably includes other minerals, commonly forms a pedestal on which the coarse thenardite and trona have grown, as if it were the earliest of the minerals to form. Diameter of field, 0.5 mm.

the ground temperatures at these marshes, the chloride is the more soluble of the three (fig. 18). It could well be that the mineralogy and chemical balance at these marshes change between night and day, and that the carbonate and sulfate move panward very much farther during the day than during the night.

It has also been found that molybdenum in the water entering these marshes becomes greatly concentrated in the carbonate and sulfate salts (Ward and others, 1960). The form in which the molybdenum occurs has not been determined.

Vegetation at these springs consists of saltgrass and rush. East of the springs, where the water table is shallow and much fresher than that discharged by the springs, grow phreatophytes including mesquite and arrowweed.

SALINE FACIES OF THE CARBONATE AND SULFATE ZONES

In parts of the saltpan, sediments of the carbonate and sulfate zones are hardly distinguishable because they are so impregnated with rock salt. This is notably so in the western part of Cottonball Basin, the west side of Middle Basin, and the northeast side of Badwater Basin.

The salt occurs as irregular layers and veinlets in the sand or in the layers of sulfate salts, as crusts on the upper parts of the sand or sulfate salts, and as thick slabs a few inches or a few feet below the surface. The slabs are best developed along the panward edge of the facies, where the upper layers and surface have been heaved into slabs having a relief of 2 or 3 feet. The rock salt must have been deposited after the other salts had become layered because the layers were broken and tilted by growth of the slabs of rock salt (fig. 25).

The protruding edges of the salt-heaved slabs develop into pinnacles, and several that were examined consist of gypsum masses cut by irregular stringers of halite and thenardite. Ulexite occurs with the gypsum. Glauberite, a common mineral in the sulfate zone, is scarce.

Probably the rock salt was introduced into these beds by the Recent lake that flooded the saltpan. Such flooding would redistribute the sodium chloride widely, and the salt would remain disseminated, except where considerable fresh water discharged into the pan. Some chemical analyses of the deposits are given in table 45. The only vegetation on these areas is sparse pickleweed.

SULFATE ZONE

The sulfate zone includes a gypsum and a marsh facies. Other sulfate deposits are impregnated with sodium chloride, constituting a saline facies, but these were not mapped separately from the saline facies of the carbonate zone. Analyses are given in table 46.

The gypsum facies consists of massive gypsum that is protected against flooding by either surface or ground water and therefore rarely is wet. The marsh facies includes some perennially flooded ground, and some that is seasonally flooded by rise of ground water. In Badwater and Middle Basins the deposits of the sulfate zone are mostly calcium sulfate, whereas in Cottonball Basin the deposits are mostly sodium sulfate (table 46). This difference in composition parallels the difference in composition of the sulfate caliche in the carbonate zone.

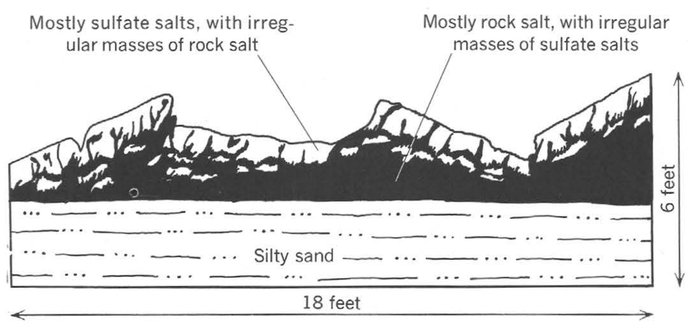

FIGURE 25.—Diagrammatic section illustrating slabby surface and layering of salts in the saline facies of the sulfate zone, western part of Cottonball and Middle Basins.

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The area of the sulfate deposits is less than half that of the carbonate zone—that is, about 10 square miles, only 5 percent of the saltpan. Thicknesses are comparable to those of the carbonate zone.

MARSH FACIES

Marsh deposits of sulfate salts are extensive in the western part of Cottonball Basin; similar ones in the other basins are small, but are especially numerous along the east side of Badwater Basin. The water in the marshes commonly contains 1–5 percent of salts.

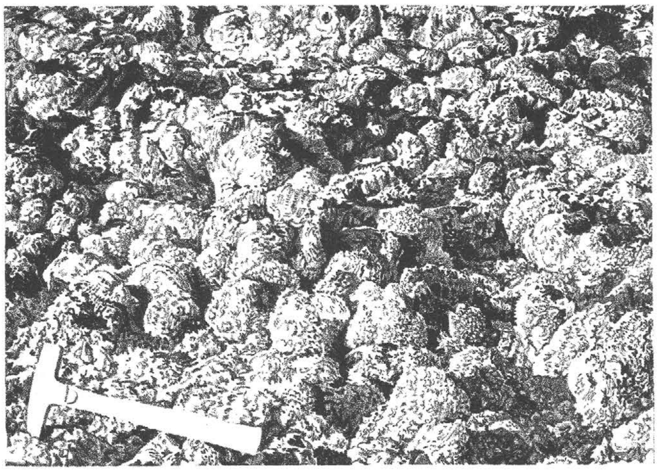

FIGURE 26.—View of lumpy growths of sulfate salts in a marsh. The lumps, composed of gypsum coated with rock salt, are 4–8 inches in diameter. Drawn by John R. Stacy, from photograph.

Most of the marsh deposits consist of cauliflowerlike lumps of sulfate salts 4–8 inches in diameter (fig. 26), but some are smooth (fig. 62). The deposits average a foot in thickness and rest on carbonate-rich mud that can be thought of as part of the carbonate zone extending panward under the sulfate zone. Some analyses of salts from the sulfate marshes are given in table 46. At the centers of the lumps are spongy masses of gypsum having the texture of wet bread crumbs; at the outside are crusts a quarter of an inch thick made firm with sodium chloride. In Badwater Basin the sulfate mineral in the crusts is gypsum or bassanite; in Cottonball Basin the crust commonly includes thenardite and glauberite as well as halite. Bassanite is common in the crusts and not so common in the interiors. An isotropic mineral with index of refraction between 1.500 and 1.505, possibly tychite, also was found in the crust on some of the lumps in Cottonball Marsh in the western part of Cottonball Basin. An efflorescence of a bitter-tasting salt, probably epsomite, is common on the surfaces of the crusts in Cottonball Marsh.

The salts in the lumps from the two marshes are different, for Cottonball Marsh is high in sodium sulfate; whereas the marsh at Badwater is high in sodium chloride. At both marshes, though, the thin crust contains most of the more soluble constituents and most of the bassanite, the hemihydrate of calcium sulfate.

Similar layering of salts is found in the crust on dried ponds along the west edge of Cottonball Marsh (fig. 27).

In Badwater Basin, mud under the marshes contains much carbonate as well as sulfate, and little chloride and sodium (see S115c and S137c, table 46). The samples that contain much chloride and sodium (S105, S114, S116, S124, and S153, table 46) were collected in 1956, a dry year. Some samples collected that year show little chloride (for example, S109, S119, and S142, table 46), but none of the samples collected in 1957, a wet year, contain much chloride (for example, S115d, S130a, S137a, table 46).

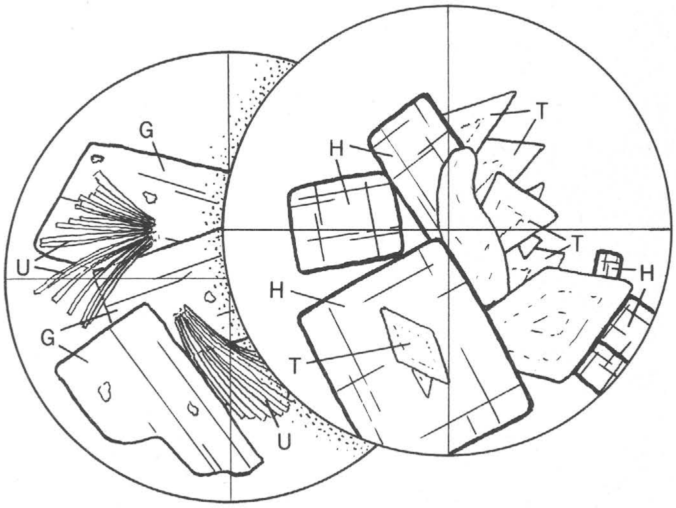

FIGURE 27.—Micrographs of powdered salts illustrating intergrowths of halite and thenardite and of glauberite and ulexite. Where there is a layered crust of salts at dried ponds on the west edge of Cottonball Marsh, the upper layer, illustrated by the diagram at the right, is mostly halite (H) intergrown with thenardite (T). the lower layer, illustrated at the left, is mostly glauberite (G) intergrown with an unidentified hydrous sodium-calcium sulfate (U). Diameter of field, 0.34 mm.

At Cottonball Marsh, largest of the marshes in Death Valley, the lumps of gypsum occur in a belt along the west edge of the marsh, at the boundary between the marsh and the saline facies of the sulfate zone. Between this belt and the flood plain to the east, the marsh has a smooth firm surface. In this part of the marsh, which is subject to seasonal flooding, glauberite and thenardite are common, and gypsum is less common.

Cottonball Marsh has some pools more than 1 foot deep of clear water tinted by multicolored algal-stained salts. Most of the pools in the marsh, however, are broad and shallow—3 or 4 feet in diameter and only 1 or 2 inches in depth—and are contained by ramparts of sulfate salts 1 or 2 inches high. All these pools contain a rich aquatic fauna and flora; many, even some of the most briny, contain desert fish. Some of the marshes contain water sufficiently fresh to grow pickleweed, saltgrass, and rush. In a few, Badwater for example, there is seepweed.

The marshes are perennially wet, or at least damp. The composition of their waters varies with the rainfall and with the relative rates of evaporation and groundwater discharge. In dry seasons the salinity is sharply increased (p. B69).

If evaporation at the marshes were less intense, some of them would appear as large springs. The marshes are most extensive and most numerous along the projected traces of faults, and they are fed by ground water rising along the faults. Several of the springs are thermal springs.

On both sides of Cottonball Basin are large springs having surface catchment areas that are inadequate to supply the quantity of water being discharged from them (p. B37 this report; also, Hunt and Robinson, 1960, p. B273). The geochemistry of the water indicates that the springs on the west side of the basin are fed by ground water escaping along faults from Mesquite Flat and the springs on the east side are fed by ground water escaping along the Furnace Creek fault zone from the higher basins to the east.

GYPSUM FACIES

Deposits of massive gypsum occur at several places in Badwater and Middle Basins. A sizable one is 1 mile north of Badwater. There are several just east of the carbonate zone between Tule Spring and Bennetts Well, and one is on the west side of Middle Basin. At these places the gypsum, 2–5 feet thick, overlies damp or wet silt and is capped by a layer of anhydrite or bassanite 1–6 inches thick.

The surfaces of these deposits are almost level, and they have a microrelief of only 1 or 2 inches. The surface layer is friable, distinctly grooved with swales, and otherwise patterned by the strong south winds. The swales trend north; the little 2-inch hillocks between the swales have steep slopes to the north and gentle slopes to the south. In places the surface is crudely ripple marked with ripples ½ inch high and 2–3 inches wide. This wind-patterned surface layer includes windblown clastic sediments mixed with detrital gypsum and bassanite.

These surfaces on the gypsum are 2 or 3 feet higher than the adjoining edge of the silt facies of the carbonate zone. The transition zone between the 2 kinds of surfaces generally is less than 10 feet wide.

Where the edges of the gypsum on the saltpan side are eroded, the gypsum ends in a small scarp 2 or 3 feet high overlooking a flood-plain surface. At such places the outer surface of the gypsum is roughened by heaving due to rock salt deposited under the gypsum by ground water seeping laterally from adjoining washes (fig. 28). The gypsum is granular rather than fibrous. Its texture is like that of dried bread crumbs and so porous that the bulk density is less than 1.0.

Beginning about 1 inch below the surface is a layer 1–6 inches thick where the gypsum ($CaSO_4 \cdot 2H_2O$) is dehydrated to bassanite ($2CaSO_4 \cdot H_2O$) (fig. 29) and locally even to anhydrite ($CaSO_4$). Along the west side of Badwater Basin this caprock is composed of bassanite, but on the east side, at the deposit 1 mile north of Badwater, it is anhydrite.

Tiny euhedral crystals of celestite (strontium sulfate) are abundant in both the gypsum and the bassanite or anhydrite layers. The celestite crystals are enclosed in both the gypsum and other calcium sulfate crystals, suggesting that the strontium sulfate is not altered when the calcium sulfate hydrates or dehydrates.

Chemical analyses of soluble salts in the sulfate zone are given in table 46. Some of the variations in composition shown in that table relate to differences in source materials shown in table 32 which emphasizes the contrast in proportion of calcium to sodium on the two sides of Cottonball Basin. Also, the similarity in composition of the marsh facies and saline facies on the west side of the basin suggests that the saline facies there formed originally in marshes that are now dry.

The massive gypsum deposits are located by marshes, and presumably the gypsum was deposited by the springs discharging at the marshes at a time when their discharge was greater than it is now. At the marshes, in wet years the total dissolved solids is less than in dry years, chiefly because the amount and proportion of sodium chloride is low. At the time of the Recent lake, discharge at the springs probably was great enough to keep the sodium chloride flushed out of the system where the calcium sulfate was being precipitated. Under this interpretation the gypsum must have been deposited after the lake had dropped below the level of these deposits, or they would have become impregnated with sodium chloride as did other parts of the sulfate and carbonate zones. This interpretation also implies that the bassanite and anhydrite caprock is due to dehydration of gypsum because of the high ground temperatures.

Another hypothesis involves precipitation of calcium sulfate where the spring water discharged into the lake. It seems unlikely, though, that the gypsum deposits could have formed in the lake and not become impregnated with sodium chloride as the lake receded.

Depending on the environment, the calcium sulfate may have been deposited as gypsum or as anhydrite. If the original deposit was gypsum, the caprock is due

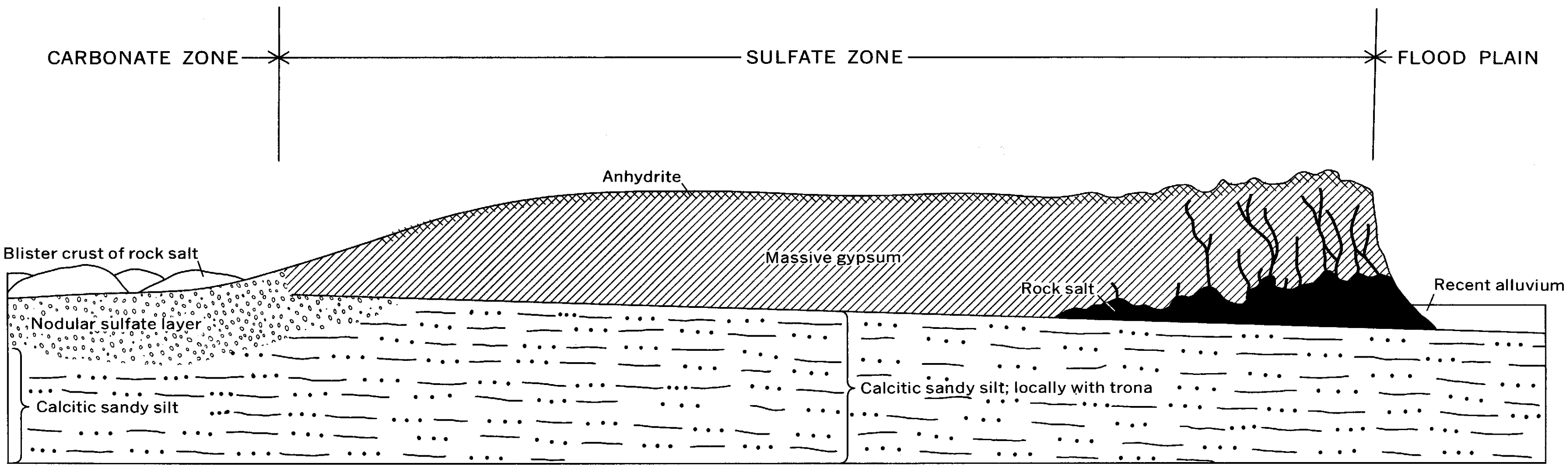

FIGURE 28.—Diagrammatic section of a massive gypsum deposit. The gypsum is 2–5 feet thick; the uppermost 6 inches is dehydrated to bassanite or anhydrite. Under the gypsum is calcitic sandy silt. Where the gypsum ends panward at a wash, as in this section, rock salt is deposited on the silty sand and rises into the gypsum in irregular veins producing a roughened surface. The relationship between the massive gypsum and the nodular sulfate layer in the carbonate zone is not known.

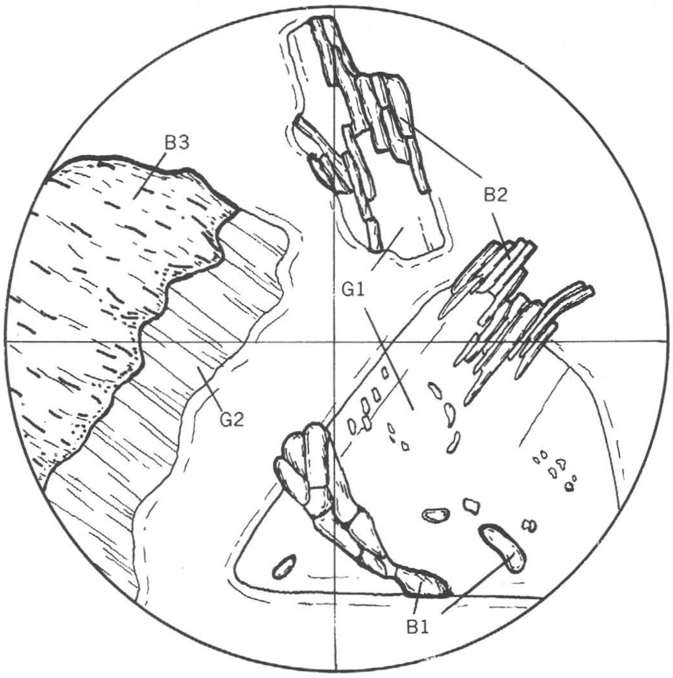

FIGURE 29.—Micrograph showing alteration of gypsum crystals to bassanite. Parts of some crystals of gypsum (G1) are replaced by nodular masses of bassanite (B1); these nodules have irregular shapes and are distributed irregularly in the crystals. Other parts of the gypsum crystals are replaced by bassanite in elongated, or even fibrous, growths (B2); these commonly parallel a cleavage. Cloudy finely fibrous growths of bassanite (B3) occur with fibrous gypsum (G2); in these cases the relative ages of the two hydrates are uncertain. Diameter of field, 0.34 mm.

to dehydration; if the original deposit was anyhydrite, the deposit is due to hydration, except the surface layer which was protected by high ground temperatures.

On the east side of Badwater Basin the caprock is anhydrite; on the west side it is bassanite (fig. 63). The content of sodium chloride in the deposits is low, and about the same on both sides of the valley. Perhaps ground temperatures are higher on the east side because of reflection of afternoon sun from the precipitous front of the Black Mountains.

No vegetation grows on the massive gypsum, and the ground water in the clastic sediments immediately under it probably averages more than 5 percent salts. The single water sample obtained (table 52, sample W100g) contained 6.6 percent of salts.

CHLORIDE ZONE

The chloride zone, by far the most extensive salt zone in Death Valley, covers the central 90 square miles, almost half the saltpan. The deposits are divided into four facies: massive rock salt facies; silty rock salt, rough facies; silty rock salt, smooth facies; and eroded rock salt facies. The two facies of silty rock salt surround the massive rock salt facies, which is nearly pure halite. The eroded rock salt includes deposits of the other three types that have been washed severely by surface water.

The chloride zone is without vegetation, except for a few stands of pickleweed along the Amargosa River in the smooth facies of the silty rock salt in the southernmost part of Death Valley. Ground water in the chloride zone generally contains more than 6 percent of soluble salts, and in the central part of the zone the water is saturated (about 33 percent).

MASSIVE ROCK SALT FACIES

Massive rock salt, at least 3 feet thick and locally 5 feet thick, covers 7 or 8 square miles in the northern part of Badwater Basin. The salt is free of silt, nearly white, and forms an exceedingly rough surface of closely set jagged pinnacles 6–10 inches wide and 1–2 feet high (fig. 30). The massive rock salt is difficult to walk across, and the jagged pinnacles discourage even a tired hiker from sitting. Underneath the massive rock salt is clay and silt that, according to borings (fig. 14), is 35–50 feet thick.

The tops of the pinnacles and other broad surfaces of the salt are grooved. These grooves, invariably alined north-south, are not quite an inch wide and are separated by paper-thin ridges of salt. Their troughs slope south. These grooves survive even the most severe rainstorms: after one rain of half an inch the ridges had become thinner and more lacy with tiny pinnacles leaning north, but there was no sign of radial grooving, although this rain (Jan. 10, 1957) was not accompanied by wind.

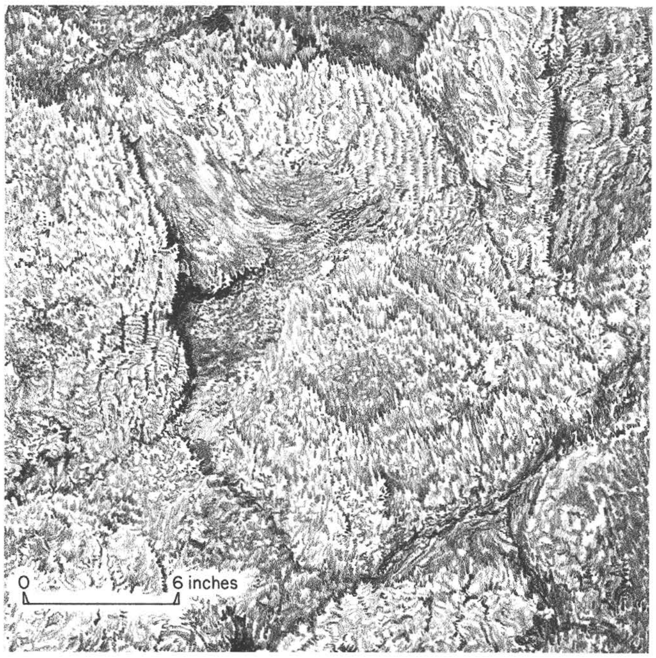

FIGURE 30.—Massive rock salt. Drawn by John R. Stacy, from photograph.

TABLE 32.—*Variations in soluble salts in the sulfate zone in Cottonball Basin*

[Along the east side the proportion of carbonate is high, and the proportion of calcium to sodium is much less than on the west side (computed from semiquantitative partial analyses as given on table 46. Items marked with an asterisk are considered to be of special interest]

	East side					West side							
	Cow Creek		Furnace Creek fan			Marshes			Saline facies of sulfate zone				
	S13	S14	S18	S19	S21	S26	S31	S47	S24	S32	S40	S41	S46
Ca	0.4	0.8	2.3	2.3	5.4	*14.2	*22.2	*13.6	8.1	6.9	5.2	7.9	5.3
Mg	.3	.5	1.0	1.0	2.6	1.3	1.3	1.5	4.0	3.6	2.4	2.8	1.9
K	.2	1.5	.4	2.0	.4	2.4	.5	1.1	.7	.6	6.0	.7	5.3
Na	*41.3	*31.3	*38.7	*32.2	*31.5	*19.2	*8.5	*21.0	*21.9	*32.8	*23.7	*29.4	*22.5
CO_3	5.1	6.5	*15.9	*18.6	*14.5	.4	.8	.3	1.8	1.7	.3	4.1	.3
SO_4	*31.4	*31.2	*34.4	*39.7	*42.7	*34.9	*58.4	*38.0	*48.2	*24.4	*32.4	*29.4	*33.5
Cl	*21.3	*28.2	7.3	4.2	2.9	27.6	8.3	*24.5	*15.3	*30.0	*30.0	*25.7	*31.2
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total soluble salts	80.4	77.9	70.3	80.9	63.5	84.0	78.2	82.3	45.9	53.2	80.3	54.7	81.6

Depressions between the salt pinnacles are solution pitted. Circular openings 1–3 inches in diameter extend downward into the salt, and evidently connect with fissures extending to the base of the salt. Circulation of moist air out of the openings is indicated by delicate efflorescences of salt around and across the top of the openings. Moisture in the clastic sediments under the salts appears to evaporate under the salt and escape through these circular vents.

The edges of the massive rock salt are erosional, and the deposit is surrounded by a flood plain of clastic sediments mantled by a thin ephemeral crust of salt. The edge of the massive salt forms a ledge 1–3 feet high overlooking the flood plain, and in places the salt has been undercut.

The massive rock salt probably averages about 95 percent or more of sodium chloride. The remaining 5 percent includes chlorides of calcium, magnesium, and potassium, and sulfates of magnesium and sodium, as well as clastic material.

The purity of the massive rock salt suggests that it is the residue from evaporation of a lake, the Recent one. At the time the salt was precipitated from the pond, the water level need not have been higher than the present top of the salt. A very shallow pond of clear brine could have been maintained by recharge for considerable time. Peripheral to the massive salt are the two facies of silty rock salt, which probably formed where the surface was more like that of a playa—where there was alternate flooding and drying.

SILTY ROCK SALT, ROUGH FACIES

The rough facies of the silty rock salt forms the weird surface in the central part of the saltpan known as the Devils Golf Course. The salt is 1–3 feet thick, brown with admixed silt, and is coated with a thin layer of silt, which, like that on the smooth facies, contains considerable sulfate. The rough silty rock salt is underlain by silt and clay.

The deposit is extensive in Middle Basin, the southern part of Cottonball Basin, and the northern part of Badwater Basin. Its area is about 25 square miles, about three times that of the massive rock salt.

The salt occurs in two forms. The most extensive form consists of ropy spires rising 1½ to 2½ feet above the depressions; their surprisingly uniform height may be wind controlled. Capping each spire is a layer of brown silt, generally about ¼ to ½ inch thick, over the middle of the spire and thinning at the edges. This silt may have a firmly crusted surface, 0.1 inch thick, containing carbonate salts. Below this is a layer of borate-bearing sulfate nodules 0.1–0.3 inch in diameter. X-ray analyses of these nodules by John Droste (personal commun., 1959) indicate that bassanite and probertite are common.

A second form of the silty rock salt occurs as thick slabs turned up like saucers 6–10 feet in diameter.

The two forms do not occur together: the spires are in the interior of the chloride zone, whereas the slabs are most common adjacent to areas subject to flooding. The deposit with the ropy spires may be a weathered form of older slabs; the slabs may have developed from a crust like that of the salt saucers developing now on the flood plain west of Badwater (p. B65,110).

The rough facies also develops from the smooth facies along the edges of flood plains, where moisture seeps laterally from the flood plain and deposits salts under the smooth facies of the silty rock salt. This ground becomes heaved and becomes part of the rough facies. Locally, this is on a scale sufficient to show on the map, as along the edges of the flood plain in Cottonball Basin. An almost endless variety of salt structures are developed depending on the stage when flooding by surface water imposes degradational forms on the constructional ones.

Changes in form of the salt structures, under the present regimen, are slow because the salt rarely is thoroughly wetted. A measure of the rate of changes in the salt structures at the surface is provided by the tracks of the original road across Death Valley (fig. 31), which was replaced by the present alinement in the early 1880's when it became necessary to improve the road for the 20-mule-team borax trains. After more than 70 years of weathering, the tracks still are distinct across the rough salt (see also p. B52).

Some semiquantitative analyses of samples from the rough silty rock salt are given in table 47. These analyses are very much like those given by Campbell (1902, p. 18) and Wheeler (1876, p. 176). The contrast between the salt layer and the silt layer is illustrated in table 33.

FIGURE 31.—Tracks of the original road across Death Valley, in rough silty rock salt. This alinement, three-quarters of a mile northwest of the present highway, crosses a narrow belt of rough salt to the channel of Salt Creek where the creek bends northeast, and leaves the creekbed by a tributary that heads on the smooth flood plain at the Devils Speedway. The distinctiveness of the tracks, unused for more than 70 years, provides a measure of the slow rate of change of the salt structures. Drawn by John R. Stacy, from photograph.

SILTY ROCK SALT, SMOOTH FACIES

The smooth facies of the silty rock salt forms an extensive plain, 18 miles long, at the mouth of the Amargosa River. It forms a similar but smaller plain in Cottonball Basin at the mouth of Salt Creek, and some still smaller areas around the base of the Furnace Creek fan. These deposits now cover about 50 square miles, about twice the area of the rough facies, and constitute the most extensive of the saltpan units.

TABLE 33.—*Differences in major constituents in the soluble salts in the silt layer and salt layer of the rough silty rock salt*

[Computed from semiquantitative partial analyses as given in table 47. Items marked with an asterisk are considered to be of special interest]

	Silt layer	Salt layer
	S97	S98
Ca	*14. 9	1. 9
Mg	4. 1	. 7
K	2. 3	1. 8
Na	*19. 3	*34. 1
CO_3	*14. 4	1. 9
SO_4	*14. 9	5. 7
Cl	*30. 1	*53. 9
Total	100. 0	100. 0
Total acid soluble salts	36. 3	82. 1

Typically the facies consists of a smooth surface layer of brown silt, 1–6 inches thick, and an underlying layer of rock salt a few inches to 1 foot thick (figs. 60, 61). The rock salt, in turn, rests on clastic sediments. Panward the layer of silt thins, whereas the rock-salt layer thickens. The salt also thickens southward along the Amargosa River and eastward from Salt Creek onto the Furnace Creek fan.

Capping the brown silt is a firm crust about 0.1 inch thick containing various carbonates, probably cemented with rock salt. In Cottonball Basin, carbonates occur throughout the silt layer.

Below the carbonate crust is a layer 1–6 inches thick containing tiny nodules of sulfates and borates. Bassanite is common. Probertite, the lesser hydrate of the sodium-calcium borate hydration series, occurs in both the surface layer and the underlying rock salt. Its identification is based on indices of refraction as determined by me and on an X-ray determination by John Droste. The upper part of this nodular sulfate layer has a pH of about 7; the base has a pH of about 6.5. The underlying layer of rock salt is neutral.

The upper part of the clastic sediments underlying the rock salt in the southern part of Badwater Basin contains, at least locally, a caliche of nodular bassanite 1–2 inches thick. The sediments below this caliche contain euhedral crystals of acutely terminated calcite.

In these layers solubility of the salts increases from the surface downward to the layer of rock salt; below this the solubilities decrease downward to the silt containing acutely terminated calcite. Probably the silts under the rock salt are or have been in the capillary fringe of the water table, and the rock salt formed at the top of the fringe; the layering is like that in the silt facies of the carbonate zone (p. B24). The silt overlying the rock salt may have been deposited by floods of surface water.

The occurrence of solution pits on the surface of the silt suggests that water percolating downward is responsible for the layering of salts in the silt above the rock-salt layer.

Analyses of samples from the smooth facies are given in table 48. Most of the samples are from the silt and sulfate layer overlying the rock salt; if the layer of rock salt had been included, the Na and Cl contents would be so high as to mask all other relationships. In Badwater Basin the sodium appears to be fully combined with chloride, but in parts of Middle Basin and in Cottonball Basin there is an excess of sodium for the available chloride, which accounts for the sodium sulfate and sodium carbonate deposits in those parts of the valley.

The surface today rarely is flooded by overflow of the streams, but it may be flooded when cloudbursts fall on it. The drainage on these deposits is disrupted. Surface water collects in broad swales that are acres in extent but only inches deep, and most of these discharge underground. In places the surface is interrupted by circular sinkholes, 2–6 feet in diameter and 6–12 inches deep, alined along swales. The water can only go downward, as the quantity is insufficient to develop through drainage.

Where the layer of rock salt has continued to form, it develops blisterlike growths like those in the silt facies of the carbonate zone. These growths disrupt the overlying layer of silt and indicate that the latest addition to the deposit has been by ground water rather than by surface water (fig. 32).

In some areas where surface water collects or where there may be flooding by the main streams, the surface is roughened by irregular growth of the rock-salt layer, and such deposits grade into the rough facies of the silty rock salt. Such roughened areas are most common along the edges of washes, where surface water seeps under the banks. Isolated areas of ground roughened by salt heaving in the midst of the smooth facies apparently mark places where aquifers bring considerable ground water to the surface of the clastic sediments in wet seasons.

Where the surface is flooded severely enough to cause erosion, the deposit becomes eroded rock salt (p. B65). The upper silt may even be washed off, leaving bare the layer of rock salt.

An anomalous hillock in the smooth facies of silty rock salt is in Cottonball Basin south of the mouth of the middle distributary of Cow Creek. The hillock is 3 feet higher than the surrounding surface of the smooth facies and 6 feet higher than Salt Creek. Its top is smooth, like the surrounding plain, but its sides are roughened by salt heaving. One side is erosional, owing to lateral cutting by the distributary of Cow Creek. This hill may be due to Recent faulting, or it may have been raised by salt deposited by springs along the faults that extend northwestward under the basin (see Hunt and others, 1965).

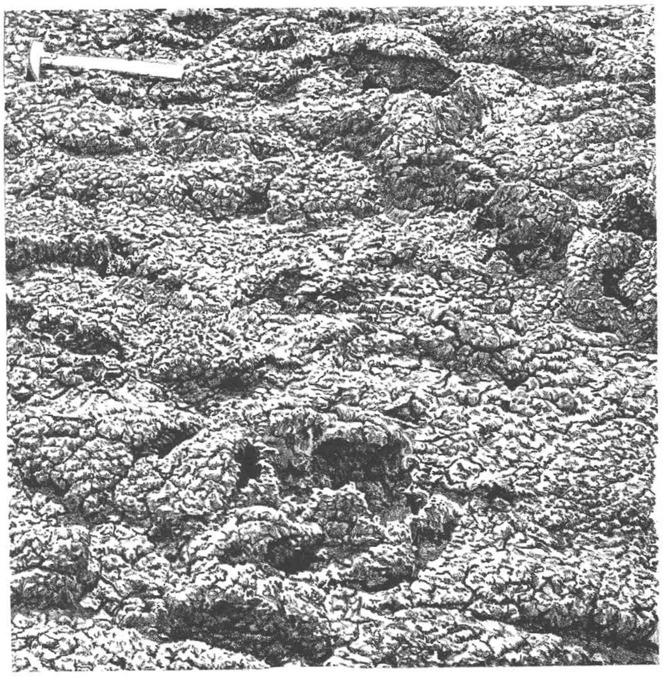

FIGURE 32.—Surface of the smooth facies of the silty rock salt where the salt layer has disrupted and roughened the overlying silt layer. Drawn by John R. Stacy, from photograph.

The difference between the smooth and rough facies of the silty rock salt probably is due to differences in in frequency of washing by surface water. The smooth facies is located where the largest streams discharge into Death Valley, and the extent of the deposits is roughly proportional to the size of those streams. The most extensive deposit is at the mouth of the Amargosa River, the least is at the mouth of Furnace Creek. The deposit at the mouth of Salt Creek is intermediate in extent. The rough facies occurs between these areas and that of the massive rock salt and is attributed to evaporation in the wet muds on the flats peripheral to the residual pond that deposited the massive rock salt.

In places, however, the smooth facies becomes roughened at the edges of the flood plains as a result of ground water seeping laterally from the flood plain (fig. 34). This form of occurrence, especially well developed in Cottonball Basin (see pl. 1), is analagous to the roughened sulfate deposits (see figs. 25, 28).

ERODED ROCK SALT FACIES

Where smooth silty rock salt has been flooded, as along the Amargosa River, the surface silt is washed away and the salt exposed (compare figs. 60, 61). In general, these salt surfaces are pitted with solution cavities rather than roughened by heaving. These eroded deposits are gradational between the smooth facies and the flood plains. The boundaries as mapped are arbitrary and gradational.

Where the rough silty rock salt is subjected to seasonal flooding, the spires may be reduced in height, and the silt washed from them collects in the depressions. The surface becomes less rough, but still is rougher than the smooth facies. The salt forming this surface contains considerable silt, but it is not capped by silt. Where erosion is advanced, the microrelief on the surface of the salt may be only a few inches.

SALINE DEPOSITS ON SEASONALLY FLOODED AREAS

The parts of the saltpan now flooded seasonally, the flood plains, are mostly flat expanses of damp or brine-soaked sandy silt and clay, in part crusted with salt. Slopes are gentle enough, so that winds can push the water upstream. Some of the flood plains are eroded planed surfaces on old deposits; others are constructional surfaces of Recent deposits. All are free of stones even where they extend to the foot of the gravel fans, although outside the saltpan the channels of washes are sandy or gravelly and are without salt crusts. These areas subject to flooding aggregate about 75 square miles, about a third of the saltpan, and are without vegetation.

The salt crust on the flood plain ranges from a thin delicate efflorescence to a firm crust several inches thick, the differences being controlled by the hydrology. The crust is thin on those parts that are flooded frequently, and thick where flooding is infrequent.

In Badwater Basin the salt crust is lacking on the Devils Speedway, which is a flood-plain surface receiving drainage from Trail Canyon fan. The salt crust is lacking in the small area a mile northwest of Bennetts Well, thin or lacking in the several square miles of flood plain extending north and southeast from Salt Well, and in the several square miles north of Mormon Point. These areas are the most frequently flooded parts of the flood plain in Badwater Basin. Channels leading from them discharge surface water to the interior of the pan, and as the ground is more sandy and more permeable than in the interior of the pan, there is seepage into the ground also. Little water can accumulate to deposit a salt crust in such areas.

The flood plain 1 mile northeast of Salt Well is being trenched. The westernmost tributary of the Amargosa River is in a channel 50 feet wide and 3 feet deep. Its tributaries, forming a dendritic pattern, are incised 1 foot into the flood plain and head in miniature badlands eroded into the flood plain. This condition contrasts with that across the valley in the cove north of Mormon Point where the flood plain is smooth, is being aggraded, and apparently is overlapping the base of the gravel fans. The difference between the two sides of the valley may be due to eastward tilting (p. B44).

Between Salt Well and Mormon Point, the Amargosa River is in a channel 20 feet wide and 6 feet deep. The channel becomes shallower and wider northward in the saltpan: 2 miles northeast of Salt Well it is 35 feet wide and 3–4 feet deep; east of Gravel Well it is 2½ feet deep and 50 feet wide. The channels are asymmetric at meander bends; on some bends the deep part of the channel is only 5 feet from the outer bank.

In Cottonball Basin, where Salt Creek crosses the smooth facies of the silty rock salt, it is in 2 distributaries, each of which is about 10 feet wide and 2 feet deep. There is sufficient flow in this part of Salt Creek to corrade the outside banks of the meanders; outside banks may slope as steeply as 60 percent; the inside banks slope only 20 percent.

In the central part of Badwater Basin, especially 2–3 miles west of Badwater, a thick crust of salt on the flood plain forms saucerlike structures of silty rock salt in polygonal slabs 5–10 feet in diameter and 1–6 inches thick (fig. 57). The slabs are turned up at the edges as steeply as 30° and as high as 18 inches. The salt is thin at the centers and thick at the edges of the polygons, and gives the appearance of having been thrust outward, but mostly northward, from the centers of the polygons. The slabs rest on wet silt and clay. Commonly there is a 1-inch hardpan, probably rock salt, 8–14 inches below the surface of the clastics.

Salt saucers that have held rainwater contain drain holes in their lowest parts. Their raised edges erode to delicate honeycombs of salt, and stalactites grow downward from overhanging edges. Continued solution leaves the saucer rims as ramparts 6–12 inches high and 4–8 inches wide surrounding polygonal flats on the clastic sediments from which the salt has been removed. The flat polygons are 4–5 feet in diameter and divided into smaller polygons by veins of salts an inch or so thick. These veins and the ramparts extend only half an inch or so down into the clastic sediments.

Similar salt saucers once covered part of the playa floor at Searles Lake, but the surface there has since been scraped smooth (Ver Planck, 1958, p. 77).

Where the salt crust on the flood plain is intermediate in thickness, the crust occurs in blisterlike growths not unlike the crust on the silt facies of the carbonate zone, although the blister crust in the flood plains is the result of the ground being wetted by saline surface water. The blister crust in the flood plain commonly is coated with the sodium-calcium sulfate, glauberite, whereas the common sulfate in the blister crust on the carbonate zone is the calcium sulfate, gypsum or its dehydrated relatives.

Some channels in this blister salt have still a third type of crust, one that is very silty and has rectangluar patterns (fig. 33).

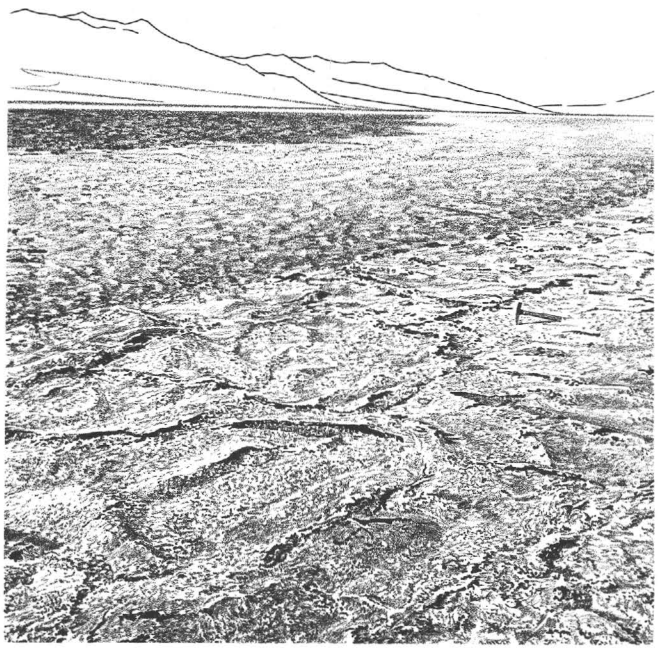

FIGURE 33.—Flood plain of a distributary of the Amargosa River with crust of very silty salt in rectangular pattern. Drawn by John R. Stacy, from photograph.

In Cottonball Basin, which has exterior drainage into Badwater Basin, the distribution of salt crusts on the flood plain differs somewhat from that in Badwater Basin. In the middle of the basin where the channel of Salt Creek is broad but shallow, the flood plain is a mudflat with only an efflorescence of salts; but along each side of this mudflat is a belt crusted with salt in blisterlike growths (fig. 34). Below the jeep trail crossing west of Furnace Creek fan, the tributaries of Salt Creek are dammed from the main channel of Salt Creek by blister salt and salt-heaved ground across the mouths of the tributary channels.

Bordering the belt of blister salt in Cottonball Basin is a third belt that is flooded infrequently, but is seasonally damp or wet with ground water apparently seeping laterally from the channel because the belt parallels the channel. This belt, when dry, is mud cracked and is crusted with salt in hexagonal plates about 4 feet in diameter and about 1 inch thick. The interiors of the plates are flat, but the outer 4 inches at the edges are turned up 45°. This platy type of crust also covers the embayment where Salt Creek enters the flood plain at the narrows 1 mile to the east.

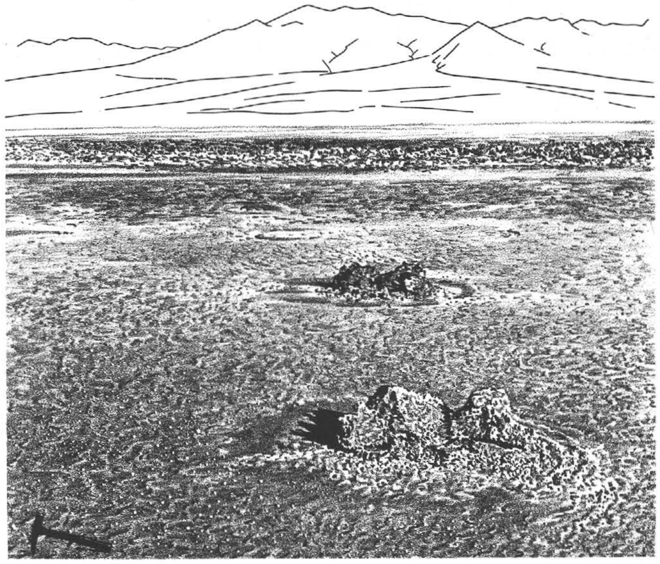

FIGURE 34.—View east across flood plain of Salt Creek in Cottonball Basin. Pellets of ulexite, cottonball, dot the part of the flood plain that is frequently flooded. The mounds in this belt are part of old mine workings. The frequently flooded area is bordered by ground that is flooded less frequently and is covered by a thin crust of blister salt. The bank of the flood plain is rough silty rock salt, evidently deposited by ground water seeping laterally from the flood plain. Drawn by John R. Stacy, from photograph.

Middle Basin is ponded and is kept from discharging into Badwater Basin because of 18 inches of Recent uplift on the anticline separating the 2 basins. The channel of Salt Creek extends into Badwater Basin, but it has been arched 18 inches and water will have to be ponded that deep in Middle Basin before it can again overflow into Badwater Basin.

The composition of the salt crusts on the flood plain varies both seasonally and from place to place. The salts that crust over a part of the flood plain during a dry year will be replaced by a different suite during a wet year. No doubt, too, the mineralogy of the efflorescence in cold seasons differs from that in warm seasons. In winter months, on cold mornings, elongate crystals of sodium sulfate, probably mirabilite, are common on the flood plain in Cottonball Basin; later in the day as the surface warms, and in warm months, the efflorescence is powdery thenardite, in part occurring as pseudomorphs of mirabilite (p. B49). Table 49 presents some analyses of soluble salts in the flood-plain deposits.

In Cottonball Basin, and to a lesser extent in Middle Basin, the upper layers of the clastic sediments contain considerable quantities of glauberite. In Badwater Basin, where the ratio of calcium to sodium available to combine with the sulfate radical is greater than in

Cottonball Basin (table 49), there is less glauberite and more gypsum and thenardite.

In Cottonball Basin the glauberite is accompanied by nodular ulexite, sodium-calcium borate, popularly known as cottonball. This mineral was the object of the earliest borax mining in Death Valley, during the 1880's. The analyses given in table 49 illustrate the high boron content of the flood plain in Cottonball Basin as compared with that in Badwater Basin.

The ulexite also occurs as cottonballs on the surface of the flood plain, but these may have been eroded from layered glauberite and ulexite in the upper part of the silty sand. The pellets on the surface commonly are coated with halite and thenardite; the fluid, squeezed from some, has a pH of 6. In addition to ulexite the efflorescence in Cottonball Basin also includes borax (fig. 35). Figure 36 illustrates some common forms of some of the salt in the efflorescences.

The boron in the flood plain of Cottonball Basin probably is largely reworked from the Furnace Creek Formation, which is extensively exposed along Furnace Creek and in the Salt Creek Hills. In the Furnace Creek area are bedded or vein deposits of borates that were important producers after production ended on the valley floor.

Differences in composition of the salts on the flood plain are most noticeable along channels crossing the edges of the saltpan. At the carbonate marshes on the

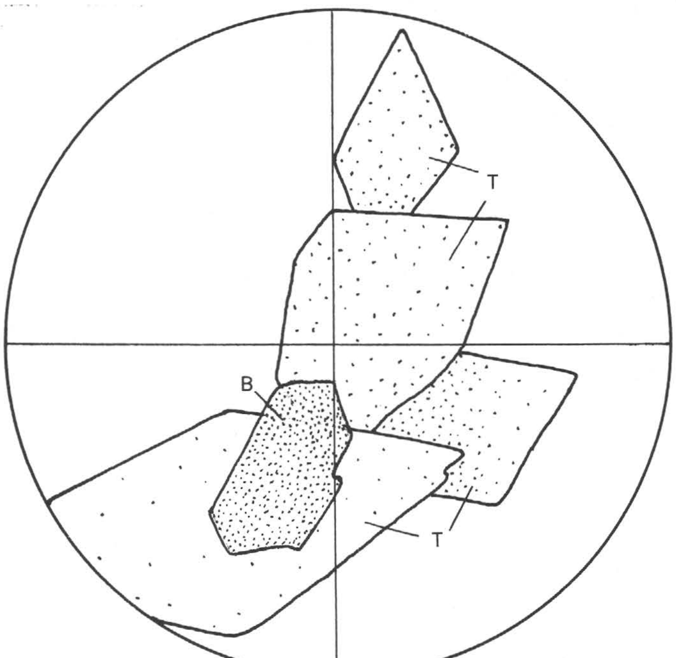

FIGURE 35.—Micrograph of borax crystal contained in thenardite. Crystals of borax (B) commonly retain their form although altered by dehydration to powdery tincalconite. At salt efflorescences near the edge of the saltpan, thenardite (T) grows in clusters around the borax. Diameter of field, 0.34 mm.

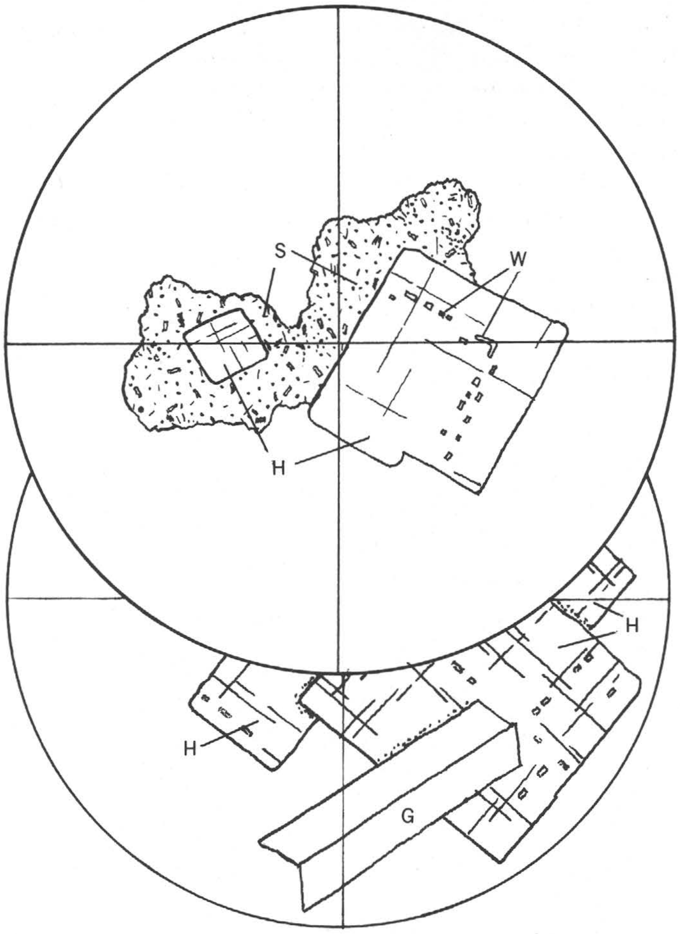

FIGURE 36.—Micrograph of salt efflorescence on flood plain. The efflorescence commonly consists of cubes of halite (H) mixed with microcrystalline aggregates of sulfate salts (S), as shown in the upper drawing. Some of the tiny rectangular vugs (W) in the halite alined with the cleavage contain water. The microcrystalline sulfate salts in Badwater Basin are mostly gypsum and thenardite; in Cottonball Basin they are mostly glauberite and thenardite. In Badwater Basin the halite commonly is intergrown with butterfly twins of gypsum (G), lower drawing. Diameter of field, 0.34 mm.

east side of Cottonball Basin, for example, there is trona and (or) thermonatrite. Along the channels draining these marshes the efflorescence is mostly halite and thernardite (and possibly bloedite). A thousand feet farther into the saltpan, where the channels are in the chloride zone, the crust is halite which is coated with another mineral so fine grained as to appear like aggregates of opaque specks, presumably a sulfate of magnesium or a chloride of calcium or magnesium.

At the mouth of Rock Alinement Wash, following a storm, the salt efflorescence at the edge of the flood plain was gypsum and thenardite. Half a mile downstream the efflorescence was thenardite without gypsum, and still farther downstream a mineral suggestive of bloedite was found with the thenardite.

Most of the efflorescence on the flood plains occurs as tiny growths of halite crystals that look like fibers or miniature stalagmites growing upward. Most are 2 or

3 mm thick and about 30 mm long; an occasional one may be 40 mm long and only 1 mm thick. They are hollow tubes, and many contain a drop or so of water. Most of them lean or are bent in the direction of the last strong wind.

Another feature of the flood plains is the salt pools which develop where the water table is shallow enough to dissolve through the salt crust, giving rise to structures collapsed into the underlying pool for the most part of salt-saturated water (fig. 37). They are most abundant and best developed 5½ miles northwest of Badwater, around the north end of the massive rock salt.

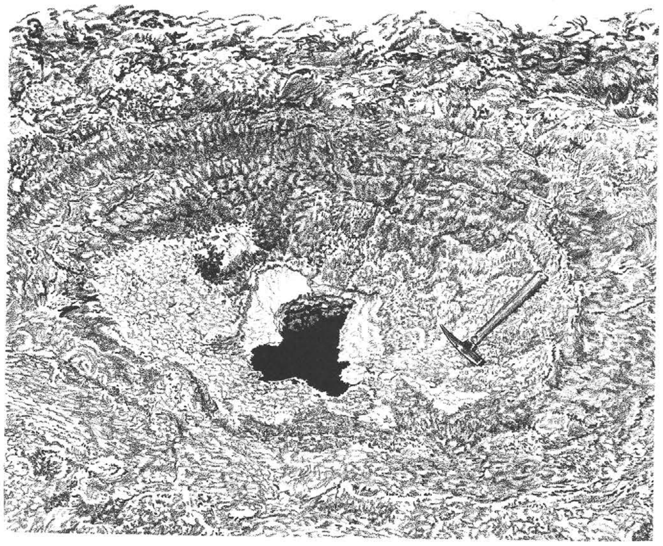

FIGURE 37.—Salt pool and collapse structure in flood plain of Salt Creek, 5 miles northwest of Badwater. Drawn by John R. Stacy, from photograph.

COMPOSITION OF THE BRINES

In general, the content of salts in the brines in Death Valley increases panward, is greater in ground water than in surface water, greater in dry years than in wet years, and greater in standing water than in running water. The increase in salts panward is due both to evaporation of water and to re-solution of salts. Semiquantitative chemical analyses of the brines are given in tables 50–52.

The effect of the several variables on the composition of the brines is illustrated by a series of graphs (figs. 38–50) representing suites of samples along ground-water and surface-drainage courses into the pan.

Differences in major constituents along a 5-mile stretch of Salt Creek where it enters the pan are illustrated on figure 38. This graph illustrates the increase in total salts panward and the increase in sodium and potassium relative to calcium and magnesium. Carbonates were not determined in these brine samples, but other analyses (table 34) indicate that along one stretch of Salt Creek there is about a fifth as much bicarbonate as sulfate. No doubt the proportion of carbonate decreases panward, as do calcium and magnesium.

TABLE 34.—*Chemical analyses, in percent, of water from Salt Creek, showing carbonate and silica content*

[Collected by T. W. Robinson, Apr. 10, 1957, and analyzed by U.S. Geol. Survey (see also table 50 for semiquantitative samples)]

	A	B		A	B
SiO_2	0.004	0.004	CO_3	0	.005
Ca	.227	.178	SO_4	.389	.328
Mg	.044	.037	Cl	.919	.757
Na	-------	-------	Total dissolved solids		
K	-------	-------	(ppm)	(?)	(?)
HCO_3	.078	.063	pH	7.9	8.4

A. From a 1-ft dug pit on west side of Salt Creek 600 ft upstream from W1-56s (see table 50 and pl. 2).
B. Salt Creek at W1-56s.

A series of samples along a 3,000-foot traverse into the northeast corner of Cottonball Basin, in the Salt Springs area, is illustrated on figure 39. This graph illustrates the panward increase in salts, but it also shows that the ground water is more saline than surface water at the same position in the pan. Later tests in this same area indicate that the uppermost layer of the ground water is more saline than deeper layers. In February 1958, a few days after a rain, the uppermost ground water, 3–4 inches below the surface, contained 4.3 percent dissolved solids, whereas ground water bailed from 3½ feet contained only 2.5 percent.

Springs used as a source of domestic water supplies in the Furnace Creek area are located along faults on the fans north of Furnace Creek Wash. Four major sources are Travertine and Nevares Springs, and springs in the bluffs near Cow Creek. Analyses of the waters are given in table 35, page B73.

The springs at Cow Creek probably are fed by ground water underflow from the Nevares Springs; the other springs are warm springs, and probably the high temperatures are due to circulation at no great depth but through warm rocks. The thermal gradient in the ground in this highly faulted area probably is higher than average, and an increase of only 30°F over the annual average temperature would heat the water to the maximum observed (104°F). This could be accomplished with circulation no deeper than about 1,500 feet (see p. B40).

The water is believed to be moving into Death Valley along faults in the Furnace Creek fault zone and derived ultimately from the Pahrump Valley (p. B38; see also Hunt and Robinson, 1960). This water is very different from that on the west side of Cottonball Basin, which probably moves in along faults from Mesquite Flat (p. B37; see also Hunt and Robinson, 1960).

The total dissolved solids in these spring waters is low compared to other Death Valley water; but by the

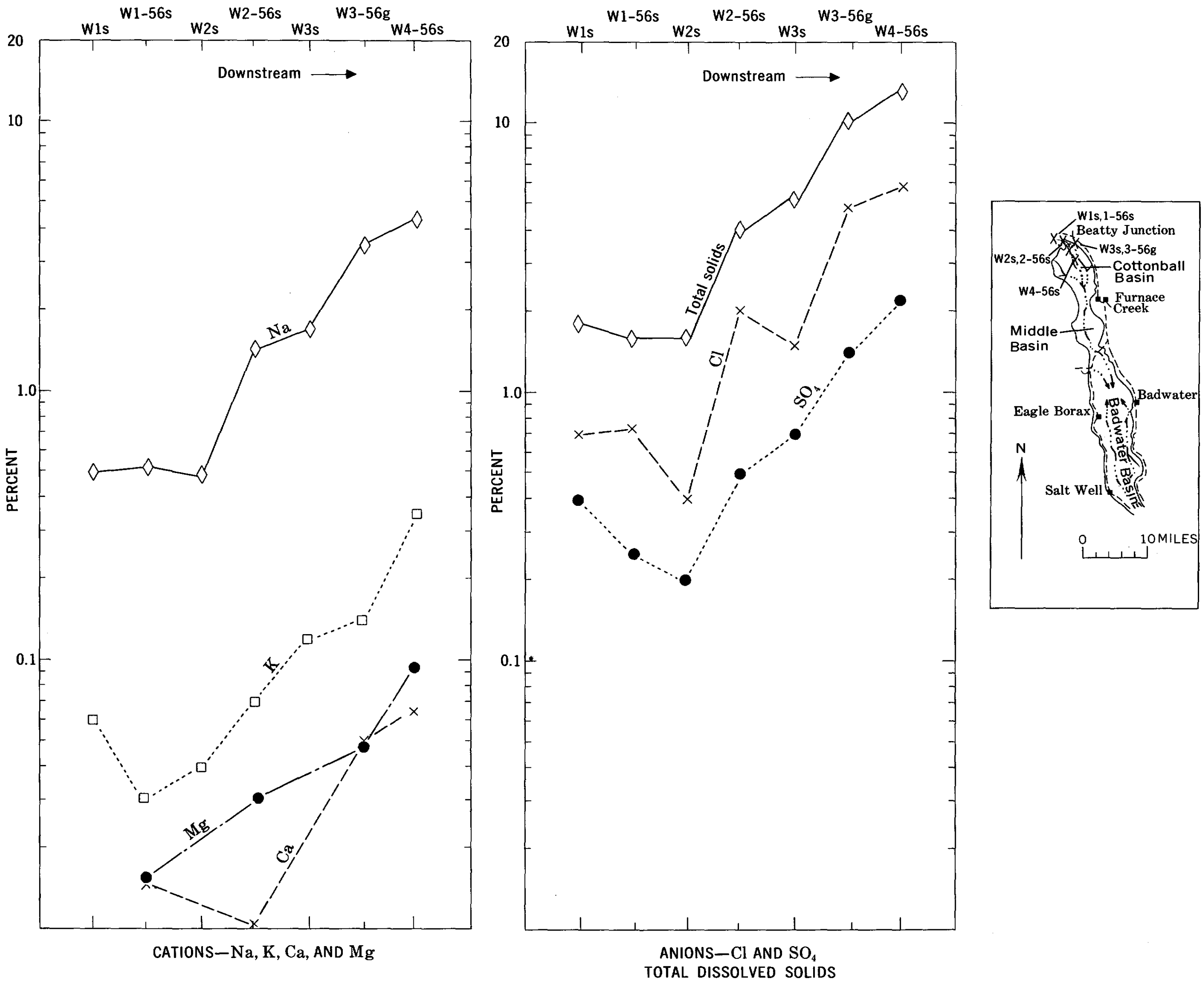

FIGURE 38.—Graphs illustrating some changes in major constituents along 5 miles of Salt Creek where it enters the saltpan. Total salts increase panward; sodium and potassium increase greatly. For locations, see plate 3; analyses are given in table 50.

time the water reaches the edge of the saltpan, its content of salt has increased several fold.

Five samples along a ½-mile stretch of Cow Creek, where it enters the saltpan (fig. 40), show differences in composition similar to those along Salt Creek and below Salt Springs; they also show that ground water at a given location contains more salts in dry years than in wet years.

Differences in composition of 3 surface-water samples along a ½-mile stretch of the wash draining northwest from the Harmony Borax Works are illustrated on figure 41. In these samples, which are from the edge of the pan where it overlaps faulted Tertiary formations, the major constituents differ only slightly from those in other nearby parts of Cottonball Basin where the brines are derived from Pleistocene gravels.

A suite of samples representing a 5-mile traverse in the west part of the pan is illustrated on figure 42. The salinity of the ground-water samples sharply increases from the spring to the marsh and from the marsh to the channel draining it.

Dry-year samples in the marsh (W13–56g and W14–56g, table 50) are notably more saline than the wet-year samples (W–38–W–41g). At the hot spring at the West Side Borax Camp dissolved solids are about the same in wet and in dry years (compare W42g and W15–56g, table 50). Also, surface water along the channel draining the marsh has substantially less salts than does the ground water, as indicated by the following pairs of samples listed in table 50: W31s and W32g, W33s and W34g, W35s and W36g. The surface water has about the same salinity and same

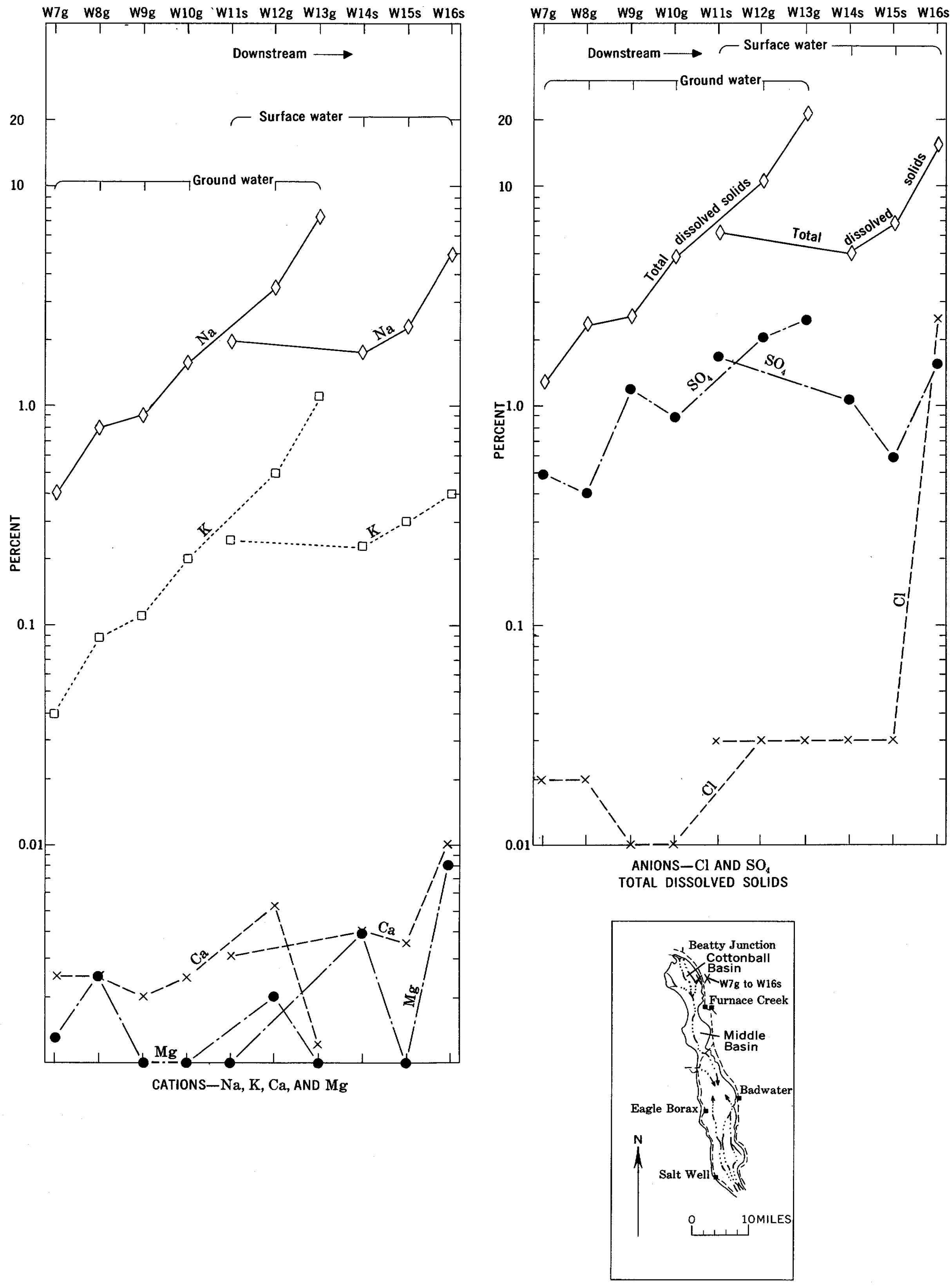

FIGURE 39.—Graphs illustrating some variations in major constituents in water in the Salt Springs area. The salts increase panward in the surface water and the ground water. The ground water contains more salts than does surface water at the same position, but the proportion of the anions and cations is about the same in both. For locations, see plate 3; analyses are given in table 50.

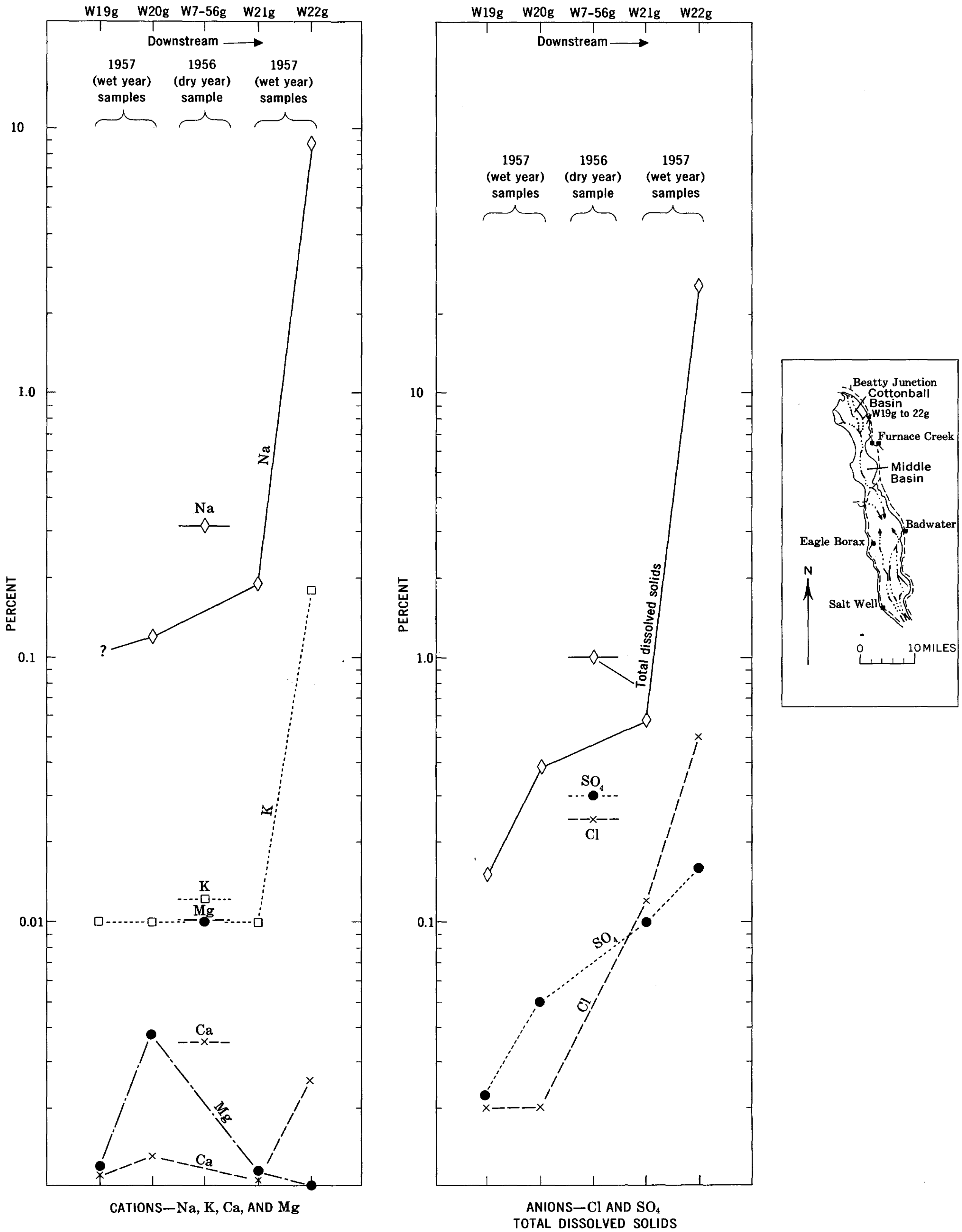

FIGURE 40.—Graphs illustrating some changes in major constituents in ground water in half a mile along Cow Creek where it enters the saltpan. Not only do the salts increase panward, the proportions of sodium, potassium, and chloride increase. The graph also illustrates that the ground water contains more salts in dry years than in wet years. For locations, see plate 3; analyses are given in table 50.

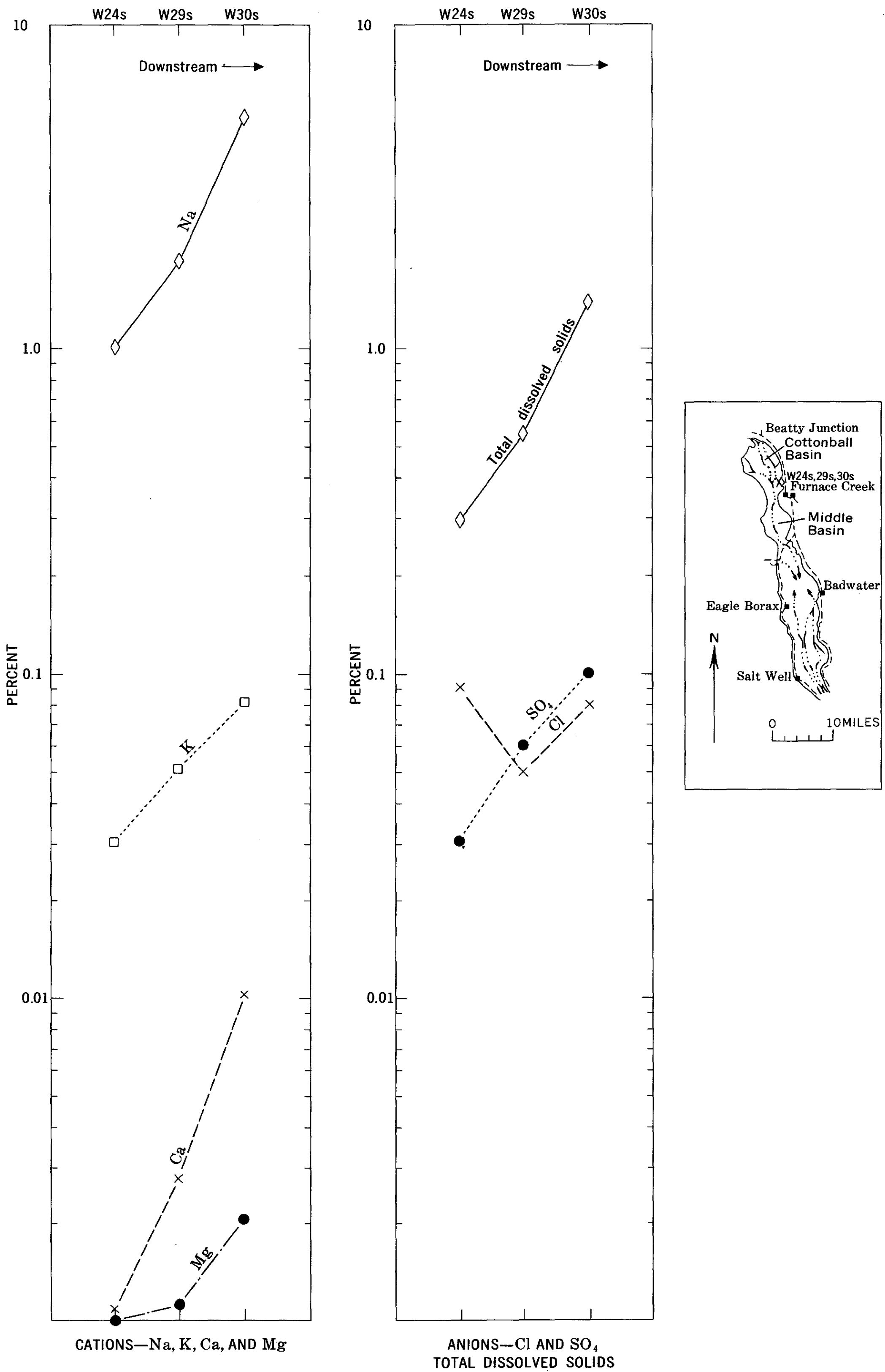

FIGURE 41.—Graphs illustrating increases in major constituents in surface water in half a mile along the wash draining northwest from Harmony Borax Works. For locations, see plate 3; analyses are given in table 50.

TABLE 35.—*Chemical analyses, in parts per million, of spring water in the Furnace Creek Wash and Park Village areas*

	1	2	3	4
SiO_2	43	25	32	--------
Al	--------	--------	.2	--------
Fe	--------	--------	0	--------
Mn	--------	--------	0	--------
Ca	26	35	43	52
Mg	22	20	21	38
Na	145	155	145	253
K	11	12	11	16
Li	.13	--------	--------	--------
HCO_3	321	348	350	455
CO_3	--------	0	0	0
SO_4	158	160	174	352
Cl	39	43	36	74
F	3.0	2.0	2.8	4.4
NO_3	0	0	0	--------
B	0	1.0	--------	1.3
PO_4	--------	--------	0	--------
Total dissolved solids	--------	716	620	--------
Sum of determined constituents	605	599	637	1,010
pH	8.05	7.9	7.9	7.7
Temperature (°F)	90	91	100	74

1. Travertine Spring, analysis by U.S. Geol. Survey, as reported by Pistrang and Kunkel (1958, p. 61).
2. Texas Spring, analysis by California Dept. of Water Resources, as reported by Pistrang and Kunkel (1958, p. 61).
3. Nevares Spring, sample collected by R. C. Scott, Dec. 22, 1955, analysis by U.S. Geol. Survey, Lab. No. 1109.
4. Spring at base of bluff, Cow Creek area, analysis by U.S. Geol. Surve, as reported by Pistrang and Kunkel (1958, p. 62).

proportions of major constituents as does the ground water a couple of miles upstream in the marsh.

A still different condition is illustrated on figure 43, a graph of 9 samples along a 1½-mile stretch of the north end of Cottonball Marsh and a wash draining into it. The surface water ponded in the wash contains more salts than does the ground water in the marsh, although the latter is downstream from the wash; two sources of water may be represented in the graph.

Two analyses of water samples from Middle Basin are given in table 51. Analyses of samples from Badwater Basin are given in tables 36 and 52.

In Badwater Basin the proportion of calcium to sodium is greater than it is in Cottonball Basin, and, as already noted (p. B48, B57), the mineralogy of the sulfate minerals in the salt deposits is very different in the two basins.

Analyses of brines encountered in borings in the Badwater area (table 26) are given by Gale (1914a, p. 411) as follows:

Analyses of brines, in percent of total dissolved solids, from U.S. Geological Survey borings in Death Valley
[R. K. Bailey, analyst]

Well	Depth (feet)	Cl	SO_4	B_4O_7	Ca	Mg	K	Na	Total salts
200	32	53.07	7.93	0.42	0.07	0.05	1.29	37.17	28.50
	38	46.81	14.81	.44	----	.05	1.35	36.54	29.95
	70	47.91	12.67	1.01	----	.08	1.95	36.38	29.67
300	1	55.74	5.05	.37	----	.04	1.62	37.18	27.71

These brines must be practically saturated with NaCl and about half saturated with Na_2SO_4. Assuming that the potassium and magnesium in these brines occur as chlorides and that the calcium occurs with sodium as a borate (ulexite), the hypothetical salts in the brines would be as follows:

Hypothetical salts (in percent of total dissolved solids) in brines in Death Valley

	Well 200			Well 300
Depth (feet)	32	38	70	1
KCl	2.5	2.6	3.7	3.1
$MgCl_2$	.2	.2	.3	.2
$NaCaB_5O_9$	.3	-----	-----	-----
$Na_2B_4O_7$	.3	.6	1.5	.5
NaCl	85.4	75.0	76.0	89.5
Na_2SO_4	8.2	16.4	14.3	3.9
SO_4 not accounted for	3.1	5.2	4.2	2.8
Total	100	100	100	100

Differences in major constituents in water in the sulfate marshes around Badwater Basin are given on figures 44–49. The percentages of major constituents in the water in marshes on the two sides of the basin are very much alike, although the marsh environments appear to be very different. Springs supplying the marshes along the east side of Badwater Basin evidenlty are located along the faults at the front of the Black Mountains. Springs supplying the marshes along the west side of Badwater Basin probably are supplied chiefly by seepage from the huge gravel fans to the west, but part of this water may circulate from deeper sources.

TABLE 36.—*Chemical analyses, in percent of water from Badwater, showing carbonate and silica content*

	A	B	C	D
SiO_2	0.005	0.003	0.012	0.001
Ca	.150	.095	.063	.100
Mg	.020	.009	.013	.012
Na	--------	} .857	--------	--------
K	--------		--------	--------
HCO_3	.020	.016	.010	.015
CO_3	.002	0	0	.002
SO_4	.592	.307	.243	.379
Cl	2.570	1.280	.753	1.569
pH	8.3	7.2	7.5	--------
Residue on evaporation at 180°F	--------	2.560	--------	3.197

A. West side pool at Badwater. Collected by T. W. Robinson, Apr. 11, 1957, and analyzed by U.S. Geol. Survey.
B. East edge of pool at Badwater; pickleweed growing here. Collector, date, and analyst as in sample A.
C. Pool at Badwater; collected Nov. 11, 1955, by T. W. Robinson and analyzed by U.S. Geol. Survey.
D. Pool at Badwater, west side; collected by W. F. White, Jr., Nov. 19, 1938, and analyzed by U.S. Geol. Survey.

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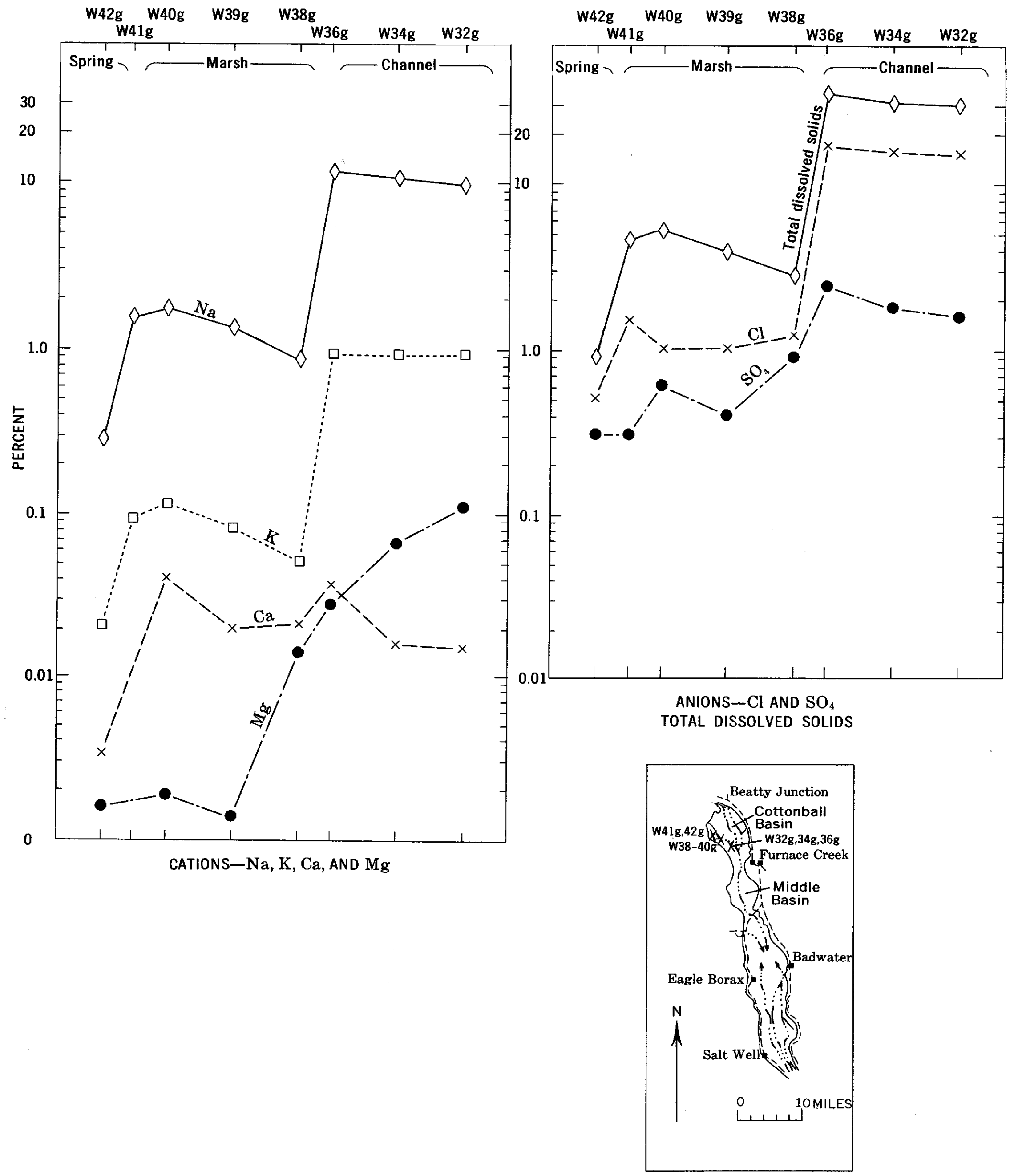

FIGURE 42.—Graphs illustrating some changes in major constituents in ground water in 5-mile traverse eastward from West Side Borax Camp. The graph illustrates the increase in salts as water moves from the spring to the marsh and from the marsh to the channel. For locations, see plate 3; analyses are given in table 50.

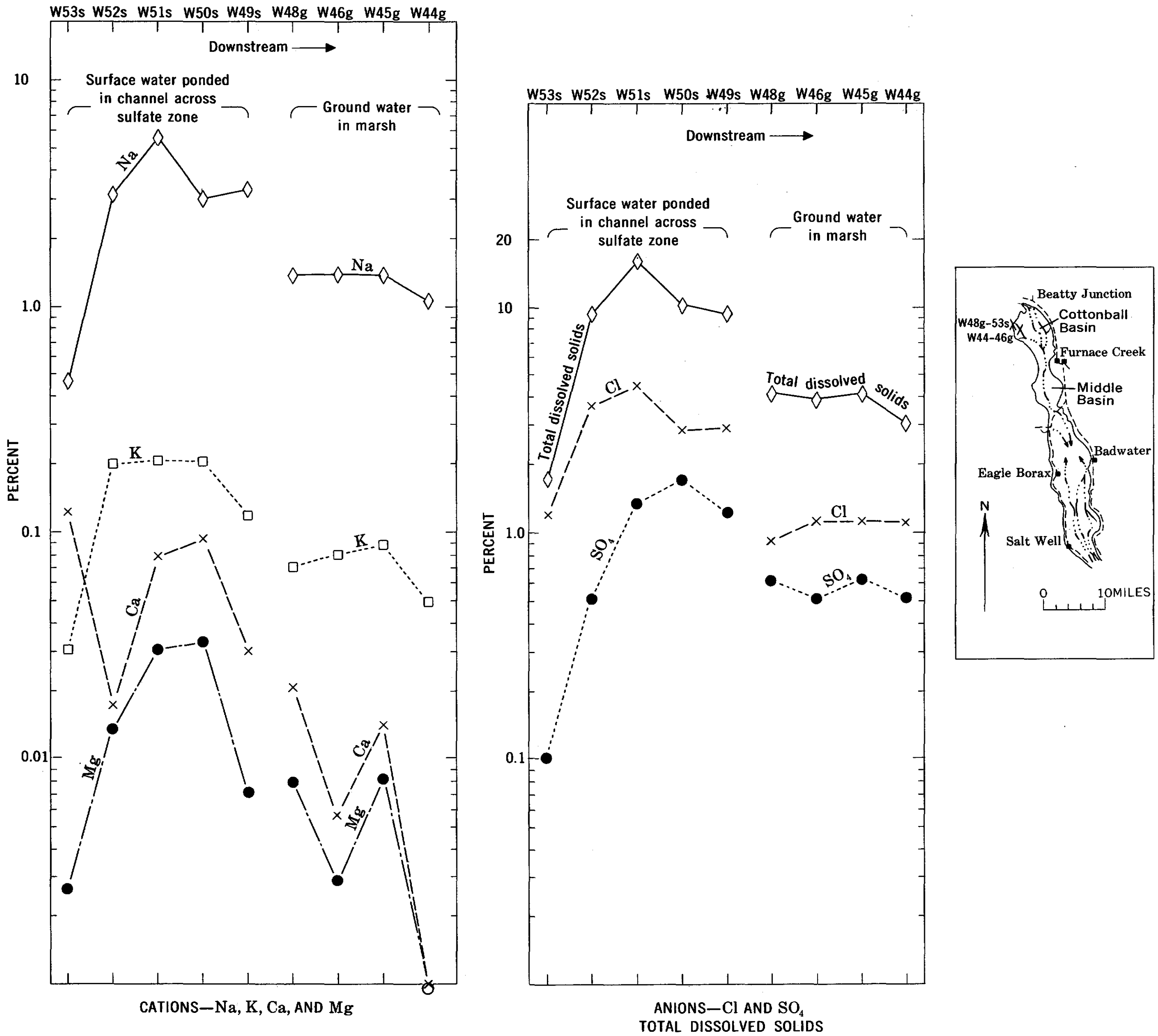

FIGURE 43.—Graphs illustrating some differences in major constituents in surface water along a channel in the sulfate zone and in ground water panward across an adjoining sulfate marsh, about 2 miles north of West Side Borax Camp. Two sources of the waters represented in the graph are suggested because the salt content of ground water in the marsh is less than that of surface water in the channel upstream from the marsh. Generally the salts increase downstream and are greater in ground water than in surface water; in this example the relationship is reversed. For detailed locations, see plate 3; analyses are given in table 50.

The freshening effect of running water as compared with ponded surface water is suggested by the flattening of the curves between W63g and W64s, figure 45. Sample W63g, although properly classed as ground water, actually is water at the surface at the edge of the marsh. This water drains into the channel represented by W64s, which is a sample of running water in the channel 250 feet north of the edge of the marsh.

Changes in major constituents in water along a 3-mile stretch of the drainage north from Salt Well are illustrated on figure 47. The graph shows the increase in salt content panward and the greater salt content of ground water than of surface water.

Analyses of water from the Amargosa River (fig. 50) show a progressive increase in total dissolved solids downstream.

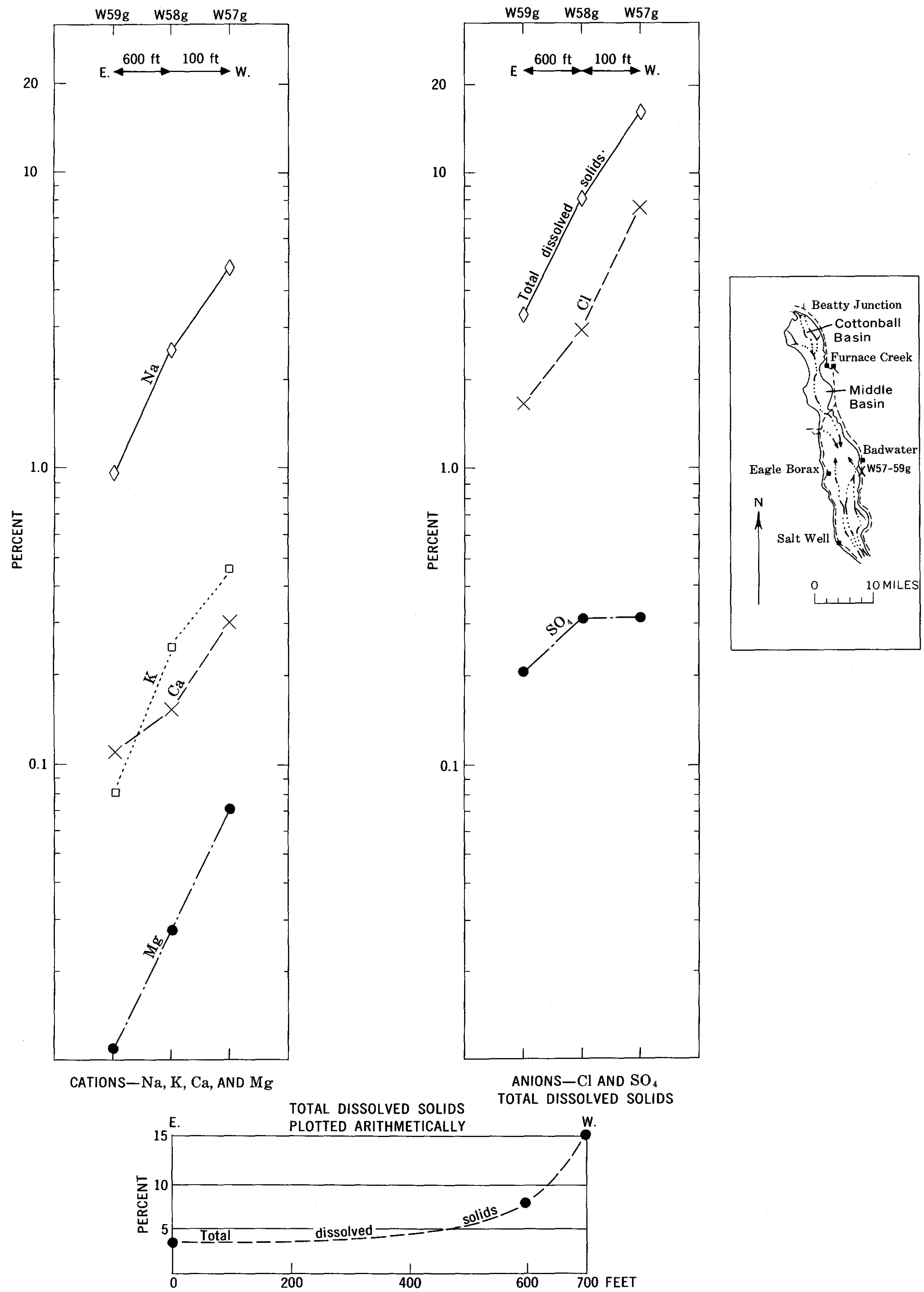

FIGURE 44.—Graphs illustrating increases in major constituents in ground water in 700 feet westward from the toe of the gravel fan in second cove south of Badwater. All the dissolved solids increase greatly in the last 100 feet of this traverse. For locations, see plate 3; analyses are given in table 52.

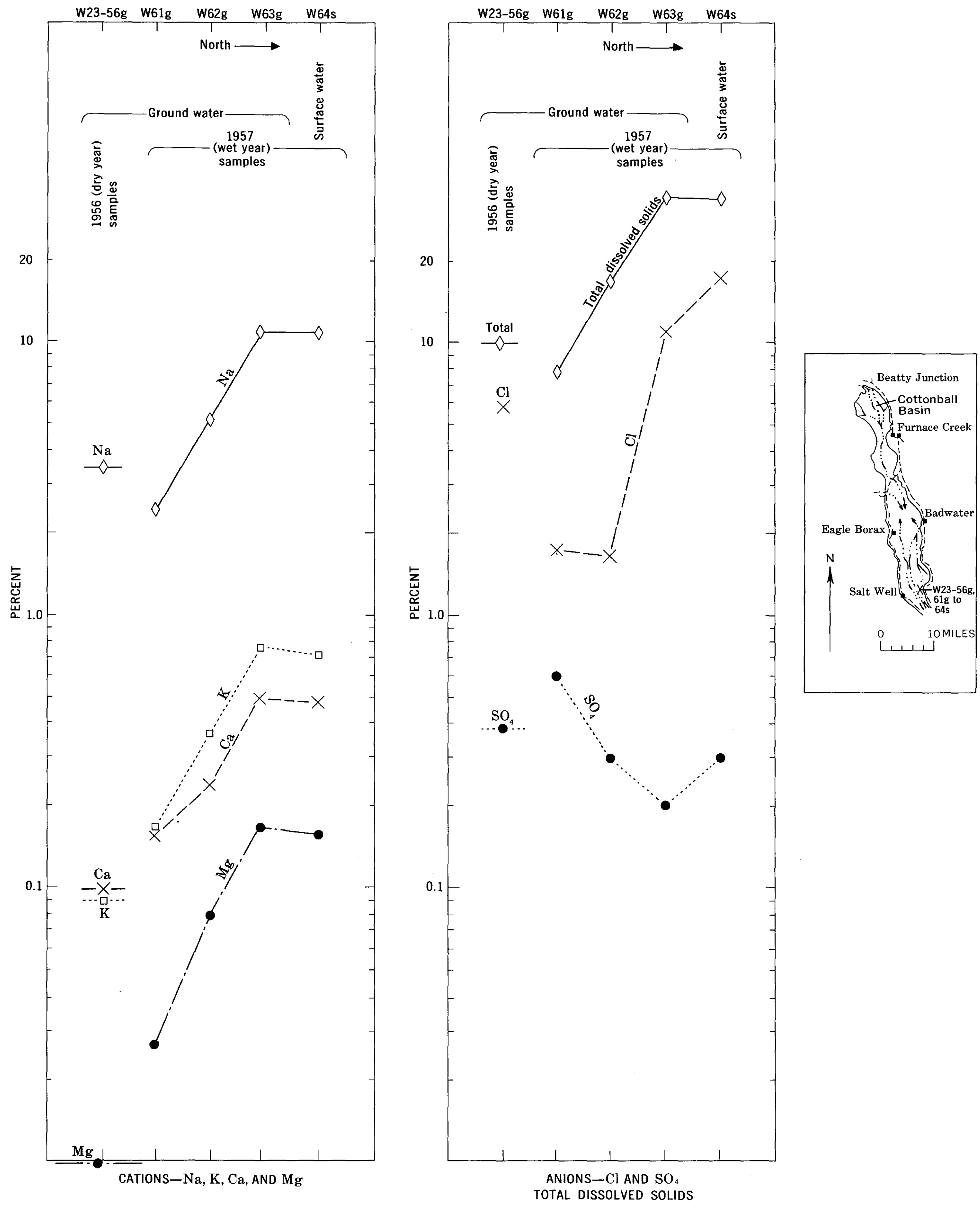

FIGURE 45.—Graphs illustrating some changes in major constituents in ground water and surface water across 750 feet of marsh and drainage channel northward from Mormon Point. The flattening of most of the curves between W63g and W64s suggests the freshening effect of the surface water between these two localities. W61g is a 1957 (wet year) duplicate of W23-56g, which contains a high proportion of sodium and chloride. For locations, see plate 3; analyses are given in table 52.

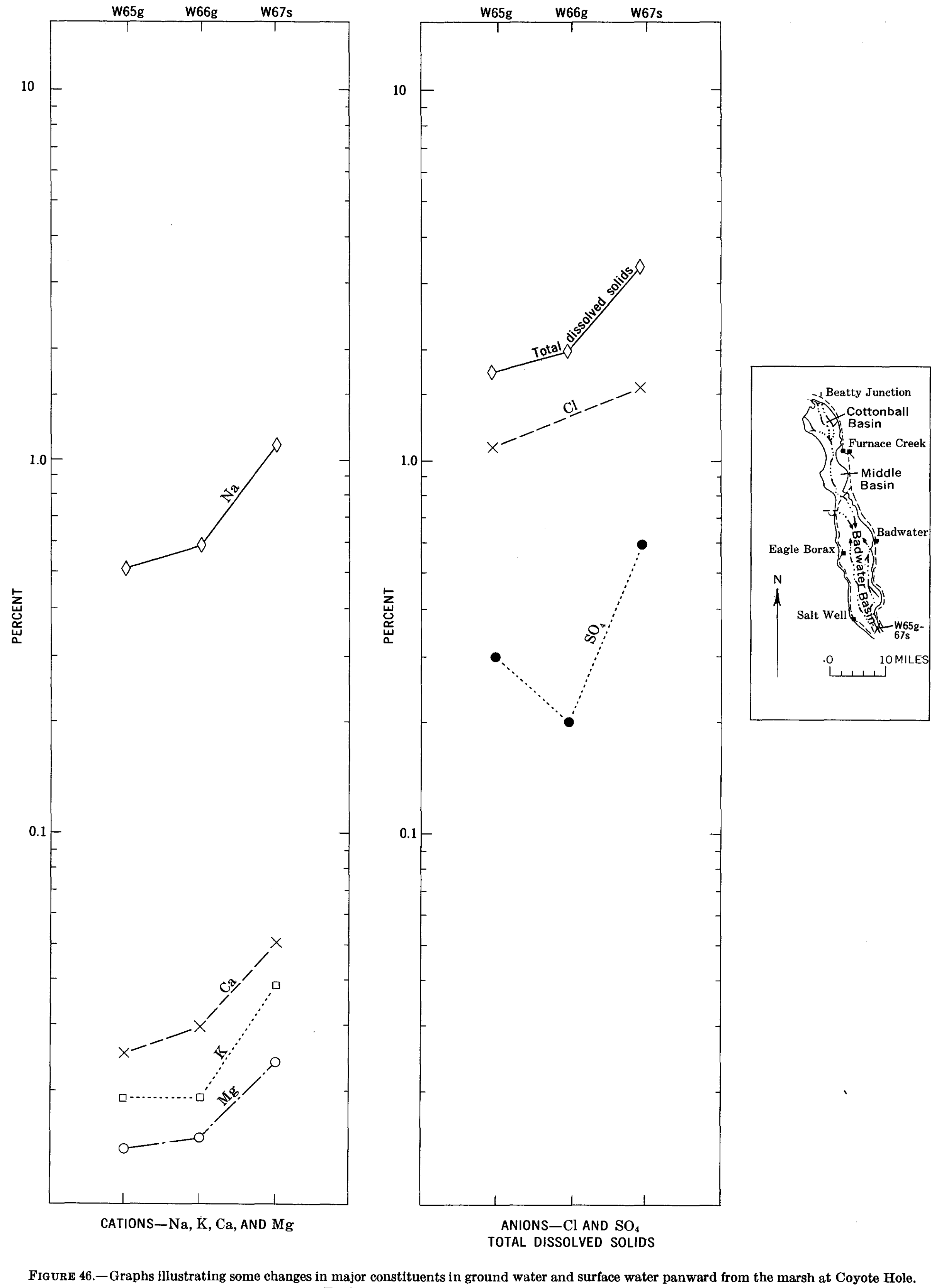

FIGURE 46.—Graphs illustrating some changes in major constituents in ground water and surface water panward from the marsh at Coyote Hole. For locations, see plate 3; analyses are given in table 52.

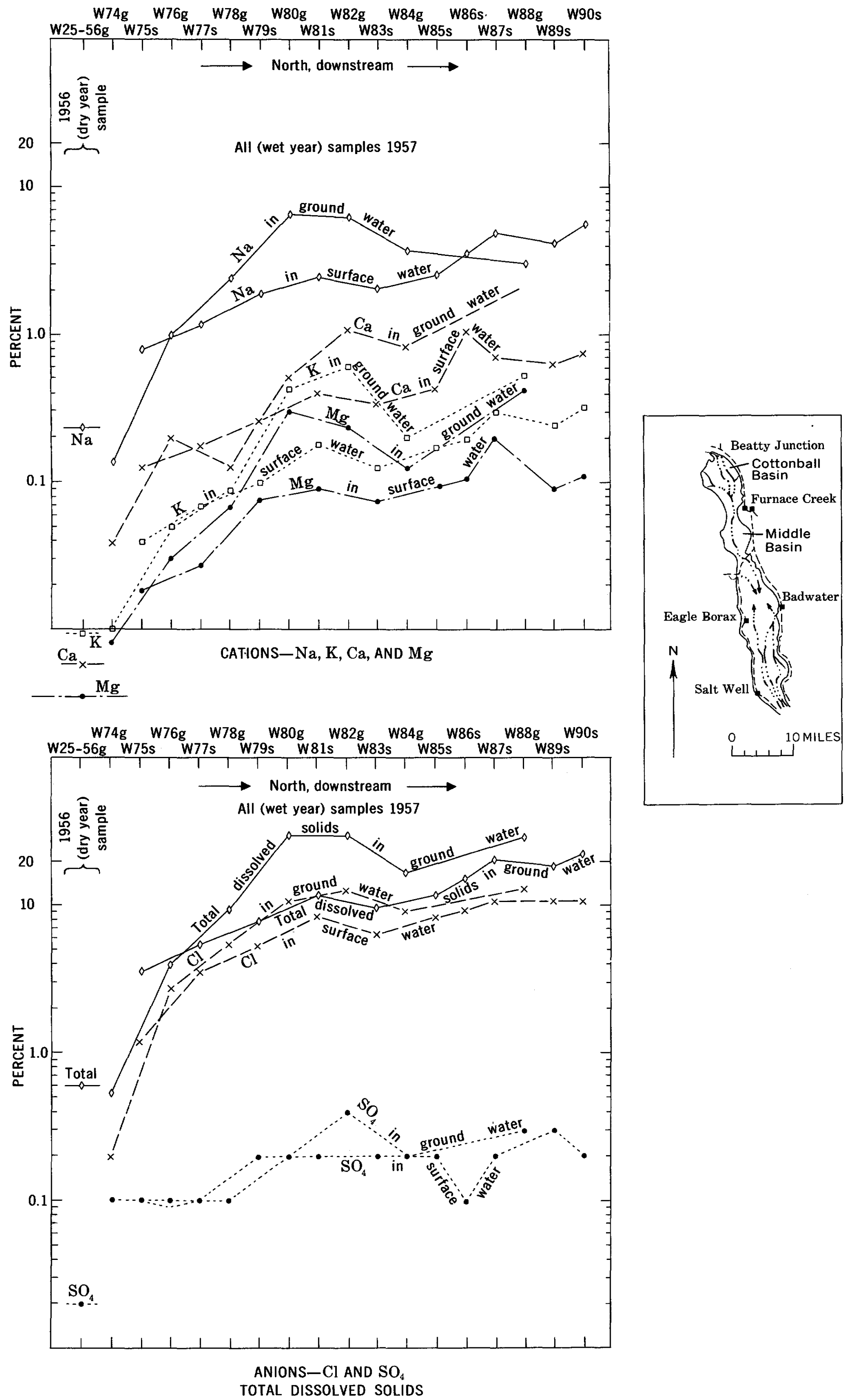

FIGURE 47.—Graphs illustrating some changes in major constituents in ground water and surface water from Salt Well northward for 3 miles into the saltpan. The proportions of the anions and of the cations remain fairly constant, although the amounts increase greatly downstream. Also, the proportions are alike in both the ground water and surface water, although the amounts differ. For locations, see plate 3; analyses are given in table 52.

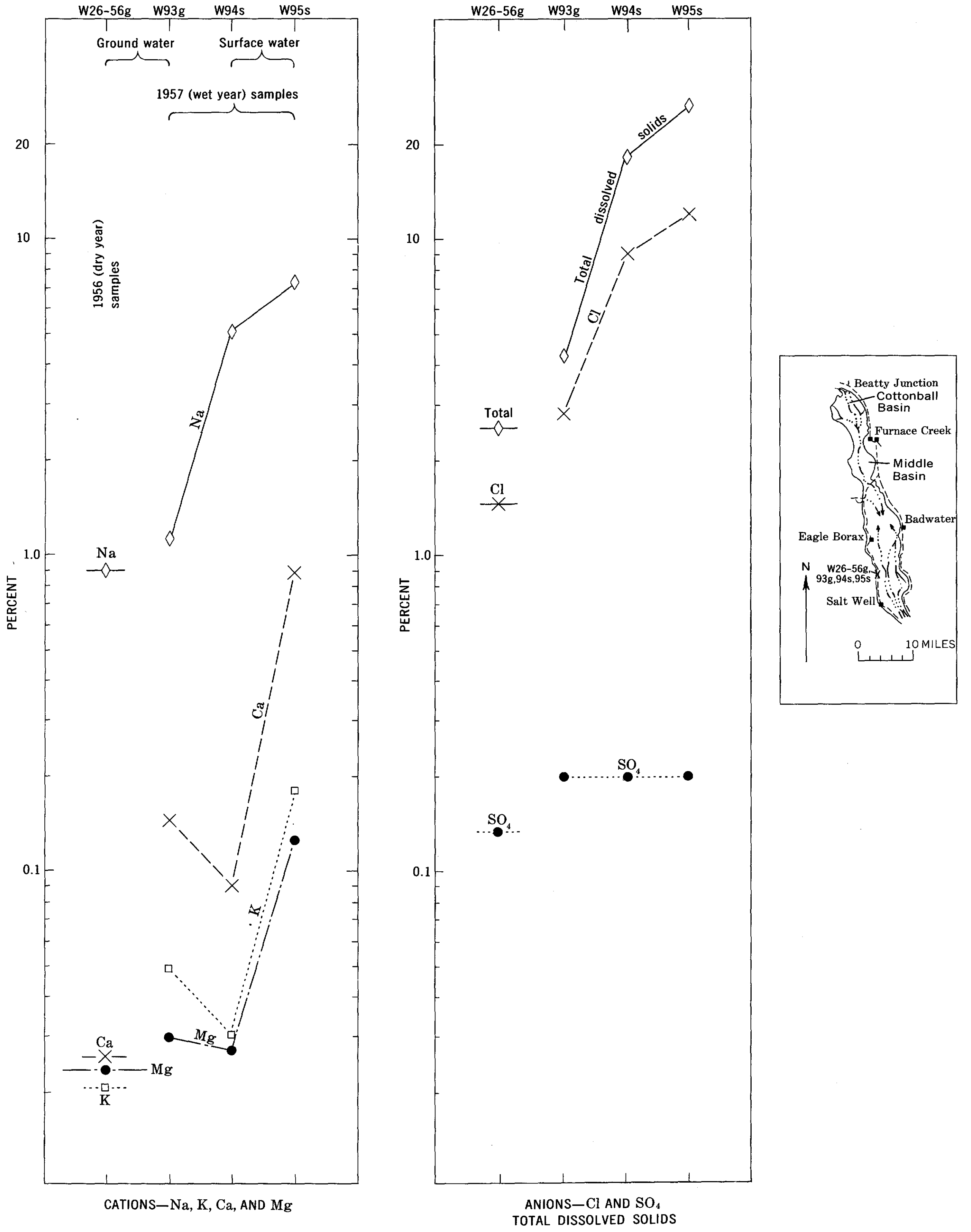

FIGURE 48.—Graphs illustrating some changes in major constituents in ground water and surface water at the marsh half a mile east of Gravel Well, and eastward 4,000 feet into the saltpan. The proportion of sodium and of chloride is less in the marsh than in the saltpan. For locations, see plate 3; analyses are given in table 52.

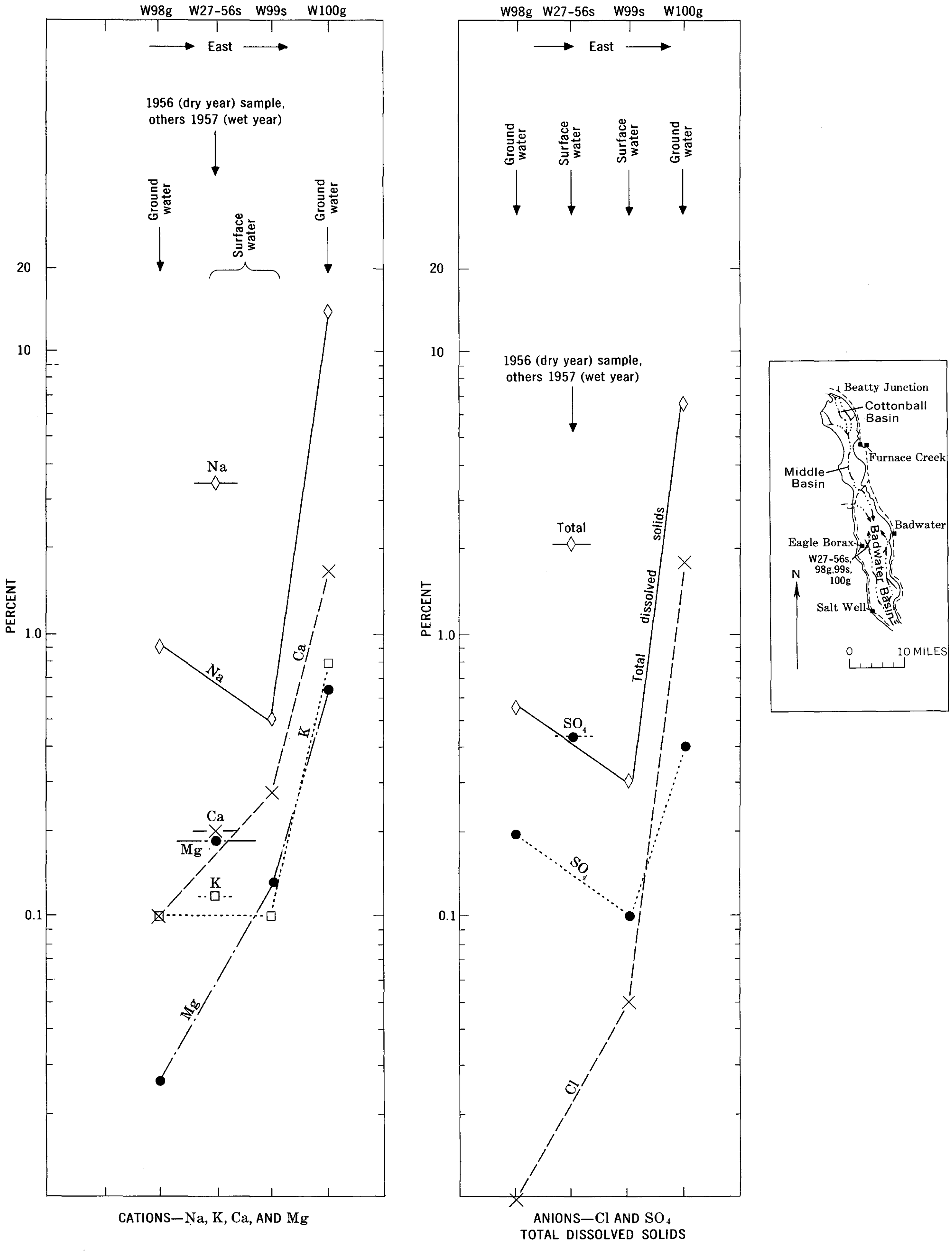

FIGURE 49.—Graphs illustrating some changes in major constituents in ground water and surface water at Eagle Borax Spring and eastward into the saltpan. The ground water at Eagle Borax Spring has little chloride compared to ground water to the east, yet the proportions of the cations are about the same in each. For locations, see plate 3; analyses are given in table 52.

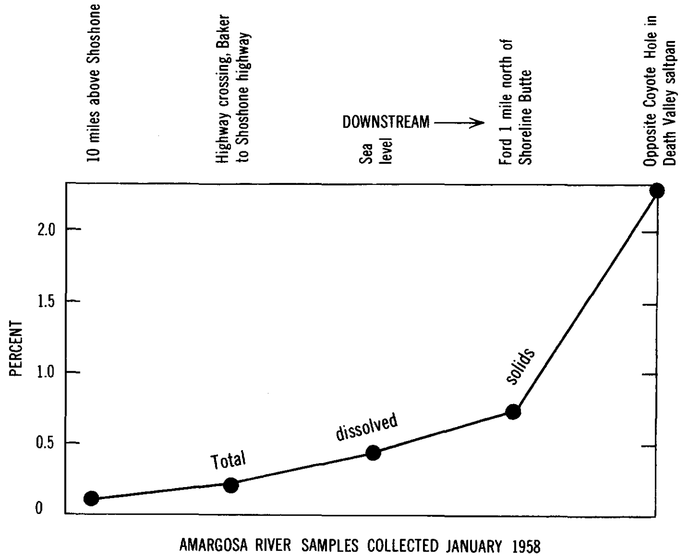

FIGURE 50.—Total dissolved solids in samples of water collected from Amargosa River in January 1958 when the river was flowing continuously from above Shoshone to the saltpan.

SOURCES OF THE SALT

Salts comprising the crust on the saltpan have been derived from 8,700 square miles of hydrologic basin that drains to the pan. There must have been at least four major sources of the salts: part must have been contributed from the atmosphere; part must have been derived from weathering of the rocks and transportation of the soluble constituents to the saltpan; part must have been contributed by volcanic emanations during the periods of vulcanism; and part has been brought into the hydrologic basin by warm springs, which apparently derive their water from surrounding basins that are higher (p. B38; see also Hunt and Robinson, 1960). I assume that losses due to wind erosion are offset by gains from other nearby saline basins to the windward.

The saltpan covers about 200 square miles, and the salt crust on it averages probably 1 foot thick. This crust therefore contains roughly 128,000 acre-feet of salts, of which sodium chloride is by far the chief constituent.

The concentration of salts in the precipitation in the Death Valley region is not known. Several tests of snow on the Panamint Range and other nearby mountains indicated chloride concentrations of about 5 ppm. This figure agrees well with some general figures that have been published (Rankama and Sahama, 1950, p. 318), but it is four to five times greater than some more recent measurements (Junge and Werby, 1958).

If rainfall in the hydrologic basin averages 4 inches per year, the total rainfall is 1,700,000 acre-feet of water. If this averages about 2 ppm of salts, there is annually added to the basin roughly 3.5 acre-feet of salts, practically all of which in due time moves either as surface water or ground water to the Death Valley saltpan. To this amount would have to be added the amounts supplied by the warm springs and the amounts derived from weathering of all rocks and solution of salts from the volcanic rocks. These latter quantities are unknown, but evidently the supply of salts from the several sources is more than adequate to provide, since Pleistocene time, all the salts that form the crust on the Death Valley saltpan.

FRACTIONAL CRYSTALLIZATION OF DEATH VALLEY BRINES

By CHARLES B. HUNT and WALTER A. BOWLES

The changes in composition of the brines entering Death Valley, as described in the preceding section, are the result of changes in the physical and geochemical environment of the brines as they move from one part of the saltpan to another. To help clarify understanding of what happens to different kinds of brines in Death Valley, eight samples of water from various locations around the saltpan were collected and evaporated in the laboratory, and the residues were analyzed to determine the sequence of salts obtained by gradual evaporation of each brine. The analyses are given in table 37. The data suggest that the chemical systems represented in the field only locally are complicated by mixing of brines or by recycling of salts.

Samples of 5 or 10 liters were collected in polyethylene bottles and shipped to Denver for analyses by Bowles.

The laboratory procedure for evaporation of the water samples was to place 2,000 ml of the brine in a large evaporating dish, which was placed under a battery of infrared lamps. The distance between lamps and surface of water was adjusted to maintain a surface temperature of 40°–45° C.

The mother liquor was separated by decanting from deposited crystals after evaporating to approximately 100, 50, and 5 ml, and the final paste to dryness. Samples of the crystal growths from rim to center of dish were removed, weighed, and set aside for mineralogical identification. The residues were then removed from the dishes, and a total dried weight established.

The percent of total solids obtained by evaporating 100 ml aliquot of each brine sample showed that only a small loss of residue resulted from transfer steps, and that the dried weights of the residues were in agreement for subsequent calculations. The residues of this independent evaporation were retained for additional study.

The brines and residues were analyzed by the methods described on pages B90–B91. Results of the analyses along with the weights of each residue fraction are shown in table 37. The column headed "Percent

TABLE 37.—*Semiquantitative analyses of waters and of the residues obtained by evaporating them*

[Analyses by Walter A. Bowles. In percent of the dissolved solids in the original sample and in percent of each residue]

	A. Salt Creek						B. Northeast corner Cottonball Basin					
	Original sample 2,000 ml		Residue after evaporating to—				Original sample 2,000 ml		Residue after evaporating to—			
	Percent wt:volume (of solution)	Percent wt:wt (of residue)	75 ml	50 ml	5 ml	Dryness	Percent wt:volume (of solution)	Percent wt:wt (of residue)	70 ml	40 ml	7 ml	Dryness
Ca [1]	0.013	0.8	3.6	1.6	0.48	0.64	0.007	0.32	0.80	0.80	0.48	0.16
Mg [1]	.034	2.1	2.2	.19	1.6	6.3	.007	.38	.24	.29	.10	.48
K [2]	.056	3.0	2.5	1.3	3.0	9.2	.13	4.5	2.5	2.3	8.4	9.6
Na [2]	.53	30	30	37	38	18	.96	32	40	40	33	32
CO_3 [3]	--------	1.8	2.4	1.9	1.4	1.4	--------	2.6	2.6	1.5	1.2	1.8
SO_4 [4]	.24	16	13	8	18	26	.31	13	7	8	25	20
Cl [4]	.78	44	39	52	39	28	1.3	40	51	52	33	35
Total dissolved solids [6]	1.73	--------	--------	--------	--------	--------	2.8	--------	--------	--------	--------	--------
Total	--------	97.7	92.7	101.99	101.48	89.54	--------	92.80	104.14	104.89	101.18	99.04
Weight of residue	--------	--------	5.38	8.72	16.84	2.55	--------	--------	25.37	10.58	14.93	3.23

	C. Cow Creek				D. Thermal Spring at West Side Borax Camp					
	Original sample 2,000 ml		Residue after evaporating to—		Original sample 2,000 ml		Residue after evaporating to—			
	Percent wt:volume (of solution)	Percent wt:wt (of residue)	25 ml	Dryness	Percent wt:volume (of solution)	Percent wt:wt (of residue)	85 ml	40 ml	6 ml	Dryness
Ca [1]	0.001	0.16	1.2	0.64	0.025	1.4	6.4	1.6	0.80	0.16
Mg [1]	.004	.48	.20	.10	.009	.86	.72	.29	.19	2.0
K [2]	.04	3.2	2.3	4.5	.035	2.28	2.0	.8	2.3	7.3
Na [2]	.41	31	37	37	.46	31	30	40	41	30
CO_3 [3]	--------	3.4	2.4	4.0	--------	2.4	5.8	2.8	1.8	2.0
SO_4 [4]	.29	26	28	1.5	.12	9	.5	8.0	9.0	18
Cl [4]	.32	28	24	28	.61	49	41	53	52	35
Total dissolved solids [6]	1.15	--------	--------	--------	1.35	--------	--------	--------	--------	--------
Total	--------	92.24	95.10	75.7	--------	95.94	86.42	106.49	107.09	94.46
Weight of residue	--------	--------	12.98	10.17	--------	--------	7.10	6.29	10.40	2.78

	E. Badwater						F. Mormon Point					
	Original sample 2,000 ml		Residue after evaporating to—				Original sample 2,000 ml		Residue after evaporating to—			
	Percent wt:volume (of solution)	Percent wt:wt (of residue)	100 ml	55 ml	6 ml	Dryness	Percent wt:volume (of solution)	Percent wt:wt (of residue)	120 ml	60 ml	5 ml	Dryness
Ca [1]	0.12	2.7	5.6	0.64	0.32	0.16	0.32	3.8	3.6	1.4	6.4	19
Mg [1]	.02	.58	.20	.10	.39	2.3	.10	1.8	.48	.58	4	4.8
K [2]	.08	1.8	1.0	.8	3.3	11.0	.20	2.5	1.3	1.3	8.4	2.8
Na [2]	1.4	32	33	40	38	25	2.3	29	33	38	17	1
CO_3 [3]	--------	2.2	.8	.2	1.2	1.8	--------	1.4	2.6	2	3	1.8
SO_4 [4]	.33	10	13	11	10	24	.16	5	6	4	13	7.5
Cl [4]	2.1	45	44	53	48	34	4.3	50	52	50	48	48
Total dissolved solids [6]	4.2	--------	--------	--------	--------	--------	8.1	--------	--------	--------	--------	--------
Total	--------	94.28	97.60	105.74	101.21	98.26	--------	93.5	98.98	97.28	99.8	84.9
Weight of residue	--------	--------	46.60	14.93	16.45	3.21	--------	--------	115.83	17.18	19.93	4.58

See footnotes at end of table.

TABLE 37.—*Semiquantitative analyses af waters and of the residues obtained by evaporating them*—Continued

	G. Salt Well						H. Bennetts Well			
	Original sample 2,000 ml		Residue after evaporating to—				Original sample 2,000 ml		Residue after evaporating to—	
	Percent wt:volume (of solution)	Percent wt:wt (of residue)	80 ml	45 ml	5 ml	Dryness	Percent wt:volume (of solution)	Percent wt:wt (of residue) [5]	55 ml	Dryness
Ca [1]	0.042	5.6	7.6	7.2	3.5	10.0	0.005	--	16.8	8.4
Mg [1]	0.14	2.4	1.9	2.2	1.7	5.6	.002	--	3.6	6.5
K [2]	.008	1.32	1	1	.8	2.5	.0002	--	.4	.6
Na [2]	.15	25	25	28	35	13	.004	--	8.5?	16
CO_3 [3]	--	(5)	(5)	(5)	1.6	1.8	--	--	(5)	(5)
SO_4 [4]	.04	5	3	10	9	7.5	.009	--	16	25
Cl [4]	.34	54	52	55	56	45	.01	--	25	41
Total dissolved solids [6]	.64	--	--	--	--	--	.04	--	--	--
Total	--	93.32	90.5	103.4	107.6	85.4	--	--	70.3?	97.5
Weight of residue	--	--	3.71	1.70	4.98	2	--	--	.32	.34

[1] Ca and Mg determined by wet chemical methods.
[2] K and Na determined by flame photometer.
[3] CO_3 determined by gas liberation method.
[4] SO_4 and Cl determined by wet chemical methods.
[5] Insufficient sample for analysis.
[6] Total dissolved solids determined separately and only approximates total in column.

wt:volume (of solution)" shows the values determined for the waters as received in the laboratory, and are expressed in grams of ion per 100 ml of brine. The residue of the separate 100 ml aliquot mentioned in the preceding paragraph was also analyzed. These values are tabulated in the column headed "Percent wt: wt (of residue)" and are expressed in grams of ion per 100 grams of residue.

The analyses of the samples used in this study do not agree in detail with the other semiquantitative analyses of nearby samples reported in tables 50 and 52. Some reasons for these discrepancies are differences in locations of samples, times of collecting, methods of concentrating, and methods of analysis. Each set of determinations is reasonably consistent within itself, but the two sets are not interchangeable.

On the basis of the ratio of sulfate to chloride, the water samples can be considered in 3 classes: in 1 sample (C) the sulfate equals the chloride; in 5 samples (A, B, D, E, and H) the chloride exceeds sulfate by 3, 4, or 5 to 1; in 2 samples (F, G) the chloride exceeds the sulfate by 10 to 1. (See table 37.)

Several generalizations can be made about the differences in proportions of the individual anions and cations in the brines at different stages of drying. Chloride is the principal anion, and its proportion changes but little, or decreases slightly as the solution evaporates. The proportion of sulfate, with one exception (C), is greater in the final residue than in the original water. The carbonate content in the samples remained surprisingly constant, perhaps because CO_2 became absorbed from the air as the brine was evaporated.

Of the cations, sodium is the principal constituent and commonly exceeds the sum of all the others by a factor of 5. With one exception (F), its curve nearly parallels that of the chloride.

In the final residues in most of the samples, the percentage of sodium is less than in earlier residues, but the proportion of sodium to chloride is slightly greater than in the original sample. This suggests either that an anion other than those considered here (probably a borate) is present, or that some of the sodium in the later residues occurs as sulfate or carbonate. This latter possibility seems unlikely because the solubility of both the sulfate and carbonate of sodium is greatly reduced by the presence of sodium chloride (p. B51). Further, the sodium curve approaches the chloride curve in the samples from Cottonball Basin (A–D), where borates are known to be plentiful.

The other alkali, potassium, is most abundant in the final residues in all but one sample tested (F). Most, if not all, of it precipitates as sylvite, the chloride.

The alkaline earths, calcium and magnesium, are less than the potassium in the waters in Cottonball Basin (A–D), but equal or exceed the potassium in samples from Badwater Basin (E–H). With one exception (C) the magnesium is greater in the final residues than in the original sample, and it occurs there, no doubt, as both chloride and sulfate. The calcium generally is at a maximum in one of the early residues, and generally is at a minimum in the final residue. However, in two samples (F and G) the proportion of calcium is greatest in the final residue.

To varying degrees these changes in composition of precipitates obtained by laboratory drying of the brines resemble or depart from the changes in composition of the natural brines as they move from one part of the saltpan to another.

As Salt Creek moves into Cottonball Basin its salinity increases from 1.6 to 13 percent (fig. 38), and its composition changes to about the same degree and in about the same way as it did (sample A) under laboratory conditions. It may be inferred, therefore, that along the stretch of Salt Creek represented on figure 38 there is little mixing with water from other sources and little recycling of salts.

Sample B from the northeast corner of Cottonball Basin gave a succession of residues different from those found in the brines under field conditions. Figure 39 shows an increase in the sodium and potassium panward as the concentration of the brines increases. Under laboratory conditions potassium increased but slightly, and the sodium remained nearly constant. This difference in reaction of the brines in the laboratory from what is observed in the field is consistent with what is known about the local geology, because brines moving southwestward into the saltpan from Salt Springs become mixed with brines moving southward from the sulfate marsh at the North Side Borax Camp. In the brines at the sulfate marsh the proportion of alkalis to alkaline earths is much higher than in the brines at Salt Springs (compare W5s and W6g with W7g and W8g, table 50).

The sample from Cow Creek (C) on the east side of Cottonball Basin contains 1.15 percent dissolved solids and is unique among those studied in having equal amounts of sulfate and of chloride. It is unique, too, in having less sulfate in the final residue than in the original sample, and it is unusual in having very little magnesium in the final residue. As the sample was dried to 25 ml (table 37) the sulfate remained about equal with the chloride, but in the final residue, chloride exceeds sulfate by 20 to 1. The change in proportions of chloride to sulfate and of alkalis to alkali earths as the laboratory brine was evaporated is similar to the change observed in the brines in the field (compare fig. 40 with table 37).

Other brines in the area of this sample that contain less than 1 percent of dissolved solids (see, for example, W19g and W20g, table 50) have sulfate greatly in excess of the chloride, by a factor of 2 to 1 or more. It might be supposed, then, that the sample represented by (C) was derived by fractional crystallization of a sulfate water.

The sample from the thermal spring at the West Side Borax Camp (D) also yielded residues whose changes in composition parallel the differences found in the composition of brines collected from the marsh and channel draining eastward from the spring (compare fig. 42 and table 37). The increase of potassium and magnesium with respect to calcium, and the increase of sulfate in later residues in the laboratory series, are paralleled by similar increases in the more panward brine samples collected in the filed.

The sample from Badwater (E) contains about the same proportions of anions as does the sample from Salt Creek (A), but differs in having a higher proportion of calcium. Nevertheless, the final residues from these two brines are about the same. The sulfate about equals the chloride, the proportion of sodium is down slightly, and the magnesium and potassium greatly exceed the calcium.

The increased proportion of sulfate in the evaporation of this brine and the decrease in the proportion of calcium and sodium contrast with the increased proportions of chloride, calcium, and sodium that were found in a series of samples collected panward from the cove south of Badwater (fig. 44). It may be inferred that in that part of the valley the brines moving panward become mixed with increasingly saline brines, presumably some seeping northward from the southern part of the saltpan. The lateral variation in the brines entering the pan from the east side evidently cannot be attributed to simple evaporation and increased concentration of the brines from the east side marshes and springs.

In the sample from the marsh at Mormon Point (F) the proportion of anions remained about the same in all the residues, but the precipitate from the 5 ml of brine and the final residue show a surprising decrease in amount of sodium and equally surprising increase in amount of calcium. Petrographic studies of the residues showed that in the first residues from the brine the calcium sulfate crystallized before the sodium sulfate. This is expectable, but in the last residues the sodium sulfate crystallized before the calcium sulfate. Gypsum was a final precipitate from this brine.

This unexpected sequence of precipitates was obtained also in the residues from evaporation of brine from Salt Well (G). These two brines have slightly more calcium and slightly less sodium than do the other brines that were tested, but otherwise they show no obvious differences. We are not aware that these samples were treated any differently from the others, either as to intensity of heat or rate of drying. Moreover, it is a fact that gypsum is common in those parts of the Death Valley saltpan where calcium exceeds 1 percent of the total dissolved solids; thenardite is the common sulfate where the calcium is less than 1 percent of the dissolved solids. On the other hand, the sample from Badwater (E) contains almost 3 percent calcium in the dissolved solids, but much or most of the calcium sulfate in that sample was precipitated in the first residues. The Badwater brine differs from the one at Mormon Point and at Salt Well in having a high ratio of sulfate to chloride.

The solubility of calcium sulfate supposedly is little affected by the presence of sodium chloride (p. B51), yet the samples that gave high calcium sulfate in the final residues also show a decrease in sodium and presumably of sodium chloride.

FRACTIONAL CRYSTALLIZATION ILLUSTRATED BY SOME OTHER BRINES AND SOME OTHER SALT DEPOSITS

The orderly differences in composition of the salt deposits in different parts of the saltpan in Death Valley, the orderly changes in composition of the brines as they move panward, and the orderly sequence of salts obtained by artificial drying of the brines all reflect the well-established differences in solubility of the different salts. Although there are exceptions, some of them inexplicable, the general sequence is—

1. Carbonate of calcium, magnesium, and, to a lesser extent, of sodium;
2. Sulfate of calcium and sodium;
3. Chloride of sodium; and
4. Chlorides of magnesium, potassium, and calcium, and sulfate of magnesium.

This same general sequence is derived from other waters that differ markedly in composition from those in Death Valley. Table 38 presents analyses of some lake waters and brines from other basins in the Basin and Range province. Using Clarke's classification of waters (1924, p. 157–180), these can be grouped as follows (analyses numbers are from table 38):

Saline-----
- Chloride water: Great Salt Lake (1, 2, 19)
- Chloro-sulfate water: Sevier Lake (3), Searles Lake (18)
- Sulfate-chloride water: Utah Lake

Alkaline---
- Carbonate water: Lake Tahoe (5), Black Lake (11), and Malheur Lake (15)
- Carbonate-chloride water: Pyramid Lake (6), Owens Lake (10), Summer Lake (12), Abert Lake (13), Harney Lake (14), Humboldt Lake (16)
- Triple waters: Walker Lake (7), Large Soda Lake (8), Mono Lake (9).

The great differences in the analyses illustrate that in an arid region, such as the Basin and Range province, the relative abundance of anions and cations in water is highly variable. The variation depends on the position within a particular drainage system; on the season, source, rate of flow, and contamination by earlier salt deposits; and on whether the water occurs as ground water or surface water.

In most of the waters entering the saltpan in Death Valley, the order of abundance of anions and cations is $Cl > SO_4 > CO_3$ and $Na > Ca > Mg$. In ocean water the order of abundance of the anions is the same, but $Na > Mg > Ca$. Analyses published by Clarke (1924, p. 76–83) indicate that in humid regions, like central and eastern United States, the order of abundance of the anions commonly is the opposite, $CO_3 > SO_4 > Cl$. In large part this must be due to the organic carbon contributed by the abundant vegetation. The relative abundance of sodium and magnesium varies, but both are exceeded by calcium.

A sample of the waters entering Searles Lake, near Death Valley (No. 18, table 38), was studied by Hicks (1917), who analyzed the salts deposited during evaporation of that brine. The sequence of changes in composition of the salts and brines as a result of that evaporation are illustrated graphically on figure 51.

Despite the fact that the Searles Lake sample contains two or three times as much carbonate as does the average water in Death Valley, the sequence of residues differs only in detail. When reduced to 50

TABLE 38.—*Major constituents, in percent, in lake water and brines from basins other than Death Valley*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Cl	58.0	55.48	52.66	26.87	3.18	41.04	23.77	35.38	23.34	25.40	7.68	18.27	36.23	30.40	4.55	31.82	55.29	36.36	53.36
SO_4	2.5	6.68	10.88	30.14	7.47	5.25	21.29	10.50	12.86	9.89	13.24	4.18	1.91	8.62	7.64	3.27	7.69	12.86	6.70
CO_3	.0	.09	.00	8.48	38.73	14.28	17.34	15.89	23.42	22.70	37.73	35.57	20.82	19.77	44.63	21.57	.20	7.72	.44
Na	35.0	33.17	33.33	18.34	10.10	33.84	34.83	35.38	37.93	37.83	39.05	39.48	38.78	39.43	24.17	29.97	30.59	33.66	34.85a
K	1.8	1.66	-------	1.75	4.56	2.11	-------	2.13	1.85	2.09	2.03	1.59	1.69	1.50	5.58	6.54	1.11	6.17	3.53
Ca	.9	.16	.12	5.34	12.86	.25	.90	-------	.04	-------	-------	Trace	Trace	.03	5.58	1.35	1.20	-------	(a)
Mg	1.2	2.76	3.01	6.85	4.15	2.28	1.56	.21	.10	-------	-------	Trace	Trace	Trace	4.13	1.88	3.73	-------	-------
Total	99.4	100.00	100.00	97.77	81.05	99.05	99.69	99.49	99.54	97.91	99.73	99.09	99.43	99.75	96.28	96.40	99.81	96.77	(b) 98.88
Salinity (percent)	------	20.35	8.64	0.12	73 ppm	0.35	0.25	11.37	5.12	11.88	1.85	1.66	2.96	2.24	484 ppm	929 ppm	3.3–3.7	34.04	0.59

1. Composite sample of brine from Great Salt Lake Desert, Utah; analyst, J. G. Fairchild (Nolan, 1927, p. 39).
2. Great Salt Lake, Utah; analyst, R. K. Bailey (Clarke, 1924, p. 157).
3. Sevier Lake, Utah; analyst, Oscar Loew (Clarke, 1924, p. 158).
4. Utah Lake, Utah; by B. E. Brown, 1904 (Clarke, 1924, p. 158).
5. Lake Tahoe, Calif.; analyst, F. W. Clarke (Clarke, 1924, p. 160). Almost 19 percent of the salinity in this sample is SiO_2.
6. Pyramid Lake, Nev.; mean of 4 concordant analyses by Clarke (Clarke, 1924, p. 160).
7. Walker Lake, Nev.; mean of 2 analyses by Clarke (Clarke, 1924, p. 160).
8. Large Soda Lake, Ragtown, Nev.; analyst, T. M. Chatard Clarke, 1924, p. 161).
9. Mono Lake, Calif.; analyst, Chatard (Clarke, 1924, p. 162).
10. Owens Lake, Calif.; analyst, W. B. Hicks (Clarke, 1924, p. 162).
11. Black Lake, near Benton, Calif.; analyst, Oscar Loew (Clarke, 1924, p. 162)
12. Summer Lake, Oreg.; analyst, Van Winkle (Clarke, 1924, p. 163).
13. Abert Lake, Oreg.; analyst, Van Winkle (Clarke, 1924, p. 163).
14. Harney Lake, Oreg.; analyst, Van Winkle (Clarke, 1924, p. 163).
15. Malheur Lake, Oreg.; analyst, Van Winkle (Clarke, 1924, p. 163).
16. Humboldt Lake, Nev.; analyst, O. D. Allen (Clarke, 1924, p. 161).
17. Mean of 77 analyses of ocean water from many localities, collected by the *Challenger* expedition; analyst, W. Dittmar (Clarke, 1924, p. 127).
18. Composite sample of brine from wells at Searles Lake, Calif. (Hicks, 1917, p. 2).
19. Columbus Marsh, Nev. Sample of water in well 23 ft below surface. (a) small amount of calcium included with sodium; (b) balance given as B_4O_7. From Hicks, 1916, p. 9.

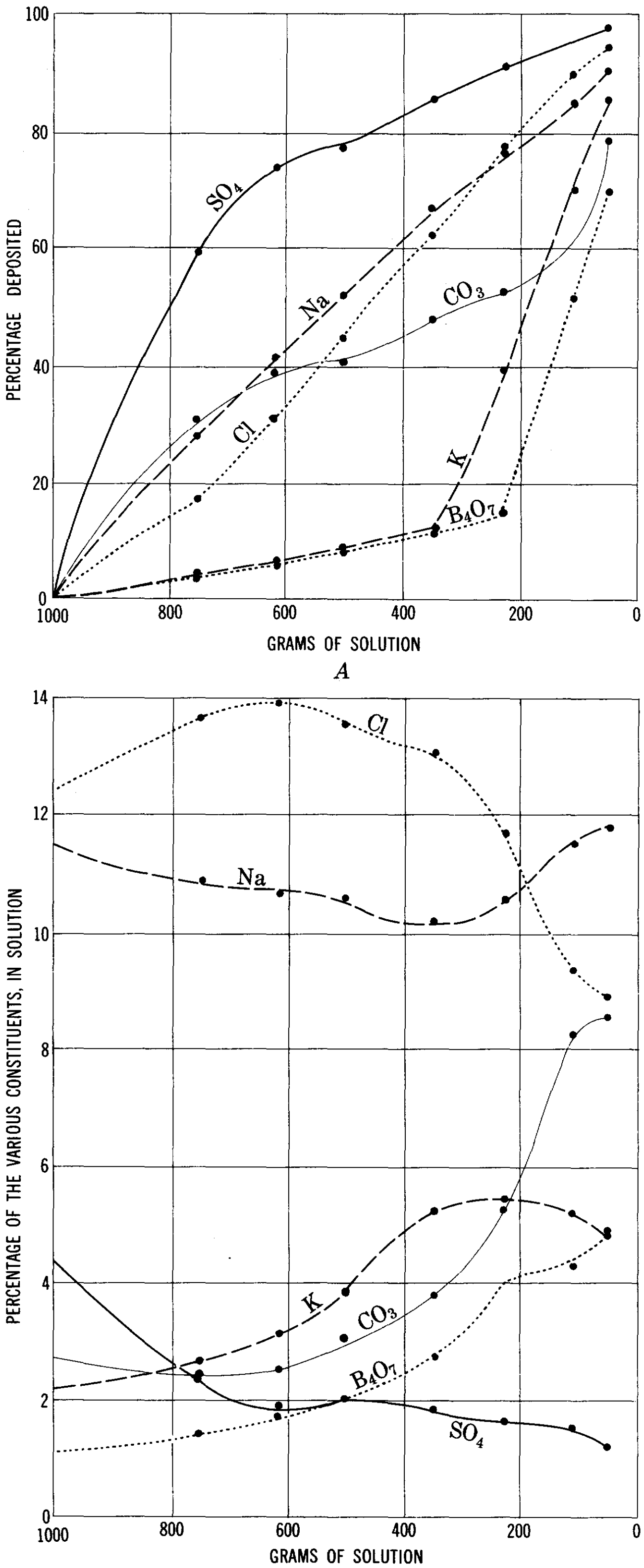

FIGURE 51.—Results of evaporation of brine from Searles Lake, Calif. *A*, Diagram showing percentages of various constituents deposited during evaporation of brine from Searles Lake. *B*, Diagram showing changes in composition of the solution resulting from evaporation of brine from Searles Lake. Adapted from from Hicks, 1917, p. 4, 5.

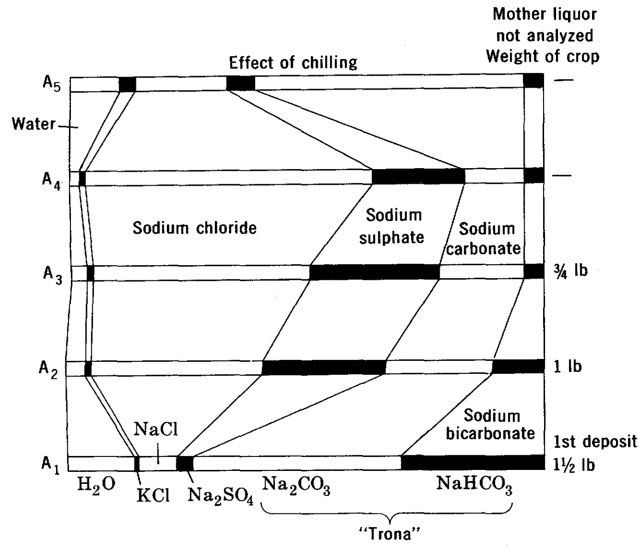

FIGURE 52.—Diagram illustrating graphically the results of Chatard's experiments with the evaporation of water from Owens Lake, Calif. A_1 to A_4 are the successive crops of salts obtained by Chatard as a result of evaporation of the brine at temperatures in the range of 77° to 96°F; A_5 is the crop obtained by chilling the remaining liquid of A_4 to 57°F. Adapted from Gale, 1915, fig. 75.

percent of its original weight, the Searles Lake brine had precipitated about 75 percent of its sulfate, about 50 percent of its sodium, chloride, and carbonate, and about 10 percent of its potassium and borate. When reduced to a quarter of its original weight, the brine still contained about 75 percent of its potassium and borate, a little less than 50 percent of its carbonate, about 25 percent of its sodium and chloride, and about 10 percent of its sulfate.

Fractional crystallization of salts from carbonate-chloride water is illustrated by the experiments of Chatard (1890) at Owens Lake, 50 miles west of Death Valley (see also Gale, 1915). The successive crops of salts that he obtained are illustrated on figure 52.

Upon evaporation of these high-carbonate waters there first develop crystals of trona with small excess of the normal carbonate, some chloride, and some sulfate. In the next three crops the carbonates diminish, but the normal carbonate is even more in excess over the bicarbonate, deposition of sodium sulfate is at a maximum, and the chlorides increase rapidly. The final chilled solution deposits chiefly sodium carbonate, with some chloride, and less sulfate. The order of deposition is trona, sodium sulfate, sodium chloride, and finally, the normal carbonate.

Great Salt Lake, a chloride brine, illustrates how seasonal changes in temperature affect the crystallization of salts. During winter months the lake deposits hydrated sodium sulfate, mirabilite ($Na_2SO_4 \cdot 10H_2O$), and redissolves this sulfate during the summer (Adams, 1938; Clarke, 1924, p. 234). At low temperatures the hydrous form is not very soluble (fig. 18). Seasonal effects in Death Valley are similar (p. B51).

The lacustrine formations of the Lake Bonneville group in the Great Salt Lake basin contain very small amounts of water-soluble salts, yet despite their small quantity even these salts are arranged in carbonate, sulfate, and chloride zones (Hunt and others, 1953, p. 31–34).

In the Great Salt Lake desert west of Great Salt Lake are brines as concentrated as those in Death Valley. These brines (Nolan, 1927) increase in salinity toward the center of that saltpan, and the environment of the brines changes from a carbonate zone at the edge to a chloride zone with a crust of rock salt at the center. In other words, in the Lake Bonneville basin, the same general zoning of salts is found whether they occur in abundance or in small amounts.

One of the first, if not the first, study of fractional crystallization of brines was by Usiglio, who, in 1849, investigated the order of separation of salts from evaporation of sea water (Clarke, 1924; see also Phillips, 1947). His results, which are of much historical interest, are given in table 39.

Usiglio's experiments showed that when sea water is evaporated to about 50 percent of its original volume, calcium carbonate begins to precipitate. When the the volume has been reduced to 15–20 percent of the original amount, calcium sulfate separates. Sodium chloride and the magnesium compounds do not separate until the volume has been reduced by about 90 percent. Unlike the Death Valley brines (table 37), the last bitterns from the evaporation of sea water contain no calcium but they contain more magnesium than sodium. Also, Usiglio's experminets showed that the solubilities of salts varied with changes in temperature; cooling of the concentrated solution from day to night was sufficient to precipitate magnesium sulfate which was partly redissolved the following day (Clarke, 1924, p. 221).

The Dead Sea also is a chloride water, but it is low in sodium and high in magnesium, whereas the Jordan River at Jericho is a carbonate-chloride water that is high in calcium (table 40). The decrease in proportion of carbonate to chloride and the decrease in proportion of calcium to sodium between the River Jordan and Dead Sea are like the changes in proportions of these constituents in waters entering Death Valley.

Fractional crystallization like that in Death Valley but in a very different environment is illustrated by the deposits and seasonal changes in equilibrium at Karaboghaz Gulf, on the east side of the Caspian Sea. This gulf frequently is cited as an example of how thick deposits of salts may accumulate in lagoons or estuaries back of partly submerged bars (Ochsenius, 1877; Chilingar, 1956a). The gulf is cut off from the Caspian Sea by a long partly submerged bar across which there is flow into the gulf, but evaporation there is great enough to prevent a return current. As a result, the salinity of the gulf is steadily increasing.

According to Grabau (1924, p. 354) and Clarke (1924, p. 168), calcium sulfate is being deposited near the margins of the gulf; sodium sulfate is being deposited in the central part. Moreover, the sodium sulfate is deposited only during winter months, for at summer temperatures the brine is unsaturated. In cold weather it is saturated with respect to sodium sulfate, but not for the chloride.

The composition of water in the Caspian Sea and Karaboghaz Gulf, as given by Clarke (1924, p. 169), is shown in table 41.

An environment and sequence of evaporite deposits not unlike those at Karaboghaz Gulf have been described at an estuary on the coast of northwestern Peru (Morris and Dickey, 1957). The estuary, about 20 km long and 2 km wide, receives little fresh-water inflow, but there is recharge from the ocean to replace water lost by evaporation. The total dissolved solids increases to 35 percent at the head, and "as precipitation of calcium

TABLE 39.—*Order of separation of salts from sea water, in grams per liter*

[Adapted from Usiglio, generalized after Clarke, 1924, p. 220]

Density	Volume	Fe_2O_3	$CaCO_3$	$CaSO_4 \cdot 2H_2O$	NaCl	$MgSO_4$	$MgCl_2$	NaBr	KCl
1.026	1.00	------	------	------	------	------	------	------	------
1.050	.53	0.003	0.064	------	------	------	------	------	------
1.104	.24	------	Trace	------	------	------	------	------	------
1.126	.19	------	.053	0.560	------	------	------	------	------
1.160	.14	------	------	.562	------	------	------	------	------
1.173	.13	------	------	.184	------	------	------	------	------
1.201	.11	------	------	.160	------	------	------	------	------
1.214	.09	------	------	.051	3.261	0.004	0.008	------	------
1.221	.06	------	------	.148	9.650	.013	.036	------	------
1.236	.04	------	------	.070	7.896	.026	.043	0.073	------
1.257	.03	------	------	.014	2.624	.017	.015	.036	------
1.278	.02	------	------	------	2.272	.025	.024	.052	------
1.307	.02	------	------	------	1.404	.538	.027	.062	------
Total deposit	------	0.003	0.117	1.749	27.107	0.623	0.153	0.223	------
Salts in last bittern	------	------	------	------	2.588	1.854	3.164	.330	.534
Total	------	0.003	0.117	1.749	29.69	2.477	3.317	0.553	0.534

TABLE 40.—*Chemical analyses, in percent, of water from Dead Sea and River Jordan*

[Adapted from Clarke, 1924, p. 170–171]

	A	B		A	B
Ca	10.67	1.68	Cl	41.47	67.84
Mg	4.88	16.72	Other	3.40	1.75
K	1.14	1.79			
Na	18.11	10.00	Total	100.00	100.00
CO_3	13.11	Trace	Salinity (percent)	0.77	25.11
SO_4	7.22	.22			

A. Jordan River, at Jericho.
B. Dead Sea, selected as representative analysis from several given by Clarke (1924, p. 170).

TABLE 41.—*Composition of water in Caspian Sea and Karaboghaz Gulf*

[Adapted from Clarke, 1924, p. 169]

	Caspian Sea	Karabo-ghaz Gulf		Caspian Sea	Karabo-ghaz Gulf
Cl	41.78	50.26	Ca	2.60	.57
Br	.05	.08	Mg	5.77	7.07
SO_4	23.78	15.57			
CO_3	.93	.13	Total	100.00	100.00
Na	24.49	25.51	Salinity		
K	.60	.81	(percent)	1.267	16.396

carbonate, calcium sulfate, and sodium chloride takes place successively, the relative concentration of these ions decreases while other ions such as magnesium, potassium, and sulfate increase" (Morris and Dickey, 1957; for a review of evaporite deposition in estuaries, see Scruton, 1953).

Probably the best known and most complete sequence of salt deposits in the world is that at Stassfurt, Germany, which were the subject of intensive and extensive studies during the early 1900's (see Van't Hoff and others, 1912; for summaries, see Clarke, 1924, p. 223; Mellor, 1952a, p. 430; Lindgren, 1928, p. 354). Much that is known about the solubilities and other properties of salts, and as exemplified in Death Valley, developed from studies of the Stassfurt deposits 50 years ago.

The salts are of Late Permian age and are overlain by Triassic sandstone and limestone. The general section is given in table 42.

TABLE 42.—*Stratigraphic section of salt deposits at Stassfurt, Germany*

[Adapted from Clarke, 1924, p. 223; Lindgren, 1928, p. 355; Mellor, 1952a, p. 430]

Top. Glacial drift, about 8 m thick.

Younger series:

1. Red clay with a little anhydrite and rock salt; 20–30 m thick.
2. Rock salt; 50 m thick.
3. Anhydrite with salt; 1–5 m thick.
4. Red clay with anhydrite and rock salt; 5–15 m thick.
5. Younger rock salt; thickness variable, commonly about 100 m thick.
6. Main anhydrite (hauptanhydrit); 30–80 m thick.
7. Salt clay; 5–10 m thick.

Older series:

8. Carnallite zone: 55 percent carnallite, 25 percent rock salt, 16 percent kieserite, 4 percent other; locally overlain by kainite and this in turn, by a mixture of sylvite and rock salt; thickness as much as 40 m.
9. Kieserite zone: 65 percent rock salt, 17 percent kieserite 13 percent carnallite, 3 percent bischofite, 2 percent anhydrite; thickness as much as 40 m.
10. Polyhalite zone: 92 percent rock salt, 6 percent polyhalite, 1 percent anhydrite, 1 percent bischofite; as much as 60 m.
11. Older rock salt, with layers of anhydrite 2–10 cm thick, interpreted as annual deposits; thickness 300-500 m.
12. Older anhydrite and gypsum; thickness 100 m.

TABLE 42.—*Stratigraphic section of salt deposits at Stassfurt, Germany*—Continued

13. Aechstein limestone or dolomite, a marine deposit; 4–10 m thick.
14. Kupferschiefer and Zechstein conglomerate; 0.5–4 m thick.

Base. Lower Permian and Carboniferous beds.

Conditions of deposition of these salts probably resembled those at Karaboghaz Gulf, but there may have been recharge from fresh-water affluents to provide the calcium sulfate. Michigan salt deposits also include interbedded sodium chloride and calcium sulfate (Dellwig, 1955; Briggs, 1958).

Clarke (1924, p. 227) contrasts the sequence of salts in the older series, which closed with deposition of potassium salts, with the sequence obtained by artificial evaporation of sea water as follows:

> In the latter case a moderate quantity of water is concentrated by itself; at Stassfurt more water was continually added from the ocean. On the one hand calcium sulfate is deposited almost wholly at one time; on the other new quantities were precipitated so long as the evaporating bay retained its connection with the sea. In the salt pan gypsum forms a bottom layer before salt begins to separate out; at Stassfurt anhydrite is found in greater or less amount through all the zones, and so also is the sodium chloride.

A very different chemical system is illustrated by the Chilean nitrate deposits in the Atacama and Tarapaca deserts. The deposits are on pediments and fan gravels flanking basins between uplands; many of the basins are salt flats (salares) containing little nitrate. The deposits consist of crude sodium nitrate or "caliche" associated with rock salt and are referred to as "calicheras." A section of a calichera in the Atacama Desert shows (Clarke, 1924, p. 255):

Section of typical calichera in Atacama Desert, Chile

Surface.	Ft	In
1. Sand and gravel	-----	1–2
2. Porous earthy gypsum	-----	6
3. Compact earth and stones	2–10	-----
4. "Costra," a low-grade caliche, containing much sodium chloride, feldspar, and earthy matter; considerable bloedite	1–3	-----
5. "Caliche" (in the Tarapaca Desert it is 4–12 ft thick)	1½–2	-----
6. Clay	-----	3±
Base.		

The composition of the caliche varies widely; its content of $NaNO_3$ ranges from about 20 to 60 percent.

The occurrence of nitrates in Death Valley (Noble, Mansfield, and others, 1922; Noble, 1931) in some ways resembles those in Chile. Both occur in caliche and are located on the hills, pediments, and fan gravels flanking saltpans having little or no nitrates, and both are in areas characterized by borate deposits and volcanic rocks. The chief resemblance between these nitrate deposits, however, is in the mystery surrounding their origin. Noble (1931, p. 239) has outlined a

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dozen hypotheses by which the deposits in the Death Valley region may have formed.

SEMIQUANTITATIVE CHEMICAL ANALYSES OF SALTS AND BRINES IN DEATH VALLEY

The analyses of salts and brines, given in tables 43–52 (p. B91–B103), were made by U.S. Geological Survey analysts by rapid semiquantitative methods; these methods are useful for obtaining a general picture, but they are not designed to give precise quantitative data.

Most of the major constituents—Ca, Mg, K, Na, CO_3, and Cl—were determined on an acid-soluble fraction; the determined cations commonly do not balance the anions, including SO_4. Some of the discrepancy is because the analyses are incomplete. For example, where there is much boron, which was not determined among the major constituents, an excess of the cations is to be expected. This excess is especially noticeable in table 49, which shows several samples with 1 percent or more of boron; in all these samples there is a large excess of cations. Except in such samples containing large amounts of boron, the lack of balance does not exceed 20 percent. Lack of balance also probably may be due partly to acid leaching of cations from clays, and possible leaching of anions from alumina and other bases.

The lack of balance is not erratic but shows some orderliness. As noted, where much boron is present, the analyses show an excess of cations. Where much sodium sulfate is present, the cations generally exceed the anions, probably because of some interference in the analytical method. Where there is much sodium chloride, the anions and cations nearly balance.

The following description of the analytical methods was supplied by H. W. Lakin.

Calcium and magnesium determination.—In most of the salt samples (tables 43–49), determination was by the Schwarzenbock method, as follows: To 20 ml of 1+3 hydrochloric acid, 0.5 gram of the sample was added and the mixture was heated for 5–10 minutes. The cool solution was filtered, if necessary, then diluted with water to 100 ml. The determinations were made by a modification of the versene titration of Schwarzenbock. Cal red was used as an indicator for calcium and EBT for magnesium. The determinations given on tables 43–49 were by H. M. Nakagawa. In a few salt samples (table 46) and in all water samples (tables 50–52), semiquantitative spectrographic methods were used; these determinations were by Uteana Oda.

Sodium and potassium determination.—To 0.25 gram of sample, 10 ml of 1 to 1 hydrochloric acid were added; after the mixture was digested on a steam bath for 30 minutes, it was diluted with water to 250 ml. The estimation was made with a flame photometer, using a wave length of 594 mμ for sodium and 778 mμ for potassium. These determinations on both salt and brine samples were by W. A. Bowles.

Chloride determination.—In the water analyses for 1957, chloride was determined by turbidimetric method. All other water and salt samples were analyzed for chloride by the Mohr method, as follows: To 50 ml of 5 percent nitric acid (weight/volume), 0.2 gram of sample was added. The mixture was heated to the boiling point, cooled, and diluted with water to 100 ml. The solution was then titrated with silver nitrate in the presence of potassium chromate. At the end point, the excess silver reacts with the chromate to provide a color indicator when viewed under yellow light. Chloride determinations on the salt samples (tables 43–49) were by H. M. Nakagawa. Chloride determinations on water samples for 1956 were by H. E. Crowe; determinations for 1957 were by E. F. Cooley.

Sulfate determination.—A mixture of 0.1 gram of sample and 0.5 gram of flux (5 parts sodium carbonate, 4 parts sodium chloride, and 1 part potassium nitrate) was fused over a burner. About 10 ml of water were added to the cooled fusion, and the containing tube was placed in a boiling-water bath for about 15 minutes. The solution was centrifuged, and the supernatant liquid diluted to 100 ml with water. The sulfate was estimated by the method of Fritz and Yamamura, in which the cations are removed by an ion-exchange column and the sulfate determined by titration with barium perchlorate, using thorin as an indicator. Sulfate determinations on both salt and brine samples were by E. F. Cooley. The determinations made on the salt samples includes total sulfate—not just the acid soluble fraction.

Carbonate determination.—Carbon dioxide was liberated from the 0.2-gram sample with 6*N* hydrochloric acid and measured in an apparatus for the gasometric determination of carbon dioxide similar to that described in "Official Methods of Analysis of the Association of Official Agricultural Chemists," 7th ed., 1950, page 118. These determinations were by C. E. Thompson and H. E. Crowe. The carbonate and bicarbonate content of the brines was not determined.

Other constituents, listed in the tables as minor constituents, were determined by semiquantitative spectrographic methods, by Uteana Oda, analyst. A. Tennyson Myers, of the U.S. Geological Survey, furnished the following description of this method.

In the semiquantitative spectrographic method, 10 mg of the sample is mixed with 20 mg of graphite powder and then burned in a controlled direct-current arc. The spectrum is recorded on film in a 1.5-meter grating spectrograph. Selected lines on the film are visually compared with those of standard spectra by means of an enlarging comparator. The standard films are prepared in a similar manner to the sample films, using standard mixtures of materials containing about 33 elements but resembling the unknowns in gross composition. The concentrations of these elements were chosen so that they increase from 1 to 10,000 ppm (1 percent) by a factor of the cube root of 10 or about 1, 2.2, 4.6, 10, etc., ppm. The standards thus form a series having three subdivisions for each order of magnitude. According to whether a spectral line of one element in the sample matches the intensity of a corresponding line of a standard or falls between the intensities of two standards, the estimated concentration is reported using approximate figures from the series (in ppm) 1, 1.5, 2, 3, 5, 7, 10, etc.

In addition to the minor constituents reported in the salt samples in tables 43–49, other elements looked for, but *not found* (except as noted otherwise on the tables), with limits of detection (in ppm), in parentheses, are as follows: As (1,000), Ag (1), Bi (10), Cd (50), Co (10), Cb (20), In (20), Mo (10), Pb (10), Sb (500), Sc (20), Se (2), Sn (20), and Zn (500).

Whereas the major constituents were determined on an acid-soluble fraction, the minor constituents were determined on the total sample. The analyses of the two groups of constituents therefore are not directly comparable.

In the water analyses (tables 50–52) the boron and strontium were determined by semiquantitative spectrographic methods, by Uteana Oda, analyst. A maximum of 10 ppm of Ba, Ti, Mn, and Mo was determined in the water samples.

Total dissolved solids and pH of water samples for 1956 were determined in the field by Charles B. Hunt; determinations for 1957 were by E. F. Cooley.

Evaporite salt minerals listed for the salt samples on tables 43–49 were identified by J. B. Droste, of the University of Indiana, by scanning X-ray patterns of the bulk samples of the mixed salts. Calcite and dolomite were identified in most samples, but these constituents are not listed in the tables because most of the calcite and dolomite is detrital. Other common clastic grains are quartz, feldspar, mica, chlorite, and various clay minerals, the last being the subject of a special study by Droste.

TABLE 43.—*Semiquantitative partial analyses, in percent, of the sand facies of the carbonate zone*

[Analysts and analytical methods given on pages B90–B91. Salt samples, S series, collected January–March 1956; localities shown on pl. 3]

Major constituents in acid-soluble fraction

	Cottonball Basin											Middle Basin								
	All layers						Caliche layer					All layers			Caliche layer					
	S1	S4	S5	S15	S30	S53	S2	S3	S17	S20	S55	S59	S61	S69	S94	S60	S62	S63	S70	S79
Ca	2.2	2.1	5.0	4.6	6.5	7.6	1.1	0.5	2.9	4.5	21.	8.3	7.5	4.5	6.4	5.1	5.9	7.0	2.4	19
Mg	.9	1.3	1.9	1.9	2.2	4.1	.8	.4	1.4	1.5	1.4	3.0	2.3	1.4	3.4	1.8	3.6	2.4	.9	1.1
K	.3	.2	.8	.4	.3	.3	.3	.2	.6	.5	.1	.4	.4	.2	.3	.3	.7	.5	.1	.2
Na	1.0	1.3	.80	.79	4.4	3.5	17	28	18	16	1.3	1.1	1.9	13	14	7.2	6.8	1.9	24	.6
CO_3	2.2	2.8	6.2	6.6	11	14	1.6	.6	13	5.2	2.2	9.0	11	4.6	11	6.0	8.0	9.0	.4	.4
SO_4	2.4	6.7	3.8	2.2	3.4	4.1	25	34	26	30	37	2.1	4.9	14	3.9	16	11	3.9	34	46
Cl	5.8	2.4	6.6	8.2	7.0	7.2	4.4	3.8	3.0	2.4	.64	10	13	10	20	6.0	1.8	9.6	3.0	2.4
Total	14.8	16.8	25.1	24.7	34.8	40.8	50.2	67.5	64.9	60.1	63.6	33.9	41.0	47.7	59.0	42.4	37.8	34.3	64.8	69.7

Minor constituents in total sample

	S1	S4	S5	S15	S30	S53	S2	S3	S17	S20	S55	S59	S61	S69	S94	S60	S62	S63	S70	S79
B	0.1	0.05	0.1	0.7	0.2	0.19	0.1	0.7	0.7	0.03	0.7	0.2	0.5	0.15	0.007	0.2	0.7	0.7	0.3	0.03
Ti	.3	.3	.15	.15	.5	.3	.15	.03	.07	.1	.02	.15	.2	.15	.07	.15	.1	.2	.05	.03
V	.007	.01	.007	.01	.01	.01	.005	.001	.007	.003	.001	.015	.015	.005	.005	.015	.01	.015	.002	.001
Mn	.07	.07	.05	.07	.05	.05	.05	.005	.05	.05	.005	.1	.07	.03	.03	.07	.07	.1	.01	.015
Ni	.003	.002	.001	.001	.003	.0005	.001	<.0005	.0005	.0005	<.0005	.003	.003	.0005	.0005	.0015	.002	.002	<.005	<.0005
Sr	.02	.1	.15	.03	.015	.03	.03	.015	.03	.05	.5	.15	.15	.02	.03	.07	.1	.1	.07	.1
Ba	.03	.05	.02	.02	.02	.03	.02	.007	.015	.02	.005	.05	.05	.015	.02	.03	.03	.05	.015	.015
Cu	.005	.005	.003	.0015	.003	.003	.0015	.0002	.001	.003	.0001	.001	.001	.003	.007	.0015	.001	.0015	.003	.0002
Cr	.003	.015	.005	.005	.005	.003	.003	.001	.002	.003	<.001	.015	.01	.002	.002	.007	.005	.007	.0015	.001

See footnotes at end of table.

TABLE 43.—*Semiquantitative partial analyses, in percent, of the sand facies of the carbonate zone*—Continued

Major constituents in acid-soluble fraction—Continued

	Badwater Basin																
	Mixed layers								Caliche layer			Layers separated					
	S100	S103	S125	S127	S131a [1]	S132	S135	S156	S104	S111a	S126	S141	S148a	S148b	S148c	S148d	S148e
Ca	3.5	4.3	5.0	5.9	1.3	2.7	3.5	2.0	17.0	15.0	14.0	1.5	5.0	5.0	7.5	5.0	3.5
Mg	1.6	2.1	2.5	1.7	1.4	1.8	2.1	1.2	1.2	2.3	1.1	.5	.7	.5	.7	.5	2.0
K	.3	.42	.6	.5	.4	.5	.3	.3	.2	.2	.3	.5	.3	.2	.2	.2	.3
Na	2.2	2.2	2.4	.8	4.4	15	4	9	.2	.2	13	.3	.3	.3	.9	.8	1.6
CO_3	4.6	4.7	6.0	2.2	.4	3.6	5.9	1.6	1.0	2.6	.6	3.8	4.8	1.4	2.4	3.0	3.4
SO_4	3.9	4.2	4.4	8.6	6.1	8.7	3.8	6.4	38	26	32	5.0	6.2	12	12	12	3.7
Cl	2.0	2.1	2.6	3.5	7.2	16	7.0	13.0	.8	.5	20	.1	1.0	.4	.6	.6	1.4
Total	18.1	20.0	23.5	23.2	21.2	48.3	26.6	33.5	58.4	46.8	81.0	11.7	18.3	19.8	24.3	22.1	15.9

Minor constituents in total sample—Continued

	S100	S103	S125	S127	S131a [1]	S132	S135	S156	S104	S111a	S126	S141	S148a	S148b	S148c	S148d	S148e
B	0.3	0.10	0.05	0.15	0.2	0.5	0.1	0.2	0.0075	0.15	0.05	0.005	0.005	0.002	0.01	0.0075	0 02
Ti	.3	.3	.3	.5	.2	.1	.2	.5	.2	.15	.15	.1	.2	.075	.35	.2	.5
V	.007	.007	.003	.01	.01	.007	.007	.01	<.001	<.001	.002	.003	.003	<.002	.003	.002	.005
Mn	.07	.07	.07	.07	.07	.07	.07	.07	.05	.05	.015	.05	.05	.015	.03	.02	.07
Ni	.003	.003	.0005	.001	.0015	.0005	.0015	.002	<.0005	<.0005	<.0005	.0005	.001	<.0005	.0005	.0005	.001
Sr	.07	.05	.2	.07	.03	.05	.03	.03	.07	.05	.15	.02	.05	.1	.1	.05	.03
Ba	.03	.02	.03	.05	.03	.02	.03	.02	.015	.01	.01	.03	.03	.015	.03	.03	.03
Cu	.007	.005	.005	.007	.003	.002	.003	.003	.0005	--------	.0003	--------	--------	--------	--------	--------	--------
Cr	.005	.005	.003	.003	.003	.002	.003	.003	.001	--------	.001	--------	--------	--------	--------	--------	--------

NOTE.—Description of sample and locality as follows:

S1. Carbonate zone, damp sand under the caliche layer. 750 ft southeast of bench mark 241, E½ sec. 11, T. 16 S., R. 46 E. (compare with S2). Evaporite minerals include halite and meyerhofferite.

S2. Caliche layer in carbonate zone at S1. Evaporite minerals include thenardite and halite.

S3. Caliche layer in carbonate zone, 6 in. thick, SE¼ sec. 11, T. 16 S., R. 46 E. Evaporite minerals include thenardite, halite, and borax(?).

S4. Sand in carbonate zone, underlies the caliche layer. SW¼ sec. 12, T. 16 S., R. 46 E. Evaporite minerals include halite.

S5. Wet sand containing carbonate salts; 1 ft below caliche layer and 2 ft below surface at old borax workings. W½ sec. 17, T. 28 N., R. 1 E. Evaporite minerals not determined.

S15. Sand; has 15 ppm Mo. 1,000 ft west of State Route 190, SE¼SE¼ sec. 9, T. 27 N., R. 1 E. Evaporite minerals include probertite and meyerhofferite(?).

S17. Has 50 ppm Mo and 2 ppm Se. Caliche layer ½–3 in. below surface. NW¼NE¼ sec. 20, T. 27 N., R. 1 E. Evaporite minerals include thenardite.

S20. Caliche layer. SE¼SE¼ sec. 20. T. 27 N., R. 1 E. Evaporite minerals include thenardite.

S30. Sand; has 2 ppm Se; by west side jeep trail 2 miles southeast of West Side Borax Camp. Evaporite minerals include halite.

S53. Top 10 in. including thin salt crust; by west side jeep road. NE¼ sec. 20, T. 16 S., R. 46 E. Evaporite minerals include halite and meyerhofferite.

S55. Caliche layer, at furrow mine workings. NE¼NW¼ sec. 16, T. 16 S., R. 46 E. Evaporite minerals include probertite, bassanite, anhydrite, and halite.

S59. Furnace Creek fan. SW¼NE¼ sec. 28, T. 27 N., R. 1 E. Evaporite minerals include probertite.

S60. Has 8 ppm Se. Caliche layer. Furnace Creek fan; S½ sec. 28, T. 27 N., R. 1 E. Evaporite minerals include thenardite.

S61. Has 20 ppm/Mo. Furnace Creek fan. SW¼ sec. 28, T. 27 N., R. 1 E. Minerals not determined.

S62. Caliche layer and 0.5 in. overlying layer of silt at toe of Furnace Creek fan. SE¼SE¼ sec. 29, T. 27 N., R. 1 E. Evaporite minerals include thenardite and meyerhofferite(?).

S63. Has 20 ppm Mo. Caliche layer 6–14 in. below surface. Furnace Creek fan SE¼SE¼ sec. 28, T. 27 N., R. 1 E. Evaporite minerals include halite and probertite.

S69. Sand and silt opposite Desolation Canyon, SW¼NE¼ sec. 10, T. 26 N., R. 1 E. Evaporite minerals include thenardite and halite.

S70. Caliche layer, 1–3 in. thick in 1 in. below surface. Opposite Desolation Canyon. NW¼SE¼ sec. 10, T. 26 N., R. 1 E. Evaporite minerals include probertite, thenardite, and halite.

S79. Caliche layer, under gravel composed of basaltic and other volcanic rocks, adjacent to, but mountainward from, the carbonate zone of the saltpan. NW¼ sec. 27, T. 26 N., R. 1 E. Evaporite minerals include bassanite.

S94. Caliche layer and salt crust on sand, 0.4 mile northwest of SW. cor. of sec. 19, T. 26 N., R. 1 E. Evaporite minerals include halite and meyerhofferite.

S100. Carbonate zone 500 ft west of toe of gravel of Artists Drive fan, 1 mile southeast of road across valley; NW¼NW¼ sec. 35, T. 26 N., R. 1 E. Shown on map as saline facies. Evaporite minerals include some probertite and gaylussite(?)

S103. Carbonate zone 500 ft west of toe of gravel of Artists Drive fan, 1.5 miles southeast of road across valley; SW¼SW¼ sec. 35, T. 26 N., R. 1 E. Shown on map as saline facies. Evaporite minerals include some probertite.

S104. Caliche layer on gravel ridge above the saltpan, opposite entrance to Artists Drive. Evaporite minerals include anhydrite, bassanite, and some halite.

S111a. Caliche, on Recent fault scarp by highway, 1½ miles north of Badwater. Minerals not determined.

S125. Channel sample through 2 ft of sand and clay in prospect pit in carbonate zone at Mormon Point (compare with S126 and S127). Evaporite minerals include halite.

S126. Caliche layer 2 in. below surface of S125. Evaporite minerals include anhydrite, bassanite, and halite.

S127. Top inch only, at S125. Evaporite minerals include anhydrite and glauberite(?).

S131a.[1] Has 15 ppm Mo and 3 ppm Se. Sand, including salt crust and caliche layer. ½ mile southeast of Coyote Hole; E½ sec. 22, T. 22 N., R. 2 E. Evaporite minerals include glauberite.

S132a. Sand, including caliche layer, 1 mile south of Coyote Hole; SE¼ sec. 22, T. 22 N., R. 2 E. Evaporite minerals include halite, thenardite, and meyerhofferite(?).

S135a. Sand, 1 mile north of Salt Well. SE¼NE¼ sec. 2, T. 22 N., R. 1 E. Evaporite minerals include halite.

S141. Reddish surface layer 3 in. thick. 1,000 ft east of road, 3 miles south of Bennetts Well. Clastic grains only.

S148a. At east edge of mesquite; ¼ mile east of Shortys Well; sand 24 in. thick with irregular nodules of hard salt-cemented sand ½–1 in. thick (compare with S148b). Evaporite minerals include gypsum, come probertite, and borax(?).

S148b. Cemented sand in S148a. Evaporite minerals include gypsum and meyerhofferite(?).

S148c. Sand 18 in. thick, damp with soft nodules of sulfate salts; overlies S148a. Evaporite minerals include gypsum, some bassanite, and trace of meyerhofferite.

S148d. Sand 8 in. thick, dry but with the nodules like S148c; overlies S148e. Evaporite minerals include bassanite and gypsum.

S148e. Sand forming surface layer 6 in. thick; surface hummocky but no salt crust; overlies S148d. Evaporite minerals include gypsum and some meyerhofferite.

S156. ½ mile north of Tule Spring. Evaporite minerals include halite and meyerhofferite(?).

TABLE 44.—*Semiquantitative partial analyses, in percent, of the silt facies of the carbonate zone*

[Analysts and analytical methods given on pages B90–B91. Salt samples, S series, collected January–March 1956; localities shown on pl. 3.]

Major constituents in acid-soluble fraction

	S121	S131b	S133	S134	S135b	S136a	S149	S155	S159	S160
Ca	0.5	1.3	2.6	3.4	2.9	2.0	0.64	3.0	5.4	5.4
Mg	1.2	1.2	.8	1.2	1.6	1.5	2.1	1.4	1.6	1.9
K	1.6	0.4	1.3	.6	.4	.5	.6	1.1	.4	.3
Na	20	23	16	14	8.0	.3	13	18	20	18
CO_3	<.2	.2	.42	.4	2.4	4.0	.8	.9	2.1	.3
SO_4	4.7	8.2	7.3	5.6	2.9	2.5	9.0	7.1	19	9.2
Cl	32	34.0	25	26	13	.6	19	26	32	27
Total	60.2	68.3	53.4	51.2	31.2	11.4	45.1	57.5	80.5	62.1

Minor constituents in total sample

	S121	S131b	S133	S134	S135b	S136a	S149	S155	S159	S160
B	0.3	0.15	0.05	0.3	0.3	0.01	0.05	0.1	0.3	0.2
Ti	.1	.07	.1	.07	.3	.1	.3	.3	.02	.3
V	.01	.002	.002	.005	.007	.003	.002	.005	.001	.002
Mn	.07	.02	.02	.05	.05	.05	.02	.05	.003	.03
Ni	.002	<.0005	<.0005	<.0005	.001	.0005	<.0005	<.0005	<.0000	.0005
Sr	.07	.05	.07	.1	.07	.03	.01	.07	.3	.07
Ba	.03	.015	.02	.02	.03	.03	.015	.015	.003	.015
Cu	.007	.002	.001	.001	.0007	----------	.002	.002	.002	.0005
Cr	.007	.001	.001	.0015	.003	----------	.0015	.0015	<.001	.0015

NOTE.—Description of sample and locality as follows:

S121. Salt crust on silty sand, in cove south of Copper Canyon fan. Evaporite minerals include halite and meyerhofferite.

S131b. Salt crust on silty sand, ½ mile south of Coyote Hole. E½ sec. 22, T. 22 N., R. 2 E. Evaporite minerals include halite.

S133. Salt crust on silty sand. NW¼ sec. 27, T. 22 N., R. 2 E. Evaporite minerals include halite and bassanite.

S134. Salt crust on silty sand, 2 miles east of Salt Well; SE¼ sec. 7, T. 22 N., R. 2 E. Evaporite minerals include halite and anhydrite(?).

S135b. Salt crust on silty sand. 1 mile north of Salt Well; NE¼ sec. 2, T. 22 N., R. 1 E. Minerals not determined.

S136a. Channel ½ mile east of Gravel Well; sample of 3 ft of damp sand and silt underlying salt crust. Evaporite minerals include gypsum and meyerhofferite(?).

S149. Salt crust on silty sand. Tule Spring. Evaporite minerals include halite and thenardite.

S155. Salt crust on silty sand. ½ mile north of Tule Spring. Evaporite minerals include halite and anhydrite(?).

S159. Salt crust on silty sand; has 2 ppm Se. 1,500 ft east of junction of West Side Highway and Trail Canyon road. Evaporite minerals include halite and anhydrite(?).

S160. Salt crust on silty sand at Devils Speedway. Evaporite minerals include halite, bassanite, and anhydrite(?).

TABLE 45.—*Semiquantitative partial analyses, in percent, of the saline facies of the carbonate zone*

[Analysts and analytical methods given on pages B90–B91. Salt samples, S series, collected January–March 1956; localities shown on pl. 3. Analyses of samples S25 and S27 show slight excess of anions; in others, cations are in excess by average of 10 percent]

Major constituents in acid soluble fraction

	Cottonball Basin							Middle Basin			
	S8	S25	S27	S45	S52	S57a	S57b	S75	S80	S83	S93
Ca	1.1	2.7	2.1	5.1	3.2	5.1	4.6	4.2	4.2	4.5	6.6
Mg	.5	1.0	.9	2.3	1.2	2.2	3.3	1.8	2.1	2.0	3.0
K	.8	.5	.6	1.5	.9	.4	.7	.4	.7	.3	.6
Na	26	13	21	18	24	12	11	5.9	8.5	17	18
CO_3	5.8	4.2	1.4	7.3	1.5	2.3	7.8	4.6	4.8	5.8	5.6
SO_4	10	7.4	4.7	6.7	15	26	3.4	2.2	3.4	4.3	9.9
Cl	24	19	42	26	31	6	12	8.2	12	28	29
Total	68.2	47.8	72.7	66.9	76.8	54.0	42.8	27.3	35.7	61.9	72.7

Minor constituents in total sample

	S8	S25	S27	S45	S52	S57a	S57b	S75	S80	S83	S93
B	0.7	0.15	0.7	0.7	0.7	1.0	0.2	0.2	0.75	0.05	0.2
Ti	.3	.07	.15	.15	.15	.15	.3	.3	.07	.15	.07
V	.01	.002	.002	.0015	.0015	.005	.003	.01	.007	.005	.005
Mn	.01	.03	.02	.02	.015	.07	.07	.07	.07	.03	.03
Ni	<.0005	<.0005	<.0005	<.0005	<.0005	.0005	.001	.001	.001	.0005	<.0005
Sr	.02	.015	.015	.01	.02	.1	.05	.05	.03	.05	.1
Ba	.015	.015	.015	.015	.01	.015	.03	.03	.02	.015	.015
Cu	.0003	.002	.001	.0005	.0003	.002	.001	.03	.005	.002	.003
Cr	.001	.002	.0015	.0015	.001	.001	.002	.015	.005	.002	.001

NOTE.—Description of sample and locality as follows:

S8. Sand. NE¼ sec. 29, T. 28 N., R. 1 E. Evaporite minerals include halite and thenardite.

S25. Caliche layer. SW¼ sec. 19, T. 17 S., R. 47 E. Evaporite minerals include halite and probertite.

S27. Salt crust on sand. By west side jeep trail, southwest side Cottonball Basin. Evaporite minerals include halite, thenardite, and probertite.

S45. Sand. NE¼ sec. 32, T. 16 S., R. 16 E. Evaporite minerals include halite and probertite.

S52. Caliche layer. NE¼NE¼ sec. 29, T. 16 S., R. 46 E. Evaporite minerals are for the most part halite and thenardite.

S57a. Caliche layer in carbonate zone, SE¼ sec. 15, T. 16 S., R. 46 E. Evaporite minerals include thenardite, halite, and probertite.

S57b. Carbonate zone, layers mixed. SE¼ sec. 15, T. 16 S., R. 46 E. Evaporite minerals include halite, thenardite, and meyerhofferite(?).

S75. Sand in saline facies of carbonate zone, opposite Artists Drive fan. E½ sec. 16, T. 26 N., R. 1 E. Evaporite minerals include halite and probertite.

S80. Sand. By road across valley at north end of Badwater Basin. NW¼ sec. 27, T. 26 N., R. 1 E. Evaporite minerals include halite and probertite.

S83. Sand. NW¼NW¼ sec. 32, T. 26 N., R. 1 E. Minerals not determined.

S93. Salt crust on sand; 1,800 ft northwest of SW. cor. sec. 19, T. 26 N., R. 1 E. Evaporite minerals include halite and anhydrite.

TABLE 46.—*Semiquantitative partial analyses, in percent, of the sulfate zone*

[Analysts and analytical methods given on pages B90–B91. Salt samples, S series, collected January–March 1956; localities shown on pl. 3]

Major constituents in acid-soluble fraction

	Cottonball Basin												
	S13 [1]	S14 [1]	S18	S19	S21	S23	S24	S26	S31	S32	S40	S41	S42
Ca [1]	0.3	0.6	1.6	1.8	3.4	2.5	3.7	12.0	17	3.7	4.2	4.3	15
Mg [1]	.2	.4	.7	.8	1.6	1.8	1.8	1.1	1.0	1.9	1.9	1.5	1.9
K	.2	1.2	.2	1.5	.3	.3	.3	2.0	.4	.3	4.3	.4	.3
Na	33	24	27	26	20	26	10	16	6.6	17	19	16	1.1
CO_3	4	4.8	11	15	9.2	2.0	.8	.3	.6	.9	.2	2.2	3.6
SO_4	25	24	24	32	27	34	22	29	45	13	26	16	30
Cl	17	22	5	3.4	1.8	16	7.0	23	6.4	16	24	14	6.4
Total	79.7	77.0	69.5	80.5	63.3	82.6	45.6	83.4	77.0	52.8	79.6	54.4	58.3
Minor constituents in total sample													
B	0.7	0.7	0.7	0.2	0.015	0.1	0.1	0.7	0.5	0.3	0.7	0.7	0.7
Ti	.015	.2	.05	.05	.07	.3	.02	.05	.03	.2	.05	.2	.2
V	<.001	.007	.002	.005	.005	.001	.007	.002	.001	.005	.001	.003	.002
Mn	.003	.005	.01	.02	.05	.01	.05	.005	.005	.02	.01	.02	.02
Ni	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	.001	<.0005	<.0005	.0005	<.0005	.0005	<.0005
Sr	.015	.03	.03	.02	.05	.07	.01	.5	>1.0	.05	.15	.02	.15
Ba	.002	.007	.01	.01	.015	.01	.03	.005	.003	.02	.007	.01	.01
Cu	<.0001	.003	.0003	.0003	.005	.0003	.01	.0003	<.0001	.0015	.0003	.001	.003
Cr	.001	<.001	.001	.002	.002	<.001	.003	<.001	<.001	.001	<.001	.003	.001

Major constituents in acid-soluble fraction—Continued

	Cottonball basin—Continued									Middle Basin			
	S44	S46	S47	S49	S51	S54a	S54b	S54c	S54d	S78	S92	S95	S99
Ca [1]	7.5	4.2	11	10	5.0	19	3.5	12	6.7	2.9	12	15	10
Mg [1]	1.1	1.5	1.2	.3	1.5	.9	2.6	2.4	5.0	1.5	3.5	2.7	2.0
K	.8	5.0	.9	.3	.4	.7	.6	.4	.4	.3	.7	.3	.3
Na	21	18	17	2.1	2.3	4.2	17	4.2	3.4	6.0	4.8	2.4	3.0
CO_3	2.0	<.2	.2	2.6	2.8	1.5	4.8	6.1	13	1.0	5.0	1.2	1.2
SO_4	21	27	31	38	17	43	16	19	9.2	9.1	21	28	23
Cl	28	25	20	3.5	3.0	2.5	21	4.0	2.1	4.8	9.4	10	4.8
Total	81.4	80.9	81.3	56.8	32.0	71.8	65.5	48.1	39.8	25.6	56.4	59.6	44.3
Minor constituents in total sample—Continued													
B	0.7	>1.0	0.7	0.02	0.5	0.5	0.7	1.0	>1.0	0.5	0.1	0.2	0.05
Ti	.05	.1	.05	.015	.15	.07	.2	.3	.5	.3	.05	.05	.1
V	.0015	.001	<.001	<.002	.003	.001	.002	.005	.007	.005	.001	.002	.007
Mn	.005	.007	.003	<.001	.03	.01	.05	.07	.07	.05	.03	.03	.05
Ni	<.0005	<.0005	.0005	<.0005	.0005	<.0005	.0005	.001	.003	.0005	<.0005	<.0005	.0005
Sr	.5	.5	>1	2.0	.07	.5	.05	.1	.1	.05	.07	.03	.007
Ba	.005	.005	.002	.005	.03	.007	.02	.02	.03	.02	.015	.01	.02
Cu	.0001	.001	.0001	--------	--------	.0002	.002	.005	.005	.005	.002	.001	.01
Cr	<.001	.001	<.001	--------	--------	<.001	.0015	.002	.003	.002	.001	.001	.003

Major constituents in acid-soluble fraction—Continued

	Badwater Basin																
	S105	S109	S110a	S110b	S110c	S111b	S114	S115c	S115d	S116	S117	S119	S122	S123	S124	S130a	S130b
Ca [1]	5.1	17	10	≥10	10	16	14	7.5	7.5	11	20	21	19	9	14	10	7.5
Mg [1]	1.5	1.6	.5	.1	.1	1.4	.4	.7	.75	.2	.6	.6	1.2	1.9	.8	.1	.7
K	.9	.4	.2	.2	.2	.8	.3	.7	.30	.3	.1	.3	.4	1.7	.3	.2	1.0
Na	12	2.7	.1	.7	.8	14	15	.7	1.3	24	4.0	2.3	2.7	10	15	8.8	20
CO_3	.4	.4	1.0	.4	.8	.2	<.2	16.0	1.8	.2	<.2	.4	.6	1.0	.4	.6	.4
SO_4	20	29	37	55	53	31	29	10.0	14.0	22	40	52	49	27	26	41	27
Cl	18	5.6	.6	1.0	1.4	19	24	.8	.8	34	9.2	3.9	3.4	18	25	7.7	14
Total	57.9	56.7	49.4	67.4	66.3	82.4	82.9	36.4	26.4	91.7	74.1	80.5	76.3	68.6	81.5	68.4	70.6
Minor constituents in total sample—Continued																	
B	0.1	0.1	0.005	0.02	0.007	0.2	0.05	0.01	0.02	0.005	0.02	0.05	0.2	0.07	0.05	0.05	0.05
Ti	.1	.05	.07	.005	.01	.02	.015	.1	.07	.007	.007	.05	.03	.05	.03	.015	.07
V	.002	.002	<.002	<.002	<.002	.001	<.001	.003	.002	<.001	<.001	.001	.002	.002	<.001	<.002	.002
Mn	.02	.03	.01	.002	.003	.007	.0015	.07	.03	.001	.003	.007	.015	.03	.003	.003	.01
Ni	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	.0005	<.0005	<.0005	<.0005
Sr	.05	.1	.35	.7	.7	.7	.7	3	.3	1.0	.3	.1	.15	.1	1.0	.7	.35
Ba	.01	.015	.01	.002	.003	.03	.001	.15	.02	.002	.001	.003	.007-	.015	.002	.005	.02
Cu	.001	.001	--------	--------	--------	<.0001	<.0001	--------	--------	.0001	.0001	.0003	.0003	.0005	.0003	--------	--------
Cr	.001	.0015	--------	--------	--------	<.001	<.001	--------	--------	.001	<.001	<.001	.001	.001	<.001	--------	--------

See footnotes at end of table.

TABLE 46.—*Semiquantitative partial analyses, in percent, of the sulfate zone*—Continued

Major constituents in acid-soluble fraction—Continued

	Badwater Basin—Continued																
	S137a	S137b	S137c	S142	S143	S144b	S144c	S144d	S144e	S150a	S150b	S150c	S150d	S150e	S151b	S153 [1]	S157
Ca [1]	10	10	5.0	19	17	10	7.5	7.5	3.5	1.5	7.5	10	>10	10	7.5	10	13
Mg [1]	.3	.2	2.0	1.2	2.2	.5	.7	2.0	2.0	2.0	1.0	.7	.7	.3	.7	.7	2.1
K	.1	<.1	.34	.4	.6	.2	.2	.6	.8	.8	.4	.3	.3	.2	.4	.3	.8
Na	4.9	1.2	.7	4.5	4.5	1.0	.34	.6	.6	1.1	1.4	1.0	7.9	.3	.3	24	15
CO_3	<.2	.2	8.2	.4	.4	<.2	1.0	.4	4.0	.6	0.4	.2	<.2	.2	.8	.4	--------
SO_4	30	37	17	33	36	41	30	17	7.5	5.0	22	36	26	24	15	22	2.3
Cl	3.4	2.4	1.0	6.3	6.5	2.6	1.6	2.2	2.2	2.8	1.8	1.4	5.9	1.4	1.0	35	28
Total	48.9	51.1	34.2	64.8	67.2	55.5	41.3	30.3	20.6	13.8	34.5	49.6	51.0	36.4	25.7	92.4	61.2

Minor constituents in total sample—Continued

	S137a	S137b	S137c	S142	S143	S144b	S144c	S144d	S144e	S150a	S150b	S150c	S150d	S150e	S151b	S153 [1]	S157
B	0.03	0.005	0.02	0.015	0.1	0.03	0.005	0.03	0.02	0.03	0.01	0.01	0.05	0.03	0.01	0.3	0.15
Ti	.01	.007	.05	.05	.15	.02	.03	.1	.15	.2	.07	.05	.07	.03	.1	.015	.1
V	.002	<.002	.003	.001	.001	<.002	<.002	.005	.003	.005	.002	<.002	.002	<.002	.002	<.001	.005
Mn	.001	.001	.015	.007	.01	.005	.007	.07	.07	.07	.03	.01	.01	.007	.03	.003	.07
Ni	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	<.0005	.001	.001	.0015	.0005	<.0005	<.0005	<.0005	.0005	<.0005	.001
Sr	.5	.15	.05	.2	.15	.7	.20	.2	.05	.1	.7	.5	1.0	.7	.2	1.0	.03
Ba	.002	.002	.05	.005	.01	.005	.007	.05	.03	.05	.02	.007	.007	.005	.03	.003	.02
Cu	--------	--------	--------	.0001	.0002	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	.0001	.003
Cr	--------	--------	--------	<.001	.001	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	<.001	.003

[1] Ca and Mg determined by wet chemical methods; H. M. Nakagawa, analyst.

NOTE.—Description of sample and locality as follows;

S13.[1] Saline facies; old marsh. Mouth of Cow Creek; SE¼SE¼ sec. 32, T. 28 N., R. 1 E. Evaporite minerals include thenardite, halite, and burkeite(?).

S14. Saline facies; old marsh. NW¼NW¼ sec. 4. T. 27 N., R. 1 E. Evaporite minerals include thenardite and halite.

S18. Saline facies; old marsh. Surface layers west of base of Furnace Creek fan; NE¼NW¼ sec. 20, T. 27 N., R. 1 E. Evaporite minerals include thenardite, halite, and burkeite.

S19. Saline facies, old marsh; surface layers west side Furnace Creek fan; due west of south side of Ranch and 1,000 ft east of toe of fan; SW¼NE¼ sec. 20, T. 27 N., R. 1 E. Minerals not determined.

S21.[1] Saline facies, old marsh, surface layers. West base Furnace Creek fan, NW¼ sec. 29, T. 27 N., R. 1 E. Evaporite minerals include thenardite, bassanite, halite, borax(?), and burkeite(?).

S23. Saline facies, at old borax workings. NE¼ sec. 31, T. 17 S., R. 47 E. Evaporite minerals include thenardite and halite.

S24. Saline facies, surface layers. NW¼NW¼ sec. 19, T. 27 N., R. 1 E. Evaporite minerals include thenardite and halite.

S26. Sulfate marsh. ½ mile northeast of west side jeep trail 3 miles southeast of West Side Borax Camp. Evaporite minerals include bassanite and halite.

S31. Sulfate marsh. South end of Cottonball Marsh. Evaporites minerals include bassanite and halite.

S32. Saline facies, including soft powdery surface layer and crusty porous lower layer. 0.4 mile northeast of west side jeep trail, 1½ miles southeast of West Side Borax Camp. Evaporite minerals include halite.

S40. Saline facies. 1,000 ft northeast of west side jeep trail, 1 mile southeast of West Side Borax Camp. Minerals not determined.

S41. Saline facies. ½ mile northeast of west side jeep trail and 1 mile southeast of West Side Borax Camp. Evaporite minerals include thenardite and probertite.

S42. Sulfate marsh at old furrow type borax workings. 2,000 ft south of West Side Borax Camp. Evaporite minerals include anhydrite, bassanite, and halite.

S44. Saline facies, at old borax workings, SW¼SW¼ sec. 33, T. 16 S., R. 46 E. Evaporite minerals include halite and bassanite.

S46. Saline facies, NW¼ sec. 33, T. 16 S., R. 46 E. Evaporite minerals include halite, and, doubtfully, colemanite.

S47. Cottonball Marsh, east edge. NE¼ sec. 33, T. 16 S., R. 46 E. Evaporite minerals include bassanite, thenardite, and halite.

S49. Crust of sulfate salts. Cottonball Marsh, NE¼ sec. 28, T. 16 S., R. 46 E. Evaporite minerals include mostly gypsum, some bassanite, rare anhydrite, and halite.

S51. Upper layers, saline facies. SW¼ sec. 28, T. 16 S., R. 46 E. Evaporite minerals include gypsum and probably anhydrite, halite, probertite, and probably meyerhofferite.

S54a. Marsh. Most northerly borax workings in marsh on west side of Cottonball Basin, NW¼ sec. 21, T. 16 S., R. 46 E. Minerals not determined.

S54b. Salt crust between stacks at S54a. Minerals not determined.

S54c. Borate-bearing silt layer caps stacks at S54a. Minerals not determined.

S54d. Layer of ulexite 2 in. below surface at S54a. Minerals not determined by X-ray.

S78. Saline facies. SW¼ sec. 22, T. 26 N., R. 1 E. Evaporite minerals include bassanite, halite, and meyerhofferite(?).

S92. Upper layers of saline facies. 2,000 ft south-southwest of NW. cor. sec. 19, T. 26 N., R. 1 E. Evaporite minerals include bassanite, anhydrite, and halite.

S95. Gypsum facies, east of marsh. 900 ft west of quarter corner on west side sec. 18, T. 26 N., R. 1 E. Minerals not determined by X-ray.

S99. Upper layers of saline facies. Middle west side, sec. 31, T. 27 N., R. 1 E. Minerals not determined.

S105. Salt-heaved sulfate marsh. 2½ miles northwest of Salt Pools. Minerals not determined.

S109. Sulfate marsh. 1½ miles southeast of Salt Pools. Evaporite minerals include bassanite, anhydrite, and halite.

S110a. Gypsum facies, top 2 in. silty layer; 1½ miles north-northwest of Badwater. Mostly gypsum and bassanite.

S110b. Anhydrite layer, 6 in. thick. Underlies S110a. Mostly anhydrite, some gypsum.

S110c. Gypsum layer 8 in. thick. Underlies S110b. Mostly pure gypsum.

S111b. Salt-heaved gypsum facies. ½ mile north of Badwater. Evaporite minerals include halite, anhydrite, and bassanite.

S114. Chloride crust on lumpy growths of sulfate salts in sulfate marsh. Reentrant 1 mile south of Badwater. Evaporite minerals include halite, anhydrite, and bassanite.

S115c. Mud underlying lumpy salt crust in sulfate marsh. Cove 2 miles south of Badwater. Evaporite minerals include gypsum, bassanite, and anhydrite.

S115d. Sulfate crust in marsh at S115c. Evaporite minerals include bassanite, some anhydrite, and halite.

S116. Sulfate marsh. West toe of fan, 3 miles south of Badwater. Evaporite minerals include halite, bassanite, and trace of gypsum.

S117. Sulfate marsh. Cove next south of S116. Evaporite minerals include bassanite and halite.

S119. Sulfate marsh. ½ mile south of Copper Canyon fan. Evaporite minerals include anhydrite and bassanite.

S122. Glauberite(?) at edge of eroded sulfate ground 1¼ miles northwest of Mormon Point. Evaporite minerals identified by X-ray include anhydrite and bassanite.

S123. Saline facies, 1 mile west of Mormon Point. Evaporite minerals include halite, anhydrite, and bassanite.

S124. Sulfate marsh. Mormon Point. Minerals not determined.

S130a. West edge of sulfate marsh; crumbly sulfate at level of pond. SE¼ sec. 15, T. 22 N., R. 2 E. Evaporite minerals include gypsum, bassanite, some halite, and anhydrite(?).

S130b. Surface crust on S130a. Evaporite minerals include gypsum, some bassanite, and halite.

S137a. Marsh, with pickleweed, saltgrass, and rush; crust on lumpy salt structure. ½ mile east of Gravel Well. Evaporite minerals are gypsum, bassanite, and anhydrite in about equal proportions, and some halite.

S137b. Interior of lumpy salt structure at S137a. Evaporite minerals are mostly gypsum, very little bassanite, some halite.

S137c. Mud underlying the marsh salts at S137a. Evaporite minerals mostly gypsum.

S142. Marsh 0.75 mile southeast of Bennetts Well. Minerals not determined.

S143. Gypsum facies. South side of Eagle Borax marshes. Evaporite minerals include bassanite and halite.

S144b. Gypsum facies. Layer of bassanite(?) and gypsum; 2–8 in. below surface. ½ mile east of Eagle Borax. Evaporite minerals determined by X-ray mostly gypsum, questionable anhydrite.

S144c. Crumbly gypsum, 8–38 in. below surface at S144b. Evaporite minerals include gypsum and possibly some borax.

S144d. Same as S144c but wet, 38–44 in. below surface. Evaporite minerals include gypsum, some bassanite, and halite.

S144e. Wet clay underlying the gypsum at S144b. Evaporite minerals include gypsum, some bassanite, and borax(?).

S150a. Gypsum facies, upper 12 in. of damp mud underlying the gypsum. ½ mile east of Tule Spring. Evaporite minerals mostly gypsum.

S150b. 1-in. layer of salts overlying S150a. Evaporite minerals mostly gypsum, some bassanite.

S150c. 7-in. layer of crumbly gypsum; damp; overlies S150b. Evaporite minerals mostly gypsum, some bassanite.

S150d. 3-in. layer tough gypsum; overlies S150c. Evaporite minerals mostly gypsum, some halite.

S150e. 3-in crumbly gypsum, 4 in. below surface; overlies S150d. Evaporite mineral is mostly gypsum.

S151b. 12 in. of brown mud and gypsum at west edge of gypsum facies ½ mile east of Tule Spring. Evaporite minerals mostly gypsum.

S153.[1] Marsh 1 mile northeast of Tule Spring. Evaporite minerals mostly halite and anhydrite.

S157. Gypsum facies. ½ mile east of West Side Highway 1½ miles south of junction with Trail Canyon road. Minerals not determined.

TABLE 47.—*Semiquantitative partial analyses, in percent, of the rough facies of the silty rock salt*

[Analysts and analytical methods given on pages B90–B91. Salt samples, S series, collected January–March 1956; localities shown on pl. 3. In the analyses of the salt layer there is very slight excess of anions; in the silt layer, cations are in excess by an average of about 15 percent]

Major constituents in acid-soluble fraction

	Silt layer				Salt layer		
	S11	S29	S74	S97	S86	S98	S147b
Ca	6.9	2.6	3.8	5.4	0.9	1.6	0.9
Mg	2.2	1.7	1.8	1.5	.5	.6	.4
K	1.2	.6	.6	.8	3.2	1.5	1.6
Na	3.7	9.9	4.4	7.0	30	28	30
CO_3	10	1.0	3.6	5.2	.3	1.6	.2
SO_4	3.8	5.9	2.4	5.4	12	4.8	4.7
Cl	3.8	13	8.8	11	43	44	47
Total	31.6	34.7	25.4	36.3	89.9	82.1	84.8

Minor constituents in total sample

	Silt layer				Salt layer		
	S11	S29	S74	S97	S86	S98	S147b
B	0.3	1.0	1.0	1.0	0.7	0.7	0.3
Ti	.2	.1	.5	.15	.07	.03	.03
V	.01	.01	.015	.007	.002	.002	.001
Mn	.07	.07	.07	.07	.01	.01	.01
Ni	.002	.002	.003	.001	.0005	.0005	.0005
Sr	.1	.015	.05	.05	.03	.02	.015
Ba	.05	.02	.03	.03	.007	.007	.007
Cu	.001	.015	.01	.007	.0002	.0005	.0001
Cr	.007	.003	.005	.005	.001	.001	.001

NOTE.—Description of sample and locality as follows:

S11. Silt, about 1 in. thick; on rock salt. NW¼ sec. 32, T. 28 N., R. 1 E. Evaporite minerals include halite and some probertite.

S29. Silt on rock salt, ½ mile northeast of west side jeep trail 3 miles southeast of West Side Borax Camp. Evaporite minerals include halite and rare probertite.

S74. Silt, about 1 in. thick, caps few feet of rock salt. NW¼ sec. 16, T. 26 N., R. 1 E. Evaporite minerals include halite, rare probertite, and meyerhofferite(?).

S86. Rock salt, underlies the silt layer. NE¼SE¼ sec. 29, T. 26 N., R. 1 E. For the most part pure rock salt.

S97. Silt layer, 1 in. thick, overlies about 4 ft of rock salt (see S98). NE¼NE¼ sec. 6, T. 26 N., R. 1 E. Evaporite minerals include halite, probertite, and probably meyerhofferite.

S98. Rock salt underlying silt at S97. Mostly halite.

S147b. Eroded rock salt, 1 mile east of Shortys Well. For the most part pure rock salt.

TABLE 48.—*Semiquantitative partial analyses, in percent, of the smooth facies of silty rock salt*

[Analysts and analytical methods given on pages B90–B91. Salt samples, S series, collected January–March 1956; localities shown on pl. 3. In most of these analyses there is about 10 percent excess of cations]

Major constituents in acid-soluble fraction

	Cottonball Basin				Middle Basin			Badwater Basin				
	S10	S12	S16	S22	S71	S72	S81	S101	S138a	S139	S146	S147a
Ca	2.1	6.2	5.9	8.0	1.8	2.6	2.0	1.6	1.6	4.3	3.5	5.9
Mg	.4	2.7	2.1	2.6	.7	1.2	1.6	.9	2.5	3.0	3.1	3.0
K	.2	.8	.4	.5	.1	.3	.8	.3	.4	1.2	1.0	.1
Na	24	4.8	7.1	7.0	30	18	15	25	6.0	7.2	7.8	14
CO_3	.2	9.4	9.3	11	.4	.6	2.1	1.7	.2	5.0	4.5	.6
SO_4	10	3.4	4.3	4.9	16	29	4.7	3.4	2.6	3.6	7.8	11
Cl	18	6.6	9	4.8	36	6.3	22	36	12	9.6	12	30
Total	54.9	33.9	38.1	38.8	85.0	58.0	48.2	68.9	25.3	33.9	39.7	64.6

Minor constituents in total sample

	S10	S12	S16	S22	S71	S72	S81	S101	S138a	S139	S146	S147a
B	>1.0	0.5	0.2	0.1	0.7	0.7	0.5	0.3	0.2	0.3	0.2	0.5
Ti	.03	.3	.07	.07	.03	.05	.07	.03	.3	.2	.3	.05
V	.001	.007	.007	.005	.002	.005	.001	.002	.01	.01	.005	.001
Mn	.007	.07	.07	.07	.01	.03	.03	.02	.07	.1	.07	.015
Ni	< .0005	.0015	.0005	.005	< .0005	< .0005	.0005	< .0005	.002	.002	.001	< .0005
Sr	.1	.07	.02	.05	.07	.05	.02	.03	.1	.1	.05	.15
Ba	.007	.03	.02	.01	.01	.015	.01	.015	.05	.05	.02	.01
Cu	.0001	.003	.0005	.005	.0003	.0015	.002	.001	.007	.007	.007	.0003
Cr	< .001	.003	.003	.003	< .001	.002	.0015	.002	.005	.003	.002	.001

NOTE.—Description of sample and locality as follows:

S10. Silt, about 6 in. thick; contains sulfate nodules and overlies rock salt about 6 in. thick. NE¼ sec. 32, T. 28 N., R. 1 E. Evaporite minerals include halite, thenardite, probertite, and borax.

S12. Silt, about 5 in. thick; overlies rock salt. SE¼ sec. 32, T. 28 N., R. 1 E. Evaporite minerals include halite and bassanite.

S16. Silt, 5 in. thick; overlies rock salt about 6 in. thick. SE¼NE¼ sec. 8, T. 27 N., R. 1 E. Evaporite minerals include halite, thenardite, meyerhofferite, and possibly kernite, northupite, and niter.

S22. Silt, overlies rock salt. NW¼ sec. 29, T. 27 N., R. 1 E. Evaporite minerals include halite, thenardite, and probertite.

S71. Silt, 10 in. thick; overlies rock salt 6–12 in. thick at old furrow-type mine workings. SW¼ sec. 10, T. 26 N., R. 1 E. Evaporite minerals include halite, thenardite, and probertite.

S72. Has 2 ppm of Mo. 1,000 ft west of S71. Evaporite minerals include thenardite and halite.

S81. Silt, 3 in. thick; overlies rock salt 1 ft thick. SW¼ sec. 27, T. 26 N., R. 1 E. Evaporite minerals include halite and probertite.

S101. Silt, 3 in. thick; overlies 1 ft of rock salt. NE¼ sec. 34, T. 26 N., R. 1 E. Evaporite minerals include halite and probertite.

S138a. Silt, 3 in. thick; overlies 10 in. of rock salt. 1½ miles east of Gravel Well. Evaporite minerals include halite and possibly some gypsum.

S139. Silt, 4 in. thick; overlies rock salt 1 ft thick. 2½ miles northeast of Gravel Well. Minerals not determined.

S146. Silt, 5 in. thick on rock salt. 2½ miles northeast of Eagle Borax. Evaporite minerals include bassanite and thenardite.

S147a. Silt, overlies rock salt; at Old Borax working 0.6 mile east of Shortys Well. Evaporite minerals include halite and anhydrite.

TABLE 49.—*Semiquantitative partial analyses, in percent, of flood-plain deposits*

[Analysts and analytical methods given on pages B90–B91. Salt samples, S series, collected January–March 1956; localities shown on pl. 3. Analyses of samples high in boron which was not included as a major constituent, in this table, average 20–25 percent excess cations. Lack of balance in samples containing less than 0.5 percent B does not exceed 20 percent. Lack of balance in samples high in sodium chloride averages less than 5 percent.]

Major constituents in acid-soluble fraction

	Cottonball Basin										
	S6 [1]	S33a	S33b	S33c	S33d	S33e	S35a	S35b	S36a	S36c	S37a
Ca	0.3	7.5	7.5	5.0	7.5	3.5	0.5	5.6	1.9	4.3	3.5
Mg	.1	1.5	1.5	1.5	1.5	1.5	1.4	3.2	2.2	3.7	.7
K	4.5	.76	.8	1.1	.9	.86	.1	1.2	.7	.8	.8
Na	33	8.2	8.0	5.2	5.5	3.5	36	7.2	14	9.6	8.7
CO_3	5.8	.8	1.4	6.0	1.2	4.8	.2	6.2	1.2	1.4	1.4
SO_4	16	15	15	11	12	10	10	11	6.7	13	17
Cl	33	4.9	3.5	3.5	3.5	2.6	38	7.5	22	8.7	6.5
Total	92.7	38.66	37.7	33.3	32.1	26.8	86.2	41.9	48.7	41.5	38.6

Minor constituents in total sample

	S6 [1]	S33a	S33b	S33c	S33d	S33e	S35a	S35b	S36a	S36c	S37a
B	0.3	1.0	>1.0	0.1	0.75	0.5	0.01	0.7	1.0	>1.0	0.15
Ti	.01	.075	.07	.1	.075	.1	.01	.15	.2	.2	.07
V	<.001	.002	.003	.003	.002	.003	<.001	.002	.005	.002	<.002
Mn	.001	.02	.02	.03	.02	.03	.002	.05	.03	.05	.01
Ni	<.0005	<.0005	<.0005	.0005	<.0005	.0005	<.0005	.0005	.001	.0005	<.0005
Sr	.01	.5	1.0	.15	1.5	.3	.07	.07	.07	.1	1.5
Ba	.001	.02	.02	.02	.02	.02	.001	.02	.02	.015	.02
Cu	<.0001	----	----	----	----	----	.0001	.005	.003	.003	----
Cr	<.001	----	----	----	----	----	<.001	.002	.002	.001	----

Major constituents in acid-soluble fraction—Continued

	Cottonball Basin—Continued					Middle Basin					
	S37b	S38	S39	S48	S50	S66	S67	S87	S88	S89	S96
Ca	3.5	1.3	6.9	5.0	7.5	4.6	5.4	6.4	1.9	2.2	3.8
Mg	1.5	.7	3.6	2.0	2.0	1.3	2.1	3.2	.6	1.9	2.7
K	.8	.6	.8	1.3	.6	.4	.5	.9	.9	.3	.6
Na	5.3	34	7.6	7.6	4.0	4.8	10	8.2	31	21	3.3
CO_3	.6	.4	.6	1.8	9.4	6.6	8.6	2.6	.4	.8	5.8
SO_4	20	6.4	16	8.0	3.7	4.4	5.3	14	14	4.9	3.9
Cl	5.5	54	7.2	6.1	5.3	1.4	7.0	8.4	46	39	5.2
Total	37.2	97.4	42.7	31.8	32.5	23.5	38.9	43.7	94.8	70.1	25.3

Minor constituents in total sample—Continued

	S37b	S38	S39	S48	S50	S66	S67	S87	S88	S89	S96
B	>1.0	0.1	0.7	>1.0	1.0	1.0	0.5	1.0	0.3	0.05	0.1
Ti	.07	.02	.1	.07	.07	.2	.2	.15	.05	.1	.1
V	.002	<.001	.007	.002	.003	.01	.015	.007	.002	.002	.01
Mn	.015	.005	.05	.01	.03	.1	.07	.07	.01	.02	.05
Ni	<.0005	<.0005	.001	<.0005	.0005	.002	.003	.001	<.0005	<.0005	.001
Sr	1.0	.15	.2	.75	.1	.1	.1	.1	.1	.03	.15
Ba	.01	.002	.015	.01	.03	.05	.05	.03	.005	.015	.03
Cu	----	.0001	.003	----	----	.002	.002	.003	.0003	.0005	.01
Cr	----	<.001	.003	----	----	.003	.007	.003	<.001	.0015	.007

See footnotes at end of table.

TABLE 49.—*Semiquantitative partial analyses, in percent, of flood-plain deposits*—Continued

Major constituents in acid-soluble fraction—Continued

	Badwater Basin												
	S107 [1]	S112	S113	S115a	S115b	S118	S128	S132	S135e	S135f	S135g	S138b	S152
Ca	3.5	5.3	2.4	7.5	7.5	2.7	1.8	2.0	1.0	5.0	3.5	3.5	3.2
Mg	3.1	3.2	1.2	1.0	.7	2.0	1.2	.7	1.5	2.0	1.0	1.5	2.0
K	.5	1.3	.1	1.0	.9	.9	.6	.7	.7	.5	.9	.7	.9
Na	4.2	10	28	2.4	2.2	16	23	2.8	1.3	.7	5.4	1.1	22
CO_3	3.6	3	.6	3.0	2.6	2.4	1.2	.4	1.0	7.2	1.4	5.6	.4
SO_4	5	11	6.6	12	11	4.3	8.7	17	1.9	17	3.1	3.7	15
Cl	6.6	11	43	3.9	2.2	17	31	2.2	4.5	1.4	9.6	2.8	31
Total	26.5	44.8	81.9	30.8	27.1	45.3	67.5	25.8	11.9	33.8	24.9	18.9	74.5

Minor constituents in total sample—Continued

	S107	S112	S113	S115a	S115b	S118	S128	S132	S135e	S135f	S135g	S138b	S152
B	0.3	0.1	0.1	0.02	0.015	0.2	0.1	0.03	0.01	0.01	0.01	0.02	0.15
Ti	.3	.15	.03	.2	.1	.07	.07	.15	.07	.1	.1	.1	.05
V	.015	.005	.002	.005	.003	.005	.002	.002	.003	.003	.003	.005	.002
Mn	.07	.07	.02	.07	.05	.07	.05	.07	.05	.07	.05	.07	.02
Ni	.01	.001	<.0005	.001	.0005	.001	.0005	<.0005	.0005	.0005	.0005	.001	.0005
Sr	.1	.05	.05	.3	.15	.05	.05	.1	.5	.05	.75	.05	.03
Ba	.03	.015	.01	.1	.05	.015	.02	.03	.07	.05	.05	.03	.01
Cu	.005	.007	.0003	------	------	.002	.002	------	------	------	------	------	.0007
Cr	.015	.002	.001	------	------	.001	.001	------	------	------	------	------	.0015

NOTE.—Description of sample and locality as follows:

S6. Has 20 ppm Mo. efflorescence on flood plain at Salt Springs. SE¼ sec. 20, T. 28 N., R. 1 E. Minerals not determined.

S33a. Top inch of mud including layer of salt efflorescence 1 mm thick. SE¼ sec. 6, T. 27 N., R. 1 E. Same locality as W31 and 32. Evaporite minerals include halite, gypsum, bassanite, some probertite, and possibly borax and anhydrite.

S33b. "Cottonball" layer ½ in. thick, 1 in. below surface of flood plain. Evaporite minerals include halite, bassanite, and probertite.

S33c. Clay layer 2 in. thick under S33a. Evaporite minerals include halite, bassanite, probably anhydrite, and trace of probertite.

S33d. "Cottonball" layer 1½ in. thick under S33c. Evaporite minerals include halite, bassanite, gypsum, and some probertite.

S33e. Glaubite (?) layer 10 in. thick under S33b. Evaporite minerals determined by X-ray include halite, bassanite, and probably anhydrite and borax.

S35a. Salt crust on flood plain. SW¼ sec. 31, T. 28 N., R. 1 E. Mostly pure rock salt.

S35b. Clay 6 in. thick, underlies S35a. Evaporite minerals include halite and probertite.

S36a. Salt crust 2 mm thick, on flood plain, between stacks at old borax workings. About 1,000 ft northwest of SW. cor. sec. 6, T. 17 S., R. 47E. Evaporite minerals mostly halite, some probertite.

S36b. 6-in. layer of glauberite (?) and ulexite (?) 6 in. below under S36a. Evaporite minerals determined by X-ray include halite and probertite.

S37a. Upper 1 in. of mud ½ mile west of SW. cor. sec. 6, T. 17 S., R. 47 E. Evaporite minerals include halite and bassanite.

S37b. "Cottonball" layer 2 in. thick under S37a. Evaporite minerals include halite and borax (or ulexite(?)).

S38. Salt crust from furrow at borax working about 1 mile south of the SW. cor. sec. 35, T. 16 S., R. 46 E. Evaporite minerals mostly halite.

S39. Same locality as S38. Glauberite layer, 4 in. thick, underlies salt crust represented by S38 and overlies clay. Evaporite minerals include halite and bassanite.

S48. Glauberite(?) and ulexite(?) layer, exposed at surface. SE¼ sec. 28, T. 16 S., R. 46 E. Evaporite minerals include halite and probertite.

S50. Channel mud at east edge of silty rock salt. NE¼ sec. 28, T. 16 S., R. 46 E. Evaporite minerals include halite and some probertite.

S66. Alluvial fan at south foot of Furnace Creek fan. SE¼ sec. 33, T. 27 N., R. 1 E. Evaporitie minerals include halite and bassanite.

S67. Mixed sulfate and chloride salt deposit subject to flooding; south foot of Furnace Creek fan. S½ sec. 33, T. 27 N., R. 1 E. Evaporite minerals include halite, thenardite, and bassanite.

S87. Silt; upper 4 in. of glauberite(?) bearing silt in Salt Creek. SE¼ sec. 20, T. 26 N., R. 1 E. Evaporite minerals include halite, glauberite, probertite, and possibly borax.

S88. Salt crust on silt at S87. Mostly nalite.

S89. Salt crust on flood plain. SW¼ sec. 20, T. 26 N., R. 1 E. Evaporite minerals include halite and possibly anhydrite and meyerhofferite.

S96. Silt from flood plain ½ mile southwest of SW. cor. sec. 6, T. 26 N., R. 1 E. Evaporite minerals include halite.

S107. Has 15 ppm Co. Silt in flood plain. 1 mile north of Salt Pools. Evaporite minerals include halite and bassanite.

S112. Clay from beneath salt saucers. 1 mile west of Badwater. Evaporite minerals include halite and bassanite.

S113. Muddy silt, probably windblown, in salt saucer 0.75 mile southwest of Badwater. Mostly pure rock salt.

S115a. Upper 18 in. of mud in flood plain in cove 2 miles south of Badwater. Evaporite minerals include gypsum, bassanite, and halite.

S115b. Upper 15 in. of mud in flood plain in cove 100 ft east of S115a. Evaporite minerals include gypsum.

S118. Saliferous silt from streambank opposite mouth of Copper Canyon. Evaporite minerals mostly halite.

S128. Sand by Amargosa River. SW¼ sec. 4, T. 22 N., R. 2 E. Evaporite minerals mostly halite, some thenardite.

S132. Flood plain of Amargosa River, SE¼ sec. 22, T. 22 N., R. 2 E.; silty sand. Evaporite minerals include bassanite, gypsum, and halite.

S135e. Brown mud in flood plain at spring zone 1 mile north of Salt Well. Evaporite minerals include halite and anhydrite.

S135f. Shale under S135e. Minerals not determined.

S135g. Flood plain 3 miles north of Salt Well. Evaporite minerals include halite, gypsum(?), inyoite(?), and probertite(?).

S138b. Laminated silt, underlies crust of mixed salts (compare with 138a); 1.5 miles east of Gravel Well. Evaporite minerals include halite and gypsum.

S152. Glauberite(?) efflorescence at edge of channel 1 mile east of Tule Spring. Evaporite minerals include halite and bassanite.

TABLE 50.—*Semiquantitative partial analyses, in percent of the water, of surface and near-surface brines in the Cottonball Basin*

[Analysts and analytical methods given on pages B90–B91. Samples marked with suffix "-56" collected January-February 1956, a dry year; others collected January-February 1957, a wet year; localities shown on pl. 3; surface-water samples designated "s"; ground water "g"; ground water issues at surface except as indicated otherwise. See also tables 12, 22]

	Salt Creek							W5–56g	W4s	W5s	W6g	Salt Springs area									
	W1s	W1–56s	W2s	W2–56s	W3s	W3–56s	W4–56s					W7g	W8g	W9g	W10g	W11s	W12g	W13g	W14s	W15s	W16s
Ca	--------	>0.02	--------	>.01	--------	0.05	0.06	0.12	--------	0.005	0.008	0.003	0.002	0.002	0.002	0.003	0.005	0.001	0.004	0.003	0.011
Mg	--------	>.02	--------	.03	--------	.05	.1	.01	--------	.002	.002	.001	.002	<.001	.001	.001	.002	.001	.004	.001	.00
K	0.06	.03	0.04	.07	0.14	.16	.35	.20	0.05	.15	.15	.04	.09	.11	.20	.26	.51	1.10	.23	.30	.42
Na	.5	.51	.48	1.44	1.7	3.50	4.41	4.2	.56	1.6	1.6	.40	.79	.86	1.6	2.1	3.5	7.7	1.8	2.3	5.0
SO_4	.4	.25	.20	.50	.70	1.4	2.2	1.8	.80	.70	.9	.5	.4	1.2	.9	1.7	2.1	2.5	1.1	.60	1.6
Cl	.7	.74	.40	2.0	1.0	4.9	5.85	5.64	1.40	.02	.01	.02	.02	.01	.01	.03	.03	.03	.03	.03	2.6
B	--------	.0005	--------	.002	--------	.005	.02	.02	--------	.002	.002	.001	.002	.001	.002	.003	.004	.008	.002	.002	.003
Sr	--------	.003	--------	.004	--------	.01	.01	.01	--------	.008	.001	<.001	<.001	<.001	.001	.001	.002	.001	<.001	.001	.002
Total dissolved solids	1.8	1.5	1.6	4	5.3	10	13	12	1.7	5.2	5.0	1.3	2.4	2.7	5.0	6.3	11	24	5.4	7.0	16
pH	7.8	--------	8.4	--------	8.4	--------	7.0	--------	7.8	7.9	7.7	8.1	8.2	8.0	8.5	8.2	8.0	7.9	8.2	8.3	8.0

	W6–56g	W17g	W18s	Cow Creek area						Harmony Borax Mill area						
				W19g	W20g	W7–56g	W21g	W22g	W23s	W24s	W25s	W26g	W27g	W28g	W29s	W30s
Ca	0.002	<0.001	<0.001	0.001	0.001	0.003	<0.001	0.002	0.001	0.001	0.003	0.003	0.003	0.005	0.003	0.010
Mg	.0005	<.001	<.001	.001	.004	.01	<.001	<.001	.001	<.001	.001	.001	<.001	.005	.001	.002
K	.03	.06	.02	--------	<.01	.012	<.01	.18	.03	.03	.05	.05	.01	.24	0.05	.08
Na	.35	.84	.25	--------	.12	.32	.19	8.8	.4	1.0	1.8	1.2	1.3	9.6	1.8	5.0
SO_4	.14	.20	.20	.02	.05	.3	.10	1.6	.7	.3	1.6	.6	1.0	2.6	.6	1.0
Cl	--------	1.20	.6	.02	.02	.25	.12	.5	.2	.9	.7	.3	.5	11.0	.5	.8
B	.003	.004	.001	<.001	<.001	.003	<.001	.009	.003	.001	.002	.002	.003	.0260	.001	.005
Sr	.0002	<.001	<.001	.001	<.001	.002	<.001	.001	<.001	<.001	.002	.002	.003	.0010	.004	.007
Total dissolved solids	1	2.4	0.75	0.15	0.38	1	0.57	25	1.3	2.9	4.9	3.6	3.5	26	5.3	14
pH	8.3	8.5	8.5	7.5	8.2	7.5	7.8	7.5	8.5	8.4	8.1	7.9	8.0	6.5	8.1	7.8

	W8–56g	Cottonball Basin											Cottonball Marsh			
		Southwest side				Central part										
		W9–56g	W10–56g	W11–56g	W12–56g	W31s	W32g	W33s	W34g	W35s	W36g	W37s	W38g	W13–56g	W39g	W14–56g
Ca	0.04	0.04	>0.1	>0.08	>0.03	0.09	0.02	0.009	0.02	0.02	0.04	0.02	0.02	0.05	0.02	0.1
Mg	.004	.02	.07	.08	0.3	.03	.1	.005	.07	.008	.03	.003	.01	.05	.001	.1
K	.04	.08	.2	.1	.1	.2	.9	.09	.9	.13	.9	.5	.05	.1	.08	.25
Na	2.78	1.44	3.5	3.14	1.19	3.1	9.9	1.5	11.0	1.8	12.0	11.0	.84	1.63	1.30	4.08
SO_4	.76	.36	1.1	1.21	.45	.60	1.6	1.0	1.8	1.2	2.4	2.6	.90	.48	.40	1.44
Cl	4.24	2.08	5.1	4.0	1.71	3.6	15	1.8	16.0	3.2	17.0	17	1.2	2.54	1.0	6.36
B	.04	.004	.02	.008	.017	.007	.032	.001	.01	.002	.007	.003	.001	.01	.001	.06
Sr	.01	.004	.01	.012	.005	.003	.001	.002	.001	.003	.001	.005	.002	.01	.003	.02
Total Dissolved solids	8	4	10	8.5	3.5	9.3	32	4.7	33	5.5	37	34	2.8	4.8	4.0	12
pH	7.0	--------	7.5	7.5	--------	7.7	6.8	8.0	6.8	7.9	6.8	6.8	7.8	8.0	7.8	7.8

	Cottonball Marsh—Continued														
	W40g	W41g	W15–56g	W42g	W16–56g	W43g	W44g	W45g	W46g	W47g	W48g	W49s	W50s	W51s	W52s	W53s
Ca	0.04	--------	>0.01	0.003	0.04	0.02	<0.001	0.01	0.006	0.01	0.02	0.03	0.1	0.08	0.02	0.13
Mg	.02	--------	.005	.002	.02	.01	<.001	.008	.003	.006	.008	.007	.03	.03	.01	.003
K	.1	.09	.01	.02	.08	.08	.05	.09	.08	.08	.07	.1	.2	.2	.2	.03
Na	1.7	1.5	.34	.27	1.4	1.4	1.1	1.4	1.4	1.3	1.4	3.4	3.1	5.6	3.2	.48
SO_4	.60	.3	.10	.30	.44	1.0	.5	.6	.5	.4	.6	1.2	1.7	1.3	.5	.1
Cl	1.0	1.5	.52	.50	2.04	1.3	1.1	1.1	1.1	.9	.9	2.8	2.8	4.4	3.6	1.2
B	.004	--------	.003	.001	.01	.002	<.001	.001	.001	.002	.001	.002	.005	.006	.006	.001
Sr	.003	--------	.001	<.001	.01	<.001	<.001	.003	.003	.003	.003	.007	.005	.008	.007	.006
Total Dissolved solids	5.4	4.6	1	0.9	4	4.1	3.0	4.3	3.9	3.9	4.2	9.4	9.8	16	9.2	1.7
pH	8.0	7.8	6.3	6.8	7.5	7.9	7.8	7.8	7.8	7.8	7.3	7.5	7.8	7.6	7.4	6.8

Note.—Description of sample and locality as follows:

W1s.	Surface water, Salt Creek, at bridge 1,000 ft southeast of McLean Spring.
W1–56s.	Surface water, Salt Creek, at lower end of gorge in SE¼ sec. 5, T. 16 S., R. 46 E.
W2s.	1957 duplicate of W1–56s.
W2–56s.	Surface water, Salt Creek, in pickleweed at edge of saltpan; N½ sec. 10, T. 16 S., R. 46 E.
W3s.	Surface water, location ¼ mile downstream from W2–56s.
W3–56s.	Surface water, Salt Creek, southernmost pool in east distributary, at south edge of rough silty rock salt; SE¼ sec. 14, T. 16 S., R. 46E.
W4–56s.	Surface water, Salt Creek, southernmost pool in west distributary, at south edge of rough silty rock salt; SW¼ sec. 14, T. 16 S., R. 46 E.
W5–56g.	Ground water at seep, NE¼ sec. 18, T. 28 N., R. 1 E.
W4s.	Surface water, pool in channel below spring, 500 ft southwest of grave by old road in NE¼ sec. 18, T. 28 N., R. 1 E.
W5s.	Surface water in channel at spring, center north side sec. 20, T. 28 N., R. 1 E.
W6g.	Ground water in gravel 16 in. below bed of channel 150 ft east of W5s.
W7g.	Ground water in gravel 3 ft below surface; by old road at boundary between xerophyte and phreatophyte zones. SE¼ sec. 20, T. 28 N., R. 1 E.
W8g.	Ground water in gravel in pickleweed zone; 1 ft below surface; 100 ft west of W7g.
W9g.	Ground water, 10 in. below surface, in phreatophyte zone near west edge, 100 ft west of W8g. SE¼ sec. 20, T. 28 N., R. 1 E.
W10g.	Ground water, 6 in. below surface, by channel at W11s. 100 ft west of W9g. SE¼ sec. 20, T. 28 N., R. 1 E.
W11s.	Surface water in channel at west edge of phreatophyte zone; 100 ft west of W9g. SE¼ sec. 20, T. 28 N., R. 1 E.
W12g.	Ground water, 4 in. below surface and same level as adjacent channel; 200 ft southwest of W11s. SE¼ sec. 20, T. 28 N., R. 1 E.
W13g.	Ground water 20 in. below surface and 10 ft to side of channel at W14s; 800 ft southwest of W12g. SE¼ sec. 20, T. 28 N., R. 1 E.
W14s.	Surface water in channel by W13g and 800 ft southwest of W12g. SE¼ sec. 20, T. 28 N., R. 1E.
W15s.	Surface water in channel 1,200 ft southwest of W14s. SE¼ sec. 20, T. 28 N., R. 1 E.
W16s.	Surface water, pond in channel 750 ft southwest of W15s. NE¼ sec. 29, T. 28 N., R. 1 E.
W6–56g.	Ground water, seep with saltgrass. NE¼ sec. 32, T. 28 N., R. 1 E.
W17g.	Ground water, 1 ft below surface, near W6–56g.
W18s.	Surface water, pond in channel near west edge of phreatophyte zone; 500 ft west of W17g. NE¼ sec. 32, T. 28 N., R. 1 E.
W19g.	Ground water 20 in. below surface; at boundary between xerophyte and phreatophyte zones. NW¼ sec. 4, T. 27 N., R. 1 E.
W20g.	Ground water 10 in. below surface in phreatophyte zone at boundary between arrowweed and saltgrass, 500 ft west of W19g. NW¼ sec. 4, T. 27 N., R. 1 E.
W7–56g.	Ground water at spring, in carbonate marsh at west edge of phreatophyte zone; 400 ft west of W20g. NW¼ sec. 4, T. 27 N., R. 1 E.
W21g.	Ground water 6 in. below surface at W7–56g.
W22g.	Ground water 4 in. below surface, in channel at boundary between carbonate marsh and chloride zone. NE¼ sec. 5, T. 27 N., R. 1 E.
W23s.	Surface water in carbonate marsh 750 ft north of W21g; saltgrass growing in this water. NE¼ sec. 4, T. 27 N., R. 1 E.
W24s.	Surface water, pond in main channel draining west from Harmony Borax Mill; 50 ft downstream from head of distributary to W25s and W26g. W½ sec. 9, T. 27 N., R. 1 E.
W25s.	Surface water, pond in distributary channel 50 ft upstream from W26g. W½ sec. 9, T. 27 N., R. 1 E.
W26g.	Ground water, 18 in. below surface, in south distributary channel draining west from Harmony Borax Mill; at small escarpment (fault) in playa beds. W½ sec. 9, T. 27 N., R. 1 E.
W27g.	Spring at west edge of hill at Harmony Borax Mill; along fault scarp south of W26g. W½ sec. 9, T. 27 N., R. 1 E.
W28g.	Ground water, 12 in. below surface; marsh gas. In distributary north of W25s and W26g at same escarpment as W26g. NW¼ sec. 9, T. 27 N., R. 1 E.
W29s.	Surface water, ponded in distributary near W28g.
W30s.	Surface water in pond about 1,000 ft northwest of W28g and about 1,500 ft southwest of Mustard Canyon. NE¼ sec. 8, T. 27 N., R. 1 E.
W8–56g.	Water at spring, south of Cow Creek and east of highway; SW¼ sec. 3, T. 27 N., R. 1 E.
W9–56g.	Spring in wash tributary to Salt Creek at jeep crossing; NW¼ sec. 30, T. 27 N., R. 1 E.
W10–56g.	Spring in sulfate marsh; SW¼ sec. 18, T. 17 S., R. 47 E.
W11–56g.	Pool at sulfate marsh; ½ mile southwest of SW. cor. sec. 7, T. 17 S., R. 47 E.
W12–56g.	Spring 1½ miles west of SW. cor. sec. 7, T. 17 S., R. 47 E.
W31s.	Surface water from pond in center of Cottonball Basin. SE¼ sec. 6, T. 27 N., R. 1 E.
W32g.	Ground water 1 ft below surface 10 ft from edge of pond at W31s.
W33s.	Surface water from main channel draining east from Cottonball Marsh. NE¼ sec. 7, T. 17 S., R. 47 E. Channel here is 4 in. deep and 75 ft wide; estimate current at 20 ft per minute.
W34g.	Ground water 50 ft north of W33s and separated from it by a salt levee 18 in. high.
W35s.	Surface water from channel about 1 mile west of W33s.
W36g.	Ground water 1 ft below surface at W35s.
W37s.	Surface water from artificial pan in a salt-crusted furrow in old mine working about ½ mile west of W35s.
W38g.	Ground water from southernmost part of Cottonball Marsh. About 1 mile south-southeast of SW. cor. sec. 34, T. 16 S., R. 46 E.
W13–56g.	Southern part of Cottonball Marsh; ¾ mile south of SW. cor. sec. 34, T. 16 S., R. 46 E.
W39g.	Ground water, in marsh; about ½ mile south of SW. cor. sec. 34, T. 16 S., R. 46 E.
W14–56g.	Cottonball Marsh, ¼ mile southwest of SW. cor. sec. 34, T. 16 S., R. 46 E.
W40g.	Ground water, in marsh midway between loc. W39g and W41g.
W41g.	Ground water, in marsh at base of Tucki Mtn. Approx 0.3 mile south-southwest of SW. cor. sec. 33, T. 16 S., R. 46 E.
W15–56g.	Ground water at warm spring (temp. 31°C) along fault at east foot of Tucki Mtn. About 1,500 ft southwest of SW. cor. sec. 33, T. 16 S., R. 46 E.
W42g.	1957 duplicate of W15–56g.
W16–56g.	Spring in Cottonball Marsh, near center sec. 33, T. 16 S., R. 46E.
W43g.	Ground water in northern part of Cottonball Marsh; at west edge at boundary with pickleweed zone. Approx Cen. N½ sec. 33, T. 16 S., R. 46 E.
W44g.	Ground water in marsh about 1,000 ft northeast of W43g.
W45g.	Ground water at east edge of marsh and west edge of flood plain. SE¼ sec. 28, T. 16 S., R. 46 E.
W46g.	Ground water at boundary between marsh and flood plain; about 1,000 ft north of W44g.
W47g.	Ground water, in northern part of marsh. SE¼ sec. 28, T. 16 S., R. 46 E.
W48g.	Ground water, ponded at north end of marsh. NE¼ sec. 28, T. 16 S., R. 46 E.
W49s.	Surface water in channel at mine workings. NE¼ sec. 28, T. 16 S., R. 46 E.
W50s.	Surface water; pond in channel about 500 ft west of flood plain. NE¼ sec. 28, T. 16 S., R. 46 E.
W51s.	Surface water; pond in silty rock salt; 50 by 30 ft and 6 in deep. NW¼ sec. 28, T. 16 S., R. 46 E.
W52s.	Surface water ponded in channel; pond 20 ft long, 1 ft wide and 3–6 in deep. NW¼ sec. 28, T. 16 S., R. 46 E.
W53s.	Surface water ponded in channel; pond 1 ft long and 3 in deep; near east edge of the carbonate zone. Vegetation: pickleweed. NW¼ sec. 28, T. 16 S., R. 46 E.

TABLE 51.—*Semiquantitative partial analyses, in percent of the water, of brines in Middle Basin*

[Analysts and analytical methods given on pages B90–B91. Samples collected January–February, 1956, a dry year; localities shown on pl. 3; ground-water samples designated "g"; surface water "s" ground water issues at surface]

	W17–56s	W18–56g		W17–56s	W18–56g
Ca	0.08	0.03	B	.01	.002
Mg	.02	.03	Sr	.008	.01
K	.09	.04	Total dissolved solids	7.8	3.5
Na	2.88	1.12			
SO_4	.57	.6			
Cl	4.21	1.71			

W17–56s. Surface water in pool in channel 300 ft south of jeep trail; SW¼ sec. 30, T. 27 N., R. 1 E. Water bugs and segmented larvae; black algae in bottom, red algae along banks. pH of algae is 7.5; pH of salts at edge of water is 6.0.

W18–56g. Ground water at marsh on west side, ½ mile west of SW. cor. sec. 7, T. 26 N., R. 1 E.

TABLE 52.—*Semiquantitative partial analyses, in percent of the water, of surface and near-surface brines in Badwater Basin*

[Analysts and analytical methods given on pages B90–B91. Samples marked with suffix "–56" collected January–February 1956, a dry year; others collected January–February 1957, a wet year; localities shown on pl. 3; surface-water samples designated "s;" ground water "g"; ground water issues at surface except as indicated otherwise See also tables 17, 18, 19]

	East Side											Mormon Point	
	W54s	W55g	W19–56g	W20–56g	W56g	W57g	W58g	W59g	W21–56g	W22–56g	W60g	W23–56g	W61g
Ca	0.015	0.06	0.16	>0.05	0.09	0.3	0.16	0.11	>0.04	>0.04	0.04	0.1	0.16
Mg	.002	.001	.01	.025	.002	.07	.03	.01	.006	.008	.04	.01	.03
K	.2	.31	.28	.075	.06	.45	.25	.08	.06	.05	.1	.09	.17
Na	12	12	11.7	1.55	1.5	4.7	2.5	.96	1.24	1.4	1.5	3.6	2.4
SO_4	1.2	1.1	2.2	.65	.90	.30	.30	.20	.37	.22	.20	.4	.6
Cl	8.6	19	18.8	2.2	1.4	7.4	2.8	1.60	2.28	2.32	1.6	5.8	1.7
B	.003	.002	.007	.02	.001	.001	.001	.001	.002	.001	.001	.0005	.002
Sr	.003	.001	.004	.01	.004	.01	.006	.01	.02	.01	.01	.01	.028
Total dissolved solids	30	31	33	5	4.5	15	7.8	3.2	4	4	4.8	10	7.8
pH	6.8	6.8	---------	---------	6.5	6.8	7.0	7.0	---------	7.0	7.0	6.0	6.8

	Mormon Point—Continued			Coyote Hole and Amargosa River									
	W62g	W63g	W64s	W65g	W66g	W67s	W68s	W69g	W70s	W71s	W72s	W73g	W24–56s
Ca	0.25	0.51	0.49	0.03	0.03	0.05	0.05	0.02	0.03	0.07	0.06	0.02	0.1
Mg	.08	.17	.16	.01	.01	.02	.05	.14	.03	.04	.03	.02	.07
K	.37	.75	.73	.02	.02	.04	.14	.42	.09	.1	.06	.1	.1
Na	5.3	11	11	.54	.6	1.1	3.5	10	2.8	2.3	1.4	3.5	3.5
SO_4	.3	.2	.3	.3	.2	.6	1	2.4	1.8	1.2	.9	1	1.1
Cl	1.6	11.0	17	1.1	1.0	1.6	3.6	14	2.4	1.6	1.3	3.2	5.2
B	.003	.007	.007	<.001	.001	.001	.002	.006	.001	.002	.002	.001	.005
Sr	.06	.12	.11	.006	.007	.002	.005	.001	.006	.005	.004	.003	.01
Total dissolved solids	17	34	33	1.8	2.0	3.4	11	28	8.6	7.1	4.3	9.8	10
pH	6.8	6.8	6.8	7.0	7.6	7.8	7.4	6.8	7.4	7.4	7.3	6.8	7.0

	Salt Well area																	
	W25–56g	W74g	W75s	W76g	W77s	W78g	W79s	W80g	W81s	W82g	W83s	W84g	W85s	W86s	W87s	W88g	W89s	W90s
Ca	0.006	0.04	0.13	0.2	0.18	0.4	0.3	0.5	0.43	1.1	0.35	0.85	0.43	1.09	0.72	2.15	0.67	0.8
Mg	.001	.008	.02	.03	.03	.07	.08	.3	.09	.24	.07	.13	.09	.1	.2	.43	.1	.1
K	.0006	.01	.04	.05	.07	.09	.10	.45	.18	.62	.13	.20	.18	.20	.31	.55	.25	.33
Na	.23	.14	.81	1	1.2	2.5	1.9	6.6	2.5	6.5	2.2	3.7	2.6	3.6	5	2.9	4.2	5.7
SO_4	.02	.1	.1	.1	.1	.1	.2	.2	.2	.4	.2	.2	.2	.1	.2	.3	.3	.2
Cl	---------	.2	1.2	2.8	3.6	5.4	5.4	11	8.6	13	6.6	9.8	8.6	9.4	11	13	11	11
B	.0003	<.001	.001	<.001	.004	.001	.001	.003	.001	.005	.001	.001	.001	.001	<.001	.002	.001	.002
Sr	.001	.001	.007	.01	.02	.03	.03	.1	.41	.11	.031	.06	.04	.05	.07	.2	.07	.1
Total dissolved solids	.6	.56	3.7	4	5.5	9.2	7.9	30	12	31	9.9	17	12	15	21	29	19	22
pH	6.5	6.8	6.7	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8

See footnotes at end of table.

TABLE 52.—*Semiquantitative partial analyses, in percent of the water, of surface and near-surface brines in Badwater Basin*—Continued

	Gravel Well area						West side north of Gravel Well								
	W91s	W92s	W26–56g	W93g	W94s	W95s	W96g	W97g	W98g	W27–56s	W99s	W100g	W101g	W102g	W103g
Ca	1.47	0.27	0.02	0.15	0.09	0.9	0.012	0.003	0.01	0.02	0.03	0.17	0.007	0.001	<0.003
Mg	.2	.05	.02	.03	.03	.13	.004	.001	.002	.02	.01	.07	.002	.001	<.001
K	.38	.86	.02	.05	.03	.2	.09	----------	<.01	.01	<.01	.08	.01	----------	.20
Na	6.4	2.1	.9	1.1	5.0	7.3	1.5	----------	.09	.34	.05	1.4	.01	----------	12
SO_4	.2	.1	.1	.2	.2	.2	.5	.2	.2	.4	.1	.4	.06	.04	.7
Cl	14	5.4	1.4	2.8	9	12	2	.01	.01	----------	.05	2.8	.02	.1	15
B	.001	<.001	.0005	<.001	<.001	.001	<.001	<.001	<.001	.007	<.001	.003	.001	.001	<.001
Sr	.06	.008	.01	.01	.02	.04	<.001	<.001	<.001	.003	.001	.007	<.001	.001	<.001
Total dissolved solids	29	7.8	2.5	4.2	18	26	10	.03	.54	2	.30	6.6	.07	.2	33
pH	6.8	6.8	7.0	6.8	6.8	6.8	6.8	7.9	6.9	6.0	7.0	7.0	6.9	6.8	6.8

NOTE.—Description of sample and locality as follows:

W54s. Surface water, ponded against west edge of silty rock salt. SW¼ sec. 33, T. 26 N., R. 1 E.

W55g. Ground water at Salt Pools, in pool on west side of massive rock salt, 1,500 ft west of end of road at the pools.

W19–56g. Salt pools, east side of massive rock salt.

W20–56g. Ground water from spring at Badwater.

W56g. 1957 duplicate of W20–56g.

W57g. Ground water, second cove south of Badwater, 18 in. below surface; west side of channel near eroded rock salt; 700 ft west of toe of fan.

W58g. Ground water, 15 in. below surface; 100 ft east of W57g.

W59g. Ground water, 15 in. below surface; in marsh at toe of fan; second cove south of Badwater.

W21–56g. Seep with water bugs, algae, and larvae at toe of fan next north of Coffin Canyon fan.

W22–56g. Ground water at marsh in cove north of Coffin Canyon. Pickleweed, rush, saltgrass.

W60g. 1957 duplicate of W22–56g.

W23–56g. Ground water in marsh at north base of Mormon Point; south edge of marsh, by highway.

W61g. 1957 duplicate of W23–56g.

W62g. Ground water in marsh 120 ft north of W61g.

W63g. Ground water in marsh 500 ft north of W61g; north edge of the marsh.

W64s. Surface water in channel draining north from marsh; 750 ft north of W61g.

W65g. Ground water, in pool at Coyote Hole. SE¼ sec. 15, T. 22 N., R. 2 E. Vegetation: saltgrass, rush, reed grass.

W66g. Ground water, west edge Coyote Hole. Vegetation: pickleweed.

W67s. Surface water, west of Coyote Hole, at west edge of pickleweed; 300 ft west of W66g.

W68s. Surface water, ponded in Amargosa River west of Coyote Hole. S½ sec. 15, T. 22 N., R. 2 E.

W69g. Ground water, 1 ft below surface, in channel of Amargosa River 10 ft east of W68s.

W70s. Surface water, ponded in Amargosa River, west distributary, about 0.8 mile upstream from W68s. SE¼ sec. 22, T. 22 N., R. 2 E.

W71s. Surface water ponded in Amargosa River, east distributary. Vegetation: pickleweed and saltgrass. SE¼ sec. 22, T. 22 N., R. 2 E.

W72s. Surface water in spring-fed tributary of Amargosa River. NW¼ sec. 26, T. 22 N., R. 2 E.

W73g. Ground water, underflow in Amargosa River channel; about 1 ft below surface; water in fine gravel or grit. Vegetation along banks, pickleweed. SE¼ sec. 27, T. 22 N., R. 2 E.

W24–56s. Amargosa River about 1½ miles south of Coyote Hole.

W25–56g. Ground water, at Salt Well, 9 ft below surface. NW¼ sec. 12, T. 22 N., R. 1 E.

W74g. 1957 duplicate of W25–56g.

W75s. Surface water in channel draining north from Salt Well; NW¼ sec. 1, T. 22 N., R. 1 E.

W76g. Ground water, 2 in. below surface, by channel at W75s.

W77s. Surface water in channel 600 ft north of W75s.

W78g. Ground water at side of channel at W77s; 3 in. below surface.

W79s. Surface water, running stream 1 ft wide and ½ in. deep; 750 ft downstream from W77s, north edge sec. 1, T. 22 N., R. 1 E.

W80g. Ground water 1 ft below surface 10 ft to one side of channel at W79s. Efflorescence of sulfate salt crust ends northward at this place.

W81s. Surface water, 1,200 ft downstream from W79s.

W82g. Ground water, 18 in. below surface and 10 ft to one side of W81s.

W83s. Surface water, flowing stream 6 ft wide and 1 in. deep; 1,350 ft downstream from W81s.

W84g. Ground water, 1 ft below surface, 5 ft to one side of W83s.

W85s. Surface water, flowing stream 6 ft wide and ½ in. deep, 1,550 ft downstream from W83s.

W86s. Surface water, flowing stream 6 ft wide, 3 in. deep; 1,500 ft downstream from W85s.

W87s. Surface water, flowing stream 6 ft wide and 2 in. deep; 1,500 ft downstream from W86s.

W88g. Ground water, 1 in. below surface, and 1 ft to one side of W87s.

W89s. Surface water, ponded in channel; pond 1,000 ft long. 1,680 ft downstream from W87s.

W90s. Surface water, ponded in channel; pond 300 ft long. 1,650 ft downstream from W89s.

W91s. Surface water, ponded in channel; pond 1,000 ft long. 3,000 ft east-southeast of bench mark 252 on West Side Highway.

W92s. Surface water, slow seep in channel, 300 ft west of W91s and 200 ft east of pickleweed.

W26–56g. Ground water in marsh ½ mile east of Gravel Well. Vegetation: pickleweed, saltgrass, rush.

W93g. 1957 duplicate of W26–56g. Although 1957 was a wet year compared with 1956, there was less water in this marsh in 1957 than in 1956.

W94s. Surface water, ponded in channel east of pickleweed and 1,500 ft southeast of W93g.

W95s. Surface water, ponded in channel 2,500 ft east-southeast of W93g.

W96g. Ground water, 4 ft below surface; in silt facies of carbonate zone. 2,000 ft east of road; 3 miles south of Bennetts Well.

W97g. Ground water, Bennetts Well. Water table reported 15 ft below surface.

W98g. Ground water, spring at Eagle Borax 100 ft east of old crystallizing vat.

W27–56s. Surface water in pond 1,000 ft east of W98g.

W99s. 1957 duplicate of W27–56s.

W100g. Ground water, 44 in. below surface of gypsum east of Eagle Borax.

W101g. Ground water, Shortys Well. Water table 10 ft below surface at well.

W102g. Ground water, Tule Spring.

W103g. Ground water, 3 in. below surface, in flood plain 6,000 ft east-northeast of Tule Spring.

PATTERNED GROUND

By Charles B. Hunt and A. L. Washburn

GENERAL FEATURES

The term "patterned ground" refers to ground whose surface has developed orderly patterns, such as polygons, circles, steplike forms (terracettes), and stripes (Washburn, 1950, 1956). Polygonal mudcracks due to drying and shrinking of the surface layer of a flood plain are a familiar example of patterned ground, but patterns may also develop in ground that is cobbly or bouldery. They may develop on ground that is flat or sloping and with or without a sod cover. Patterned ground is not restricted to one or even a few climatic regions, for it tends to develop wherever marked changes in volume of surface or near-surface layers of the ground occur as by desiccation, thermal change, and hydration or other chemical changes.

Patterned ground occurs in most regions, but it is particularly well developed where frost action is intense, as in polar, subpolar, and alpine regions. Freezing and thawing are major factors in the processes by which some kinds of patterned ground develop. Yet many different kinds of patterned grounds, much of it resembling that of cold climates, are also developed in warm arid climates where solution and reprecipitation of salts and above-freezing thermal changes have substituted for frost action.

For instance, some occurrences of patterned ground involving salts in warm arid regions include the following:

Africa. Tunisia (Bellair, 1957), central Sahara (Meckelein, 1959).

Australia. Several varieties of polygons in the sodium chloride crust of Lake Eyre (Bonython, 1956; Madigan, 1930), polygons with marginal ridges in highly saliferous mud at the bottom of Lake Hart (Kindle, 1926), and "pimpled prairies" in clayey soils in New South Wales where rainfall is seasonal (Hallsworth and others, 1955).

China. Pentagonal saucer-shaped polygons of rock salt in the salt desert of Lop, Sinkiang Province (Huntington, 1907).

Egypt. Polygons with low rims in salt crust of the Salina near Mex (Walther, 1912) and polygons in the Arabian desert observed by geologists of the Arabian-American Oil Co. (Richard C. Kerr, oral commun., 1959).

Iran. Polygons in salt crust in the Great Kawir, Central Iran (Bobek, 1959).

Jarvis Island (lat 1° S., long 156° W.). Irregular polygons involving alkali salts and lacking sodium chloride (Kindle, 1926).

Mexico. Polygons, believed to be due to thermally induced volume changes in gypsum, at Purpuri Salina, studied by George W. Moore and Philip T. Hayes (George W. Moore, oral commun., 1959).

Mongolia (and probably China). Wedgelike features, simulating ice-wedge casts, in the Gobi Desert (Hörner, 1950).

Peru (northwest). Hexagonal polygons outlined by marginal ridges of rock salt of a salina south of Punta Parinas (Bosworth, 1922).

United States. Polygons with marginal ridges in sodium sulfate at the bottom of a desiccated lake on the Carriso plain in San Luis Obispo County, Calif. (Kindle, 1926), large-scale rectangular polygons in a playa at the southwest end of the San Angustin Plains, N.Mex. (Potter, 1957), and "pimpled prairies" on the Snake River Plains, Idaho (Maldé, 1961).

Patterned ground in salt environments is probably widespread. Also, many desert occurrences, including probably some of the above and large forms simulating ice-wedge polygons (Lang, 1943; Knechtel, 1951, 1952), are associated with desiccation cracking. If desiccation forms are added to those developed by other processes in warm arid climates, it is clear that patterned ground in such climates is very common. Nevertheless, it has not been extensively studied, and some aspects of the origin of patterned ground in warm arid climates are as puzzling as in cold climates.

In cold climates the extent and degree of development of certain kinds of ground patterns are proportional to the intensity of the frost action; there is a lower latitude and lower altitude limit to such features. The low parts of Death Valley are practically without frost, and the extent and degree of development of patterned ground here is proportional to the salt content of the ground. The extent of this patterned ground is limited by the occurrence of salts.

Although solution and reprecipitation of salts has been a major factor in the development of some kinds of patterned ground in Death Valley, the other factors causing volume changes in soil have operated too, and on kinds of ground as different as that of the saltpan and that of the gravel fans.

The different areas of patterned ground in Death Valley are alike climatically. Rainfall averages about 1.5 inches per year; the evaporation rate is about 150 inches yearly. Air temperatures as high as 134°F and ground-surface temperatures as high as 190°F have been recorded. Temperatures below 32°F are rare, and frozen ground is virtually unknown because of the high salinity of most of the surface water and soil moisture. Data on rainfall, evaporation, temperature, humidity, and wind are given on pages B5–B11.

PATTERNED GROUND IN DEATH VALLEY

OCCURRENCES ON THE SALTPAN

A major factor in the development of patterned ground on the saltpan is the evaporation of the brines and the resulting accumulation of salts on the surface and in the capillary fringe which may or may not reach the surface. The ground patterns therefore are affected by such hydrologic variables as frequency of flooding by surface water, depth to the water table, amount of ground water discharge, and the composition and total salinity of the surface or ground water being evaporated.

Most of the patterned ground on the saltpan exhibits sorting of salts from the clastic sediments, but because the clastic sediments are fine grained, except at the very edge of the saltpan, there is no size sorting of the clastic material. Patterned ground on the saltpan is accentuated by deposition of salts on desiccated surfaces, and the salt deposit itself, in turn, develops distinctive patterns.

On the flood-plain part of the saltpan the patterned ground is ephemeral, for these areas are subject seasonally to alternate flooding and desiccation. Elsewhere on the saltpan the patterns have been developing over a long period of time, at least scores and, perhaps, hundreds of years. Except on the flood plains, the salt crust in which ground patterns have developed formed as the result of desiccation of a Recent lake that flooded the valley floor to a depth of about 30 feet. Archeologic evidence indicates that this lake existed about 2,000 years ago (Hunt, A. P., 1960, p. 289); the patterned ground has developed since that time.

PATTERNED GROUND IN MUD AND SALT ON THE FLOOD PLAIN

Patterned ground differs from one part of the flood plain to another in an orderly way that faithfully reflects differences in the hydrologic regimen of the ground.

At the lowest places where surface water collects, as in the areas of flood plain west of Badwater and in the central part of Middle Basin, the mud rarely, if ever, completely dries, and a salt crust 1–12 inches thick forming on the surface of the mud has a complex pattern of polygons and superimposed nets formed of irregular low hummocks.

The drainage lines tributary to these low parts of the flood plain are frequently flooded, but the water does not collect there. These parts of the flood plain are mostly wet mud flats coated only with an efflorescence of salts 1–2 mm thick. The surface layers of this mud occasionally dry, and desiccation cracks develop in them; but frequent washing by surface water prevents salts from accumulating on the surface and removes, by solution, salts that accumulate in the desiccation cracks. Such ground is water saturated repeatedly and for considerable periods each year.

Where flooding by surface water is intermediate in frequency, more persistent desiccation cracks develop in the mud, and more salts accumulate in them than can be removed by succeeding floods. The resulting patterns are polygonal; various forms develop, depending on accidents of flooding and of ingress of ground water seeping laterally from channels.

Farther from the low parts of the flood plain, where flooding by surface water is infrequent, the mud is nevertheless wet or damp much of each year because ground water seeps laterally from the nearby lower channel areas. Netlike patterns develop here and are related to accumulation of salts in the capillary fringe above the ground water.

Open salt pools associated with circle patterns develop where salts that have accumulated in the surface layers of the mud become dissolved from below, causing the surface layers to collapse.

The clastic fraction of the mud is silty clay or clayey silt throughout the flood-plain area. There are, however, important differences in texture due to differences in composition and amount of salts in the mud. These mineralogic differences affect both the water regimen and the development of the patterned ground.

POLYGONAL PATTERNS

Surface water collects at two low places in the Death Valley saltpan. One place, west of Badwater, collects surface runoff from the Amargosa River and the area tributary to the northern part of Badwater Basin. Another, in the central part of Middle Basin, collects surface runoff from the closely surrounding area and from Cottonball Basin and Salt Creek to the north. This basin is slightly higher than the low part of Badwater Basin, but the channel connecting them crosses a divide 1½ feet higher than the low part of Middle Basin. A vast area will have to be flooded before Middle Basin again overflows into Badwater Basin.

The water that collects in these low places is highly saline; its evaporation forms a salt crust, as much as 1 inch thick, that is practically all sodium chloride. The mud below the salt remains wet most of the time between floodings. The result is a complex hydrologic regimen involving precipitation of salts both from evaporation of surface water and from subsequent evaporation of ground water. The crust that forms by the evaporation of surface water is cracked polygonally into slabs 1–2 feet in diameter. Evaporation of ground water from the underlying mud deforms this pattern by depositing new salts in the polygonal cracks and at the contact between the mud and the overlying salt crust. As a result, both the edges and central areas of the polygonal slabs of salt become bulged into irregular blisterlike forms 6–12 inches wide that arch over a hollow space 1–2 inches high forming a net pattern superimposed on a polygonal pattern (fig. 53).

Drainage courses on the flood plain tributary to these low places are subject to frequent washing by surface water. When this ground dries, polygonal cracks de-

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FIGURE 53.—Blisterlike net pattern superimposed on polygonal pattern in salt crust in low part of Middle Basin where surface water collects. The polygonal pattern is due to cracking of a crust deposited when the surface water evaporated; the net pattern superimposed on this results from subsequent evaporation of ground water from the mud under the crust. Photograph by John R. Stacy.

velop in it because of desiccation. Their spacing and width of gaping are controlled by the amount and texture of the salts that have crystallized in the mud. The relationships are illustrated in figure 54, a view along the channel of Salt Creek below Cottonball Basin showing how the mud in the middle of the channel, where both the content of salt (sodium chloride and sulfate) and size of the crystals are greatest, has dried faster than mud in the slightly higher ground along each side of the channel. The coarser textures seem to facilitate drying. The clastic sediment is the same in all three belts—silty clay. At the time the photograph was taken the mud in the middle of the channel would support a jeep; but the vehicle sank hub deep in the wet mud along each side of the channel. An unusual crossing! The cracks in the middle extend downward about 5 inches and end at a coarsely crystalline layer of glauberite, a sodium calcium sulfate.

Rather generally, the ground at the edge of standing water is softer than that under the water, probably because of textural differences in the salts in the muds.

FIGURE 54.—Three zones of desiccation cracks along the channel of Salt Creek 3 miles south of Cottonball Flat. Along the center of the channel the mud is damp and the cracks, 1–2 feet apart and about 5 inches deep, gape as much as 1 inch. This mud contains the most salt (5 percent by volume of both sodium chloride and sulfates) and the salt crystals, especially the sulfate (glauberite), are 3 mm in diameter. Along each side of this zone are parallel belts of somewhat wetter mud having narrower cracks 6–8 inches apart; in these belts the salt content is 4 percent by volume and the crystals are 1.5 mm in diameter. Along the side of these belts, at the edge of the channel (dark ground), the mud is still wetter and is without cracks; its salt content is 3.5 percent and the crystals are no larger than half a millimeter.

On other parts of the flood plain, especially in Badwater Basin, the clayey silt may have desiccation cracks extending downward about 1½ inches and ending at a porous layer of coarsely crystallized gypsum. At still other places on the flood plain where such coarsely crystallized layers are absent, and other noticeable changes in texture are lacking, as on parts of the Devils Speedway, the cracks can be followed into the mud as deeply as 15 inches.

But all these areas are subject to frequent severe washing, and salts that accumulate (mainly by capillary rise) on the surface or along the walls of the desiccation cracks are removed by the next flood. This patterned ground is ephemeral in comparison with the occurrence in non-flood-plain environments. In parts of these areas, at any given time, cracks may may not be discernible; but circular spots of salt efflorescence 1 or 2 feet in diameter occur, surrounded by belts of damp or wet clayey silt 1–2 feet wide. Well-defined cracks first become noticeable still farther from the channels, beyond the spots.

Progressing outward, polygonal cracks become apparent on ground that is washed less frequently or less severely. Salts accumulate in the cracks even though the washing may be sufficient to clear salts from the surface between the cracks. This accumulation is probably largely due to capillary rise and to differential efflorescence along the cracks, and as a result ramparts of salt grow around polygonal areas of mud (fig. 55).

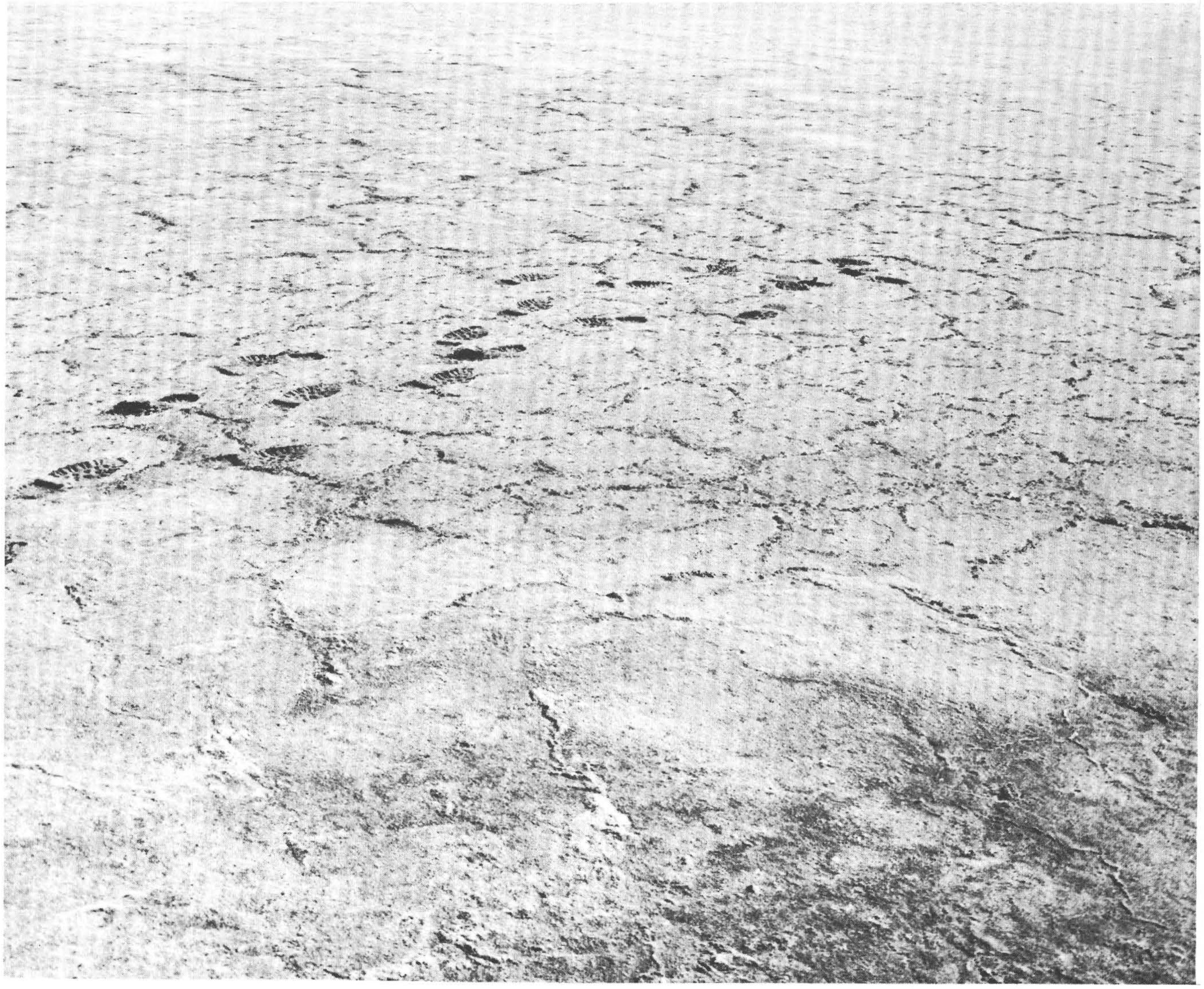

FIGURE 55.—Polygons in mud outlined by salt veinlets on flood plain in Cottonball Basin. Compare with figure 56.

One such place has an efflorescence 0.5 to 2 mm thick in spots 8 inches to 1½ feet in diameter and outlined by cracks containing salt in veins 1–50 mm wide. These veins form ramparts as much as 10 mm high. The ramparts are in the form of inverted V's, partly hollow and partly filled by veins of later salt. Under some of the thickest and highest ramparts the mud is slightly higher than it is in the interior of the polygons. Some small ramparts grade laterally into depressions 2–10 mm wide and 1–2 mm deep. Between the cracks and the spots of efflorescence in the interior are numerous tiny holes, 1–2 mm in diameter, that permit subsurface water or vapor to escape to the surface.

Still farther from the area of washing there is enough salt to completely cover the polygons. Some of these clearly are formed by continued growth of the kind already described. Where the ramparts are sufficiently high and continuous, surface water may be ponded within the polygons and deposit a crust of salt across the surface between the ramparts. Such growth may progress far beyond the stage illustrated in figure 56.

The polygons illustrated in figure 56 range in size from 2 by 4 feet to 7 by 8 feet. The interiors are smooth and contain salt crystals as much as one quarter of an inch in diameter. The salt crust in the interiors is 1 inch thick; the mud below it is wet, and green algae live on the underside of the salt crust.

Ramparts around the small polygons are 2 inches high and 8 inches wide; those around the large polygons are as much as 2½ inches high and 12 inches wide. Salt crystals in the ramparts are smaller than those in the crust across the interior of the polygons. Under the ramparts is a ridge of mud having open cracks, some 1 mm wide. Salt collects in the cracks to a depth

FIGURE 56.—Polygonal pattern in salt crust on flood plain northeast of Cottonball Flat. The veins of salt that developed in the cracks are high enough to form ramparts that pond water within the polygons, and a layer of salt extends across the surface between the ramparts.

of more than 1 inch. Several generations of vein salt can be distinguished. On the surface, flanking the ramparts, is a delicate efflorescence of salt crystals that looks very much like hoar frost and probably formed in the same way, as a sublimation.

The polygons are 4 to 6 sided, but their borders are irregular and many are curved. Some of the ramparts forming the borders are discontinuous and tend to be en echelon. About two-thirds of the polygons are subdivided into secondary ones by cracks, and small ramparts of salt as much as 1 or 2 inches wide. Some of these borders too are discontinuous and subdivide the polygons incompletely, and some are arcuate. No differences were seen between those oriented north-south and those oriented east-west. Similar polygons at Lake Eyre, Australia, were described by Bonython (1956, p. 73, pl. 1, fig. b) as "crocodile-skin" salt.

Samples of the mud under the polygons were collected and tested for their salt content. A water solution of 100 cc of mud from a 3-inch layer under the interior of a polygon contained 9.5 grams of salts; an equal solution from a 3-inch layer of mud under a rampart had 7.5 grams.

A somewhat different form of polygon, also 4–6 sided, observed only in Cottonball Basin, is outlined by troughs instead of ridges. The troughs, ½–2 inches wide and ¼–½ inch deep, outline polygons about 5 feet in diameter. The troughs are flanked by a thin salt crust that slopes and thins away from the troughs. These crusts, ⅛ inch thick and 2–5 inches wide, are along each side of the troughs. In the interior of the polygons the salt occurs as a thin efflorescence, except for some spots where the salt is thickened to a crust like that bordering the troughs.

An adjoining area of somewhat drier ground has similar 4- to 6-sided polygons 3–7 feet in diameter. These polygons are outlined by faint discontinuous troughs a ¼ inch deep bordered by salt ridges 1–6 inches wide and ½ inch high. The ridges may occur along either or both sides of a trough. Around many polygons no trough remains; the edge is marked only by a salt ridge that consists of mud and salt with a thickened cap of salt. Veins of salt extend downward into the mud ridge.

An extreme and spectacular development of the salt polygons is in Badwater Basin 2–3 miles west of Badwater where huge polygonal slabs have grotesque forms referred to locally as "salt saucers" (fig. 57). These saucerlike structures are as much as 35 feet in diameter and more than 1 foot thick. Their edges are turned up as steeply as 30° and as high as 2 feet. They are arranged as a series of shingles, mostly overlapping northward as if there had been a growth or thrust in that direction. This is one of the few examples in Death Valley where direction of exposures appears to have affected the patterned ground. The salt at the edges of the saucers generally is at least 1 foot thick; the interiors are thin, in places less than 1 inch thick. The saucers have been attacked by solution along cracks and where the salt is turned up at the edges. The raised parts erode to a delicate honeycomblike structure, and stalactites of salt grown downward from the overhanging edges. Where the surface is weathered, it also develops tiny salt pinnacles half an inch high that generally rise southward. The slabs rest on wet, or damp, clayey silt. About 1 foot below the surface of this mud is a hard layer, presumably rock salt.

The large saucers are divided into second-order plates; these, in turn, are divided into third-order ones. The large ones range from about 30 by 20 feet to 35 by 30 feet. The turned-up rims may be overlapped by adjacent rims, but most of them are joined as a rampart from which the salt slopes in both directions into the adjoining saucers. The width of the ramparts is 1½–4½ feet. They have open cracks ranging from less than 1 inch to 7 inches wide.

The second-order plates range from 2 by 3 feet to 5 by 10 feet. Their edges are 1–12 inches high and are marked by cracks as much as 1 inch wide along which several generations of vein salt can be distinguished.

The third-order plates are about 2 by 3 feet and occur only in the largest second-order ones. The edges of these plates are sealed with salt in ridges half an inch high at most; these edges appear to be healed fractures filled with vein salt, commonly in 2 generations with the youngest vein only 1 mm wide. These plates have 4–5 sides.

The cracks in the salt saucers, of whichever set, tend to join in threes. Junctions commonly are at right angles, with one crack terminating where it meets another.

The interiors of many plates have a solution hole an inch or so in diameter, where rainwater that collected in the saucer has escaped. Around these sinkholes is a radial pattern of salt veinlets each about 1 mm wide.

Possibly the salt saucers began their growth very much like the salt polygons already described, that is, by desiccation cracking of the mud and accumulation of salts in the cracks and on the surface between them.

The second- and third-order cracks in the salt saucers clearly are younger than the first-order ones. The second-order cracks extend into the polygons from the primary ones, and the third-order cracks extend from either of the other two. Moreover, the vein salt in the third-order cracks, is shown by the layering, younger than that in second-order cracks which, in turn, is younger than that in the first-order cracks, as is shown by the vein intersections. The second- and third-order cracks developed in the salt crust, presumably because of thermal contraction and expansion of this crust. Further evidence of the effectiveness of this process in Death Valley is found in the polygonal cracking of the older and thicker salt crust of the chloride zone.

The development of salt polygons on the flood plains may be interrupted at any stage because of washing by floods due to accidents of drainage changes. When a well-developed salt polygon becomes washed by fresh flood water, the last salt to be removed by the water is the thick mass in the ramparts. A complex series of different kinds of patterned ground results,

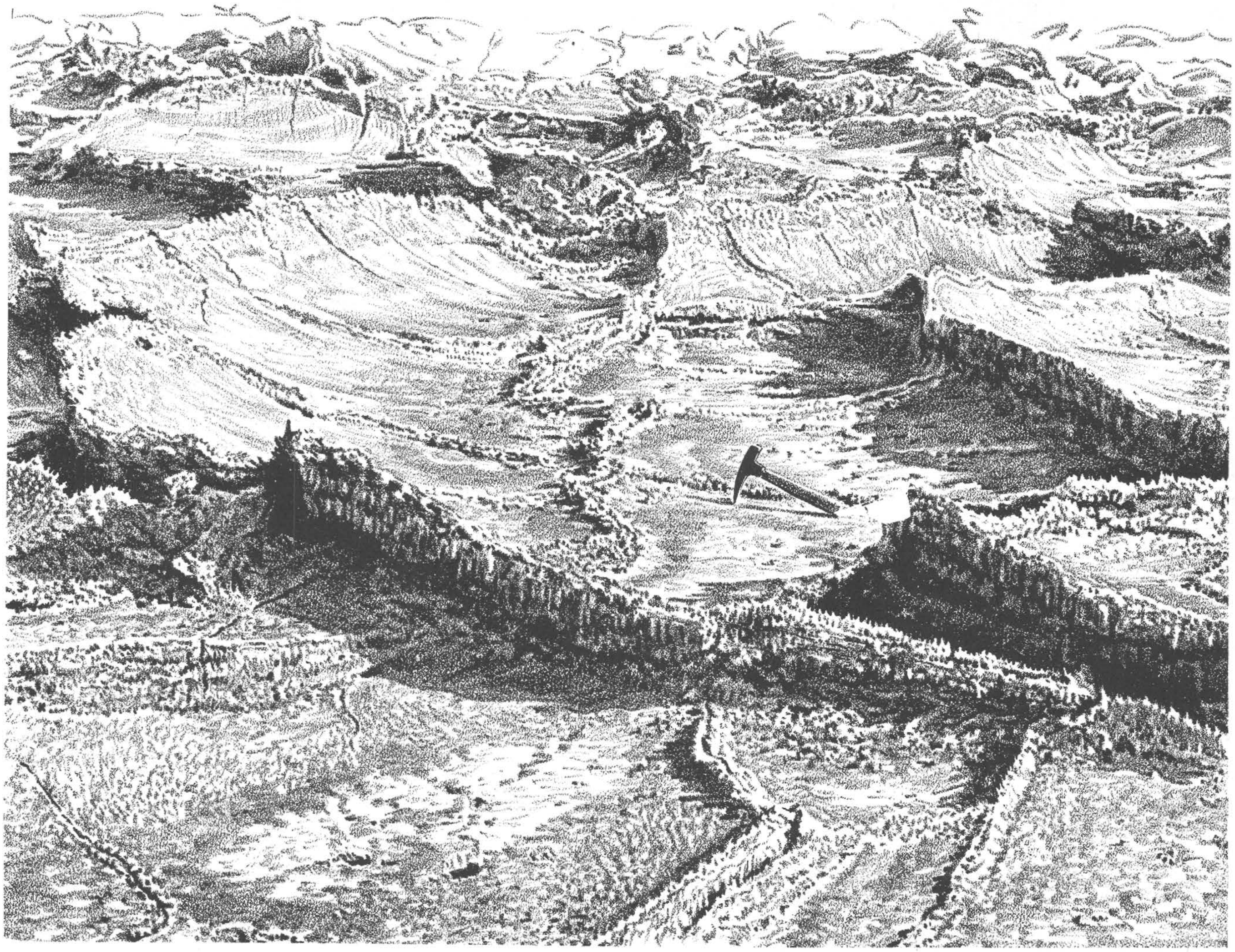

FIGURE 57.—Salt saucers west of Badwater. Drawn by John R. Stacy, from photograph.

some members of which are suggestive of the beginning stages of the development of salt polygons; that is, the ground has a polygonal pattern formed by ramparts of salt surrounding mud that is bare except for a thin efflorescence.

Huntington (1907, p. 251–252) ascribed similar features in the salt desert of Lop, Sinkiang Province, China, to desiccation, followed by filling of the resulting cracks.

> The wind, or some other agency, apparently deposited dust in the cracks; when rain or snow fell, the moisture brought up new salt from below; and thus the cracks were solidly filled. When next the plain became dry, the pentagons appeared again. This time the amount of material was larger, and the pentagons buckled up on the edges and became saucer-shaped.

Why the greater amount of material should result in buckling, if reappearance of the polygons is associated with drying and contraction, is not clear. Grabau (1920, p. 272) described "cakes of salt" in Death Valley, probably salt saucers, "tilted at various angles, probably by the expansive force of growing crystals * * *" According to Madigan (1930, p. 229), who found salt-saucerlike forms at Lake Eyre, southern Australia,

> The explanation seems to lie in thermal expansion. One could expect the slabs to fall on the contraction of the surface. They are held up by the ends becoming cemented in by the crystallization of further salt in the cracks and angles formed * * * Where the crust is a foot or more thick, it is still only the surface inch or so that is buckled up, with solid salt in the cracks below the slabs.

A rectangular very different form of polygonal pattern occurs locally along some distributaries of the Amargosa River in Badwater Basin. The salt crust at these places is silty, and the channels are narrow. The cracks in the silty salt extend transversely across the channel, and some longitudinal ones parallel the sides. In channels 15 feet wide, the cracks commonly are 3–5 feet apart. Rectilinear ice-wedge polygons form in analogous situations in oxbow channels in the Arctic (Hopkins and others, 1955, pl. 41).

NET AND CIRCLE PATTERNS

Net patterns on the flood plain are formed by blisterlike growths of salt crust ½–1 inch thick on damp or wet mud. Accumulation of the salts in the surface layers of the mud raises the crust in blisterlike forms above a hollow space 1–3 inches high and 12–18 inches wide (fig. 58). The blisters are spaced rather regularly with their centers 3–4 feet apart. Between them is rough salt crust.

The crust is composed of 35–60 percent salt, chiefly sodium chloride, mixed with mud.

The net pattern formed by the blister salt develops on ground where surface water is infrequent, but where there is much evaporation of ground water, causing salts to accumulate in and heave the upper layers of the mud. The net pattern develops as a late-stage ground pattern superimposed on an earlier polygonal one in the low part of the flood plain where surface water collects (p. B108). It develops alone without polygonal patterns along some edges of the flood plain seldom reached by surface water, but it is kept damp or wet by lateral seepage of ground water from the channels. It also develops on the silt ground of the carbonate zone (p. B54).

The importance of ground water for the development of the net pattern of blister salt crust can be seen also along narrow washes at the edges of the saltpan. Mud in the bottom of the wash may have desiccation cracks and be dry, whereas that along the banks still is damp and covered by a net pattern of blister salt crust. The damp banks contain as much as 10 percent by volume of salts, owing to repeated lateral seepage of water into that ground from the wash, and subsequent evaporation. The bed of the channel, though, is washed of its salts by the surface water, and the mud, with desiccation cracks, may have as little as 0.2 percent by volume of water-soluble salts.

At many places, but for unknown reasons, the blisterlike growths are arcuate, and the ground surface has about the same appearance as the surface of a large bun. The arcuate growths are 1–3 inches high, 4–8 inches wide, and 10–20 inches long. The arc commonly is that of a circle having a radius about equal to the length of the arc; it invariably is convex towards the flood plain as if the crust grew with thrust in that direction.

Circular collapse structures have developed on the flood plain at the salt pools in Badwater Basin. These structures consist of depressions in the flood plain 12–18 inches deep and 5–10 feet in diameter. At the center is a pool of water a foot or so deep that has overhanging banks of muddy salts. The water is clear but nearly saturated with sodium chloride. The slopes of the depressions consist of concentric, but discontinuous, terraces of salty mud that appear to represent the surfaces of slump blocks (fig. 59).

In the area of the salt pools, the water table is only 1 foot or 2 feet below the surface. During long periods of drought, the salt pools dry up and become crusted over the salt; but in wet weather after there has been much runoff from the nearby fans, old pools reopen and new ones appear. The salt pools probably represent places where the influx of fresh ground water during floods has been sufficient to dissolve salts in the upper layers of the flood plain and cause those layers to collaspe into the pool below. The process visualized is suggestive of the hypothesis of rise of subsurface water that has been suggested to explain some kinds of circle patterns in permafrost areas and elsewhere (Nikiforoff, 1941).

POLYGONAL PATTERNS IN THE CHLORIDE ZONE

The chloride zone of the saltpan consists of four facies: massive rock salt, rough silty rock salt, smooth silty rock salt, and eroded rock salt (p. B61). The salt in these deposits is generally more than 6 inches thick and locally is 5 feet thick. The surface of the salt is 1–2 feet higher than the flood plain and is therefore too high to be flooded by surface water. The salt rests on damp mud.

Silt that caps smooth silty rock salt develops desiccation cracks outlining small polygons 1–3 inches in diameter. The silt commonly has a porous layer of sulfate salts ½ or 1 inch below the surface, and the desiccation cracks extend downward to that layer. Some of the cracks are half an inch wide at the surface.

The salt underlying the silt also is fractured by cracks outlining polygons that commonly are five sided and 2–6 feet in diameter. Locally, these fractures extend through the overlying silt, but generally they do not show at the surface (figs. 60, 61).

Solution pits through the salt are reflected at the surface. Many of these are located at the junction of the polygonal cracks; in the salt and at the surface these pits have three rills draining to them, marking the alinement of the cracks.

Except for the desiccation cracks in the surface layer of silt, the patterned ground in the smooth silty rock salt is an old feature that is being modified very slowly at present. The cracks in the salt layer predate a flood from Cow Creek that deposited silt in and across cracks in the smooth silty rock salt along that drainage. The litter deposited by this flood includes abundant wagon

FIGURE 58.—Blisterlike growths of salt crust on the flood plain produce net patterns like those shown in this view. The locality is along a channel draining the Devils Speedway. Photograph by John Stacy.

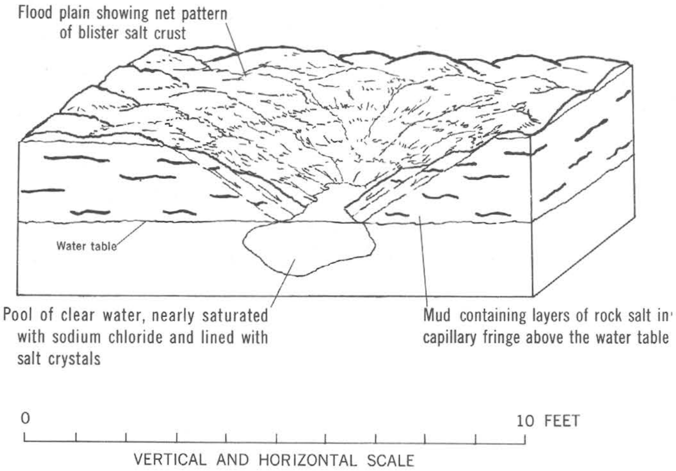

FIGURE 59.—Block diagram of salt pool showing probable faults accompanying surface collapse.

boards and lumber with square nails, and evidently dates from before 1915. Additional evidence is provided by an old trail to a prospect camp in Cottonball Basin; the trail has been abandoned at least 30 years, but it has not been obscured by changes in the surface of the patterned ground in the smooth silty rock salt. On the other hand, it has been destroyed where it crosses washes, because of washing and the development of more recent patterned ground there.

Polygonal cracks like those in the smooth silty rock salt occur also in the much thicker massive rock salt and rough silty rock salt. Both these deposits have exceedingly rough surfaces of closely set jagged pinnacles, 12–18 inches wide and 1–2 feet high, surrounded by moatlike depressions about 1 foot wide. The cracks are mostly along the depressions, but a few cross

FIGURE 60.—Silt surface of smooth silty rock salt showing desiccation cracks and solution pits. The silt in this view is 3 inches thick and is underlain by 4 inches of rock salt broken by cracks into polygonal slabs, 2–6 feet in diameter, like those on figure 61. The pits, which reflect solution pits in the underlying salt, commonly are at the corners of the polygonal slabs. Photograph by John R. Stacy.

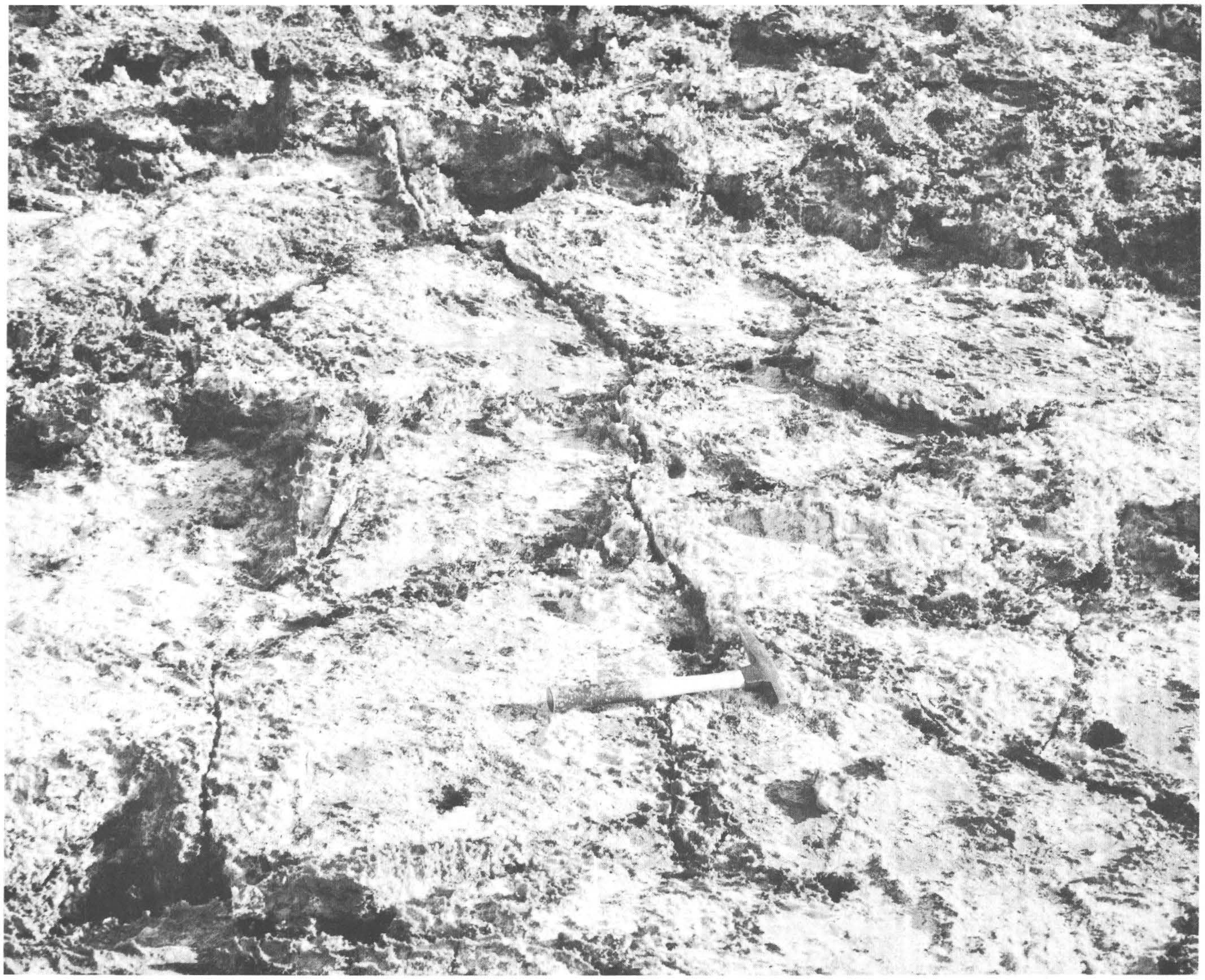

FIGURE 61.—Smooth silty rock salt, where the silt layer has been removed by erosion, showing polygonal cracks in the salt. The polygons are 3-5 feet in diameter; the cracks are open and as much as one-eighth inch wide. Along most cracks there is a ridge of salt, but no new salt has been deposited in the cracks.

the pinnacles. The cracks commonly join in threes, but the polygons may have four, five, or six sides. As in the smooth silty rock salt, the cracks are without secondary salt deposits, and they are as much as three-fourths of an inch wide. Many cracks have been widened by solution.

The cracks are old features and apparently have controlled the pattern and location of the depressions around the salt pinnacles. At the Salt Pools, a part of the rock salt was leveled for a road about 1944. No pinnacles of salt remain on this smoothed ground, but the polygonal cracks are plain. The only discernible change there in 15 years is a roughening of about 25 percent of the surface by the development of delicate knifelike ridges an inch or so high, all trending north and separated by grooves with rounded bottoms. In this disturbed ground, the ridges are concentrated along the cracks, but similar lacelike growth oriented north characterize the whole surface of the rock salt.

Polygonal cracks also are preserved in rock salt that has been eroded, smoothed, or otherwise partly destroyed through washing by surface water. Erosion is most rapid at the depressions where the cracks are located; where erosion is most advanced, the salt may be completely removed from the positions of the cracks, exposing bare mud between relics of the pinnacles of rock salt.

It seems very possible that the cracks in these thick layers of rock salt are due to changes in volume resulting from thermal changes. On a warm day one can hear the cracking, which causes a series of sharp and rather melodious "pings."

NET PATTERNS AND POLYGONS IN THE SULFATE ZONE

Two kinds of ground patterns, nets and polygons, have developed on the gypsum deposits in the sulfate zone. A net pattern has formed where the ground is marshy, as along the west side of Cottonball and Middle Basins and along both sides of Badwater Basin. The ground consists of cauliflowerlike lumps of gypsum and other salts, 4–8 inches in diameter and about as high (fig. 26). Water standing between the lumps contains 1–5 percent dissolved solids. The lumps consist of a highly porous and generally damp or wet core of coarsely crystalline gypsum coated with a less porous and firmer crust of finer grained gypsum cemented with sodium chloride. The lumps clearly are constructional features due to the deposition of the salts, presumably by capillary rise of water wherever salts protude above the water surface, but this generalization does not explain why the lumps are so uniform in their dimensions and spacing.

In the parts of the marshes that are frequently flooded by surface water, the surface of the gypsum deposit is smooth and divided into polygons a few feet in diameter (fig. 62). The cracks outlining the polygons are accentuated by lumpy growths of gypsum and other salts. The lumpy growths evidently form when the water level falls below the ground surface and water rises by capillarity along the cracks and deposits new salts there and at the surface.

Polygonal patterns also form on the surface of the dry massive gypsum—for example, near Tule Spring. These gypsum deposits consist of 3–5 feet of massive, but crumbly and porous, gypsum capped by a firm, but discontinuous, caprock of bassanite, the hemihydrate of calcium sulfate, or anhydrite 2–6 inches thick.

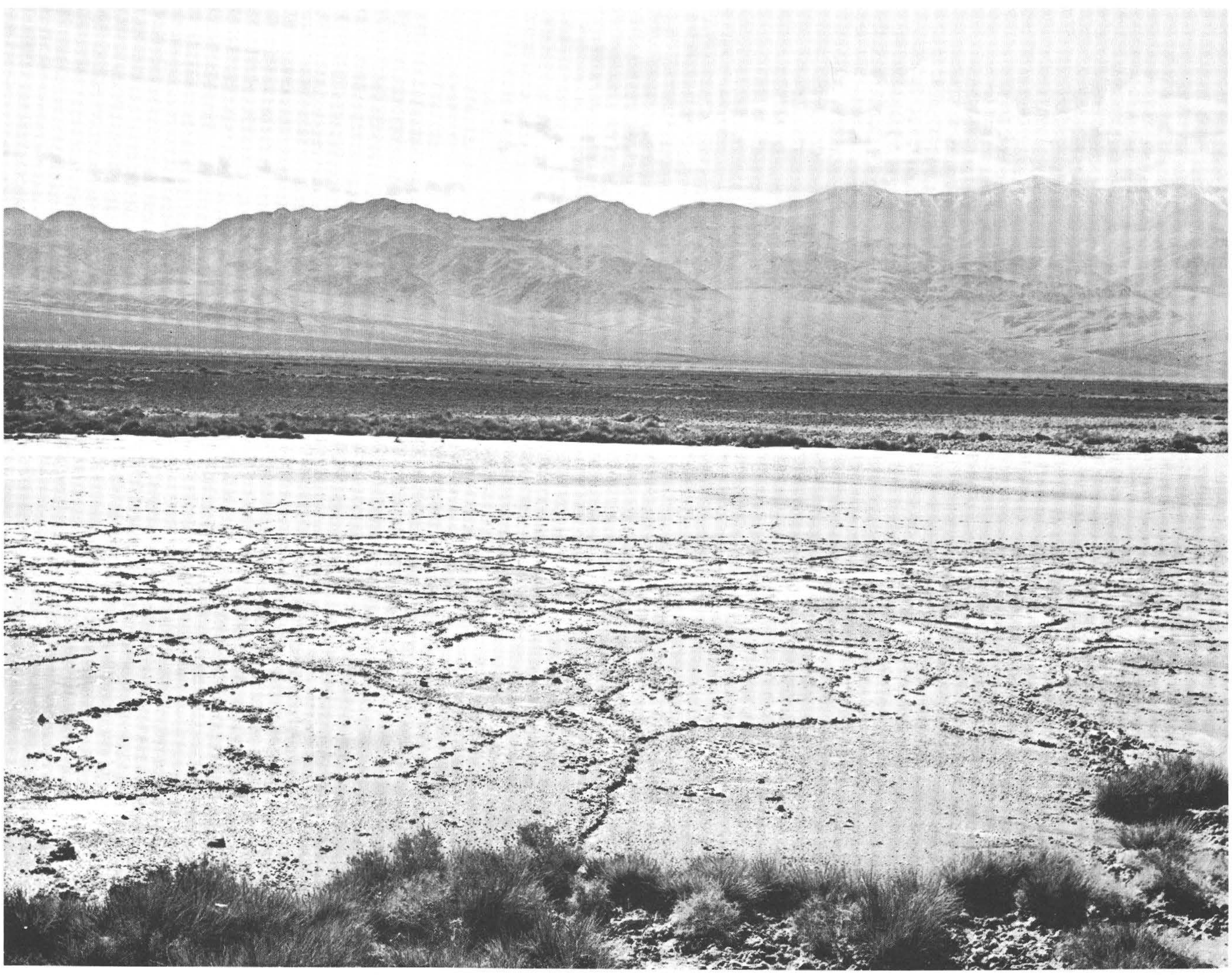

FIGURE 62.—Polygonal pattern in sulfate marsh. The smooth surface with polygonal cracks, 3–5 feet apart, is mostly gypsum with some bassanite and halite. The lumpy growths, 1 to 2 inches wide, along the cracks are gypsum coated with halite. Photograph by John R. Stacy.

About 1 inch of granular calcium sulfate mixed with windblown clastic material forms a surface layer overlying the anhydrous caprock (fig. 63). After a wetting this layer first cracks polygonally into primary plates 4–5 inches in diameter. On continued drying, the plates subdivide into minor ones 1–2 inches wide. When completely dried, the near-surface part of the plates becomes porous and fluffy and readily eroded by the wind; the open cracks become filled with the fluffed material, and the polygonal pattern is destroyed. The surface is changed to a microdune pattern having no relation to the previous polygonal-patterned ground.

The primary crack pattern in the surface layer faithfully follows a crack pattern that extends downward into the anhydrous caprock and through it to the crumbly porous gypsum. The secondary cracks in the surface layer are restricted to that layer and end downward at the caprock. The firm layer of caprock is of irregular thickness and is lumpy rather than continuous. The lumps are thickest along the walls of the cracks; away from the cracks, in the interior of the polygons, the anhydrite and bassanite may be reduced to irregular veins in gypsum.

The second-order cracks in the surface layer clearly are desiccation cracks. Those in the caprock appear to be both a cause and an effect of mineralogic changes in volume of the calcium sulfate due to its hydration or dehydration or, most likely, both alternately.

NET PATTERNS IN THE CARBONATE ZONE

The carbonate zone of the saltpan consists of an outer sand facies that grades panward to silt. The percentage of salts is much less than in the sulfate and chloride zones. Carbonate salts are minor but characteristic of the zone. The sulfate salts are mostly in a

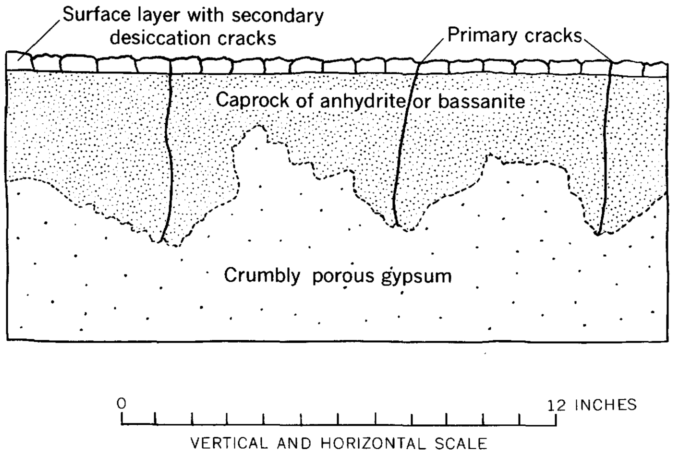

FIGURE 63.—Diagram of upper layers of massive gypsum deposit. The surface layer is broken by closely spaced desiccation cracks that end downward at the firm caprock. Wider spaced cracks in this firm layer end downward at the underlying crumbly gypsum, and the caprock is thickened along the cracks.

thin caliche layer a few inches below the surface, and the chloride salts form a thin crust on the surface.

The surface of the sand facies of the carbonate zone consists of hummocks 1 or 2 inches high and a few inches in diameter; the ground pattern is that of nonsorted nets. Where gravel has been washed onto the sandy ground, it collects in the depressions between the hummocks to form sorted nets.

The deposit on which this pattern occurs is fine to medium sand, consisting of rounded or subrounded grains of quartz with a little dolomite, limestone, and feldspar, and some mica and hornblende. Locally, there may be substantial percentages of volcanic glass or other volcanic rocks. The deposit, 3–10 feet thick, crops out in a belt about half a mile wide along the west side of the saltpan and along the east side of Cottonball Basin and Middle Basin. Panward, the deposit grades into silt.

The surfaces on the sand where the sorted and nonsorted nets have developed are nearly flat. They are a few inches to a few feet higher than the washes and are thus protected against flooding.

The upper 2 or 3 feet of the sand can be divided into 3 layers differing in their salt content. The surface layer, 3–20 inches thick, contains as much as 10 percent of water-soluble salts. Below this is a fluffy caliche layer 1–3 inches thick composed largely of sulfate minerals, chiefly sodium sulfate around Cottonball Basin and chiefly calcium sulfate elsewhere. Under this fluffy layer is the parent sand containing 5–10 percent of disseminated mixed salts. The net pattern is best developed around Cottonball Basin where the salts include a high percentage of the readily soluble sulfates and carbonates of sodium. In Badwater Basin, where the salts include a high percentage of comparatively insoluble calcium sulfate, the net pattern is poorly developed and masked by polygonal desiccation cracks.

This net pattern can develop in 50 years. Old trails that have been abandoned that long (see Hunt and others, 1965) still are distinct where they cross this kind of patterned ground, though they are destroyed where they cross washes. The trail surfaces, once smoothed, have developed a new net pattern even though the salt heaving or other changes have not been sufficient in this period of time to obscure the alinement. Examples of this may be seen near the North Side Borax Camp at the northeast corner of Cottonball Basin and at a segment of old trail preserved just west of the West Side Highway, half a mile south of the road to Trail Canyon.

The sorted nets that occur on the sand facies of the carbonate zone are like the nonsorted ones, except for the stones that have washed onto the surface and collected in the depressions. The stones do not occur in the sand under these nets. In this respect these sorted nets are unlike some of those in cold climates where stones from within a deposit become segregated from the fine fractions.

Nonsorted nets built of blisterlike growths of salt crust on the surface and entirely like those on the flood plains (p. B112; fig. 58) have developed on the silt facies of the carbonate zone. The ground is kept wet or damp by ground water seeping panward, and the capillary fringe reaches the surface in this silt. The ground water contains 3–6 percent of salts which accumulate at the surface in the crust forming the blisterlike growths. The crusts are ¼–1 inch thick and contain as much as 80 percent salts, mostly sodium chloride. In the silt 2–3 inches below this crust of sodium chloride is a layer containing scattered nodules of the less soluble gypsum; below that layer the silt contains tiny euhedral crystals of acutely and doubly terminated calcite. These layers are not cracked polygonally. The only vegetation is pickleweed; the nets occur on the bare ground between the shrubs.

SORTED POLYGONS AT EDGE OF THE SALTPAN

Sorted polygons were noted at two places at the edge of the saltpan. Both localities are at the shoreline of a Recent lake (Hunt and others, 1965) and evidently are related to it; both are on south-sloping hillsides. One is by the highway across Death Valley opposite Artists Drive; the other is on the west side of Cottonball Basin about 2 miles south of Salt Creek by the road to the West Side Borax Camp.

These sorted polygons, illustrated on figure 64, are as much as 9 feet in diameter, 5 to 6 sided, and the edges join in threes. They are outlined by troughs ¼–¾ inch deep and 3–10 inches wide. Stones collected in the troughs are mostly about 1 inch in diameter, but some are as large as 3 inches. The stones are angular like the gravel uphill. The bottoms of the troughs are caked sandy silt. Many stones in the interior of the polygons stand on pedestals; those in the troughs do not. Some stones in the interiors of the polygons stand on edge, and probably are in the process of being ejected from the ground. But even in periods of protracted rain, this ground probably does not become wet below about 2 inches, and this depth of wetting would be the limit for heaving that is going on at present. The stones in the troughs have been transported there by slope wash from the gravel just uphill (fig. 64).

The crack system extends downward 6–8 inches where the cracks end at the top of a layer of rock salt at least 3 inches and perhaps many inches thick. The layer above the rock salt to the surface is stony and highly gypsiferous.

The troughs at the edge of the major polygons show no cracks at the surface, but at a depth of 6 inches they are underlain by a crack system in the layer of rock salt which is ridged along the cracks (fig. 65). Similar ridges occur along the cracks of the rock salt layer associated with the smooth silty rock salt (fig. 61). Measurements at one excavation showed the ridges to be 8 inches wide and 2 inches high with rounded tops and a well-developed medial crack ½–¼ inch wide at the top and almost vertical, into which a knife blade could be inserted to the hilt (3 in.). As shown here and at several other excavations, the ridge and the crack parallel the troughs above, and the gypsiferous ground overlying the crack is a hardened wedge-shaped mass that widens upward from the cracks.

The major polygons are subdivided into smaller ones by open fissures that are as much as 2 mm wide and spaced about 1 foot apart.

The gypsiferous ground at these locations is an old caliche formation that rises with the topography away from the saltpan. The more nearly horizontal rock salt cuts across the gypsiferous caliche and is younger. Presumably it formed when the Recent lake stood at this level, for there would have been evaporation from the water table that extended into the stony and gypsiferous hillside. The cracks that have developed in the rock salt and the construction of the ridge along the crack on top of the salt have occurred since that time. Both locations having sorted polygons are on south-facing slopes, and the layer of salt must be expanding and contracting because of thermal changes. Little moisture is available at present to contribute to volume changes by desiccation, except in the surface inch or two of the gypsiferous layer overlying the rock salt.

OCCURRENCES ON THE GRAVEL FANS

The gravel fans (fig. 53) comprise many different kinds of ground. The youngest gravel, that along the present washes, contains very little fine grained sediment or salt except at the very foot of the fans where it grades into the sandy playa beds. In that gradational belt at the foot of the fans some irregular net patterns have developed, owing to salt heaving, but in general the youngest gravel is without patterned ground.

The next older gravel also is without much fine grained sediment or salt; but it is old enough to stand in small benches 1 or 2 feet above the present washes, and the stones on it are coated with desert varnish. The boulders and cobbles are firm and not weathered. In places on these surfaces, cobbles that have collected in natural levees along the sides of small washes have produced a striped effect; but this ground is without polygonal, net, or circle patterns, and the stripes are hardly true patterned ground. This gravel is at least as old as the Recent lake, that is, more than 2,000 years old, judging by its elevated geomorphic position, desert varnish, and archeologic remains (Hunt and

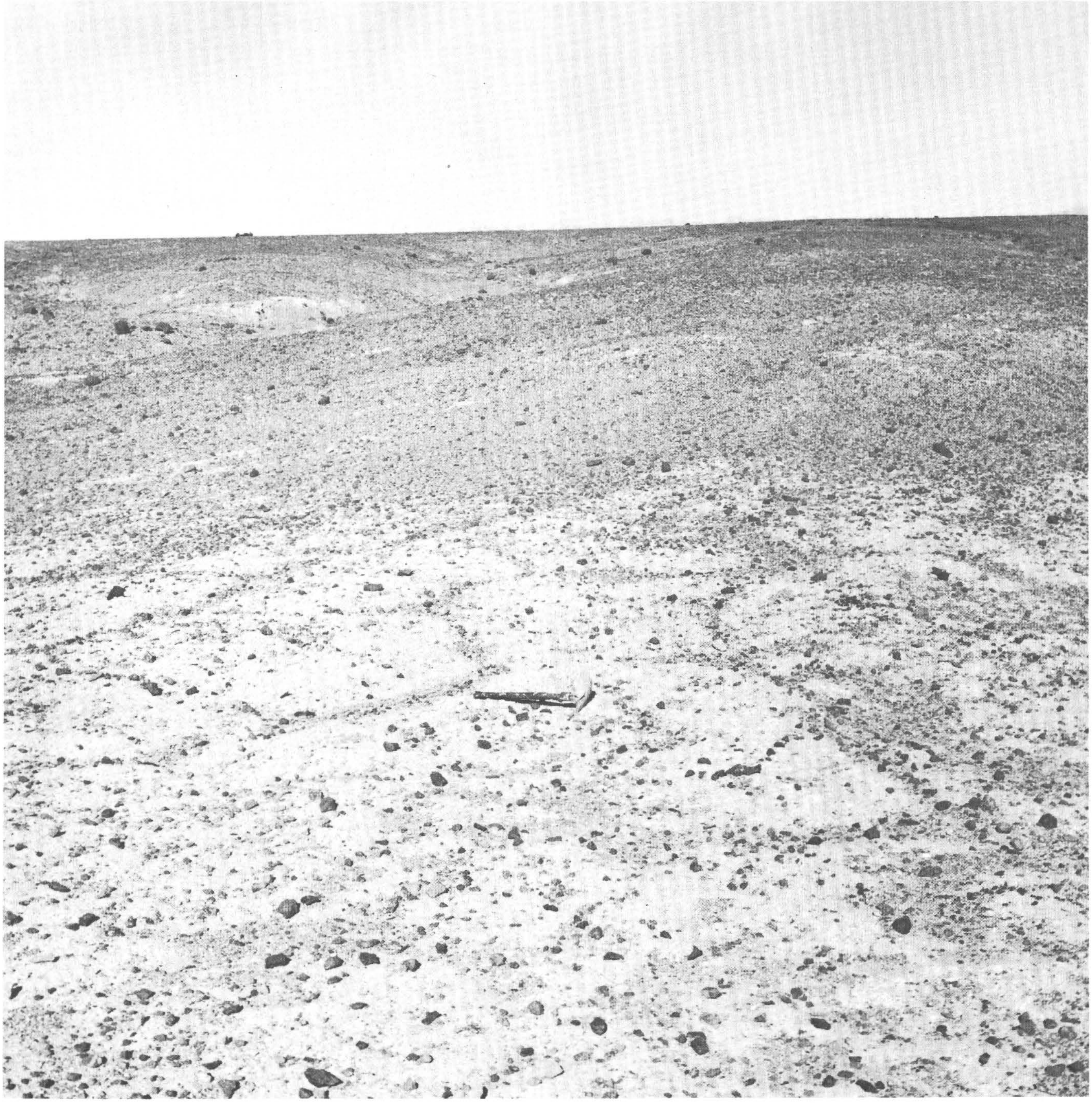

FIGURE 64.—Sorted polygons at shoreline of Recent lake, just north of the road across Death Valley to the Devils Golf Course. The polygons are outlined by shallow troughs in which stones have collected. Trench shovel as scale.

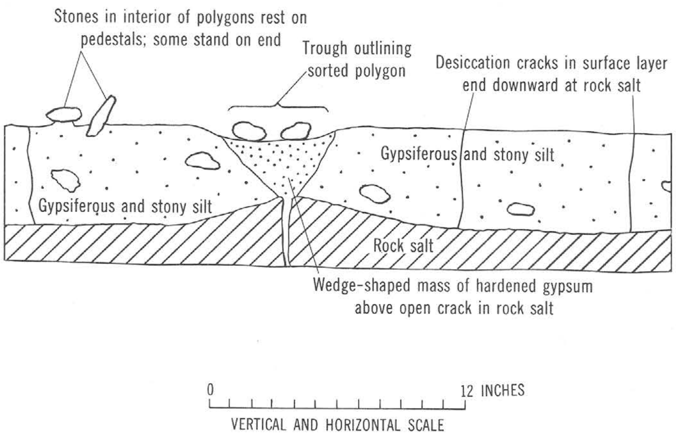

FIGURE 65.—Section illustrating relation of troughs at borders of sorted polygons to ridges and cracks in the underlying layer of rock salt.

others, 1965). Yet in the same time span, patterned ground of many kinds has developed on the saltpan; the absence of patterned ground in this gravel probably is accounted for by the fact that the ground contains little fine grained sediment, little salt, and rarely is wet.

The oldest of the gravel formations on the fans is characterized by smooth surfaces of desert pavement. Boulders that formerly were round on these surfaces are disintegrating to form a new crop of angular rock fragments that form the smooth pebble surface and are underlain by a few inches of silt. Under the silt is the parent gravel. Slopes on the fans are 200–400 feet per mile on the fan surfaces, but hillsides are steep at the edges of washes. These formations have well-developed sorted steps and some sorted polygons.

At a few places on the gravel fans there are deposits of well-sorted shingled beach gravel. The percentage of fine grained sediment in these deposits is small, but they are highly saliferous. Locally, terracettes have developed on these gravel deposits.

A still different type of ground is in the area north of Furnace Creek where many hillsides and hilltops are formed of fine grained playa deposits of Tertiary age protruding through the gravel. Sorted polygons, sorted nets, and sorted stripes are well developed where this ground is saliferous. Similar patterns have developed locally on old spring deposits that are fine grained, poorly consolidated, and powdery.

SORTED STEPS AND TERRACETTES IN GRAVEL

Sorted steps are patterned ground with a steplike form and a sorted appearance due to a downslope border of stones embanking an area of finer material upslope (Washburn, 1956, p. 833). They are a striking feature of hillsides of the oldest gravel formation, and they occur on the gently sloping surface of desert pavement too. The steps are more abundant on the fans northeast of the saltpan than on those around the other sides, which correlates with the fact that the fans to the northeast have more salt in their surface layers than do the other fans. The saliferous fans lie leeward of the saltpan, and their salts were probably derived from the pan and transported there by wind.

The importance of mass wasting on the gravel fans is illustrated by the trains of chips, slabs, and blocks that extend downslope from disintegrating boulders.

Where studied the sorted steps are small lobate terraces 3–12 inches high, 1–4 feet wide across the contour, and as much as 15 feet long parallel to it. They fade out on slopes of less than about 10°. The treads slope 3°–11° and consist of fine gravel; the risers in front slope at angles as much as 37° and are of coarse gravel that commonly forms an embankment 1 inch high around the periphery of the tread. In general, the steeper the slope where steps occur, the higher the riser. Most treads have more salt on the surface than does the surrounding ground; they are without desert varnish or nearly so and are lighter colored than the darkly stained surrounding ground.

Some sorted steps were excavated in an effort to learn details of their subsurface structure. One of these, on a south-facing slope, has the following dimensions:

Hillside slope	14° to the south
Slope of tread	7°
Maximum slope of riser	37°
Maximum height of riser	8 in.
Length of tread	6 ft
Width of tread	7 ft

The riser had a dozen cobbles as much as 6 inches in diameter and a concentration of stones 1–2 inches in diameter. This gravel merged downslope with the tread of a lower step. Some of these stones are varnished. Stones larger than 1 inch in diameter formed a layer 2 stones deep on the riser. One of the stones stood edgewise, protruding ¼ inch and extending 1 inch into the ground.

On the tread were 8 cobbles as much as 6 inches in diameter, a few stones 1–2 inches in diameter, and a concentration of pebbles less than 1 inch in diameter. The scarcity of large stones on the tread, considering its area, contrasts not only with their concentration on the riser but with the surrounding desert pavement. A comparable area of desert pavement in that location has twice as many cobbles 2–6 inches in diameter and about five times as many pebbles 1 inch in diameter as were on the tread. The total number of stones and the range of sizes on the tread and on the riser combined about equal that of the surrounding ground. On a nearby tread a stone standing on edge was found; it extended 2 inches into the ground and protruded 2 inches.

Stones on the large treads are not varnished, and these treads are therefore lighter colored than the surrounding desert pavement. Stones on these treads are slightly more disintegrated than those on the desert pavement, and their desert varnish is being flaked off and destroyed. On some steps that are small and where the sorting is less distinct than on the large ones, stones on the treads are varnished.

The tread on one step that was excavated had 7 spots of salt efflorescence (epsomite, thenardite, bassanite, and possibly glauberite) each covering 4–8 square inches. Figure 66 is a cross section of this step.

The surface of the fine-grained sediment just below the pebbles on the tread is irregular and knobby. The knobby areas, nearly 1 foot wide, are bounded by cracks that extend downward 6–9 inches. The walls of the cracks are cemented; material in the cracks is powdery. At the surface some cracks are open as wide as one-eighth of an inch. Many stones in the fine-grained layers (*B* and *C* in fig. 66) are disintegrated like those at the surface. Caliche coats the bottom and uphill sides of the buried pebbles. The buried pebbles show a slight orientation. Foliation and lineation in the different layers of the tread and riser were as follows:

Treads:
- Surface layer of pebble pavement:
  - Foliation: 90 percent mostly parallel the slope; only 10 percent are inclined more than 45°.
  - Lineation: Random.
- Upper layers of fines (*B*, on fig. 66):
  - Foliation: Tends to parallel slope but less distinctly so than in the surface layer.
  - Lineation: Tends to parallel the slope.
- Bottom layer of fines in tread (*C*, on fig. 66):
  - Foliation: Stones parallel the slope.
  - Lineation: Random.

Risers:
- Surface layer:
  - Foliation: 90 percent tend to parallel the surface; only 10 percent are inclined 45° or more to the surface.
  - Lineation: Slight tendency to aline parallel to the contour, especially at the toe of the riser.
- Cemented layer of riser:
  - Both foliation and lineation nearly random.

Another step (fig. 67) that was excavated on a north-facing slope near Cow Creek, 1 mile south of Park Village, is composed of fine-grained sediment and is without pebbles on the surface. It is moundlike, and around it is a concentric band of fine gravel 3 inches wide on the upslope side and 24 inches wide downslope on the riser. Surrounding this gravel is desert pavement having small cobbles and pebbles. The step is without desert varnish, and the quartzite stones on it are pitted. A cross section of this step is given on figure 67.

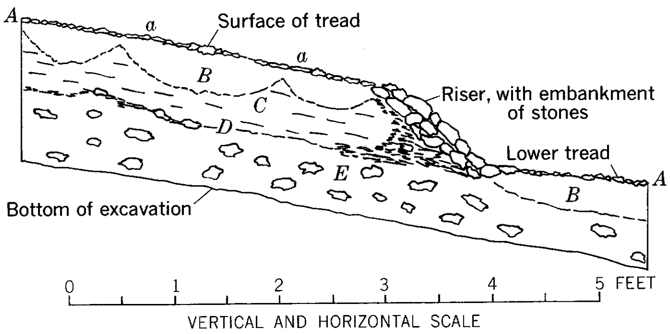

FIGURE 66.—Section of sorted step. *A*, Pavement of fine pebbles on tread of sorted step. *a*. Locations of salt efflorescence on tread. *B*, Dry porous light-gray layer cemented by salts; some stones. *C*, Damp soft brown layer with reddish spots; rises to within 0.5 inch of surface under spots of salt efflorescence. *D*, Firmly cemented stony layer. *E*, Parent gravel, not well cemented.

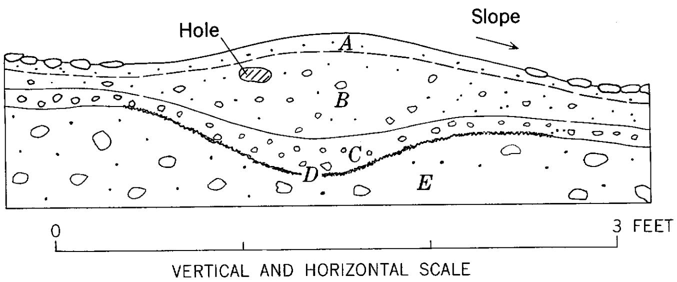

FIGURE 67.—Section of moundlike sorted step. *A*, Surface layer; silt, few pebbles 0.5 inch. *B*, Fine gravel, coarser than *A*; silt increases upward. *C*, Pebble layer; coarser than *B*, contains little silt. *D*, Coarsely crystalline gypsum. *E*, Parent gravel.

The salt content of the top inch of fine-grained sediment on the treads of the steps is four to eight times that of the similar layer directly below the surrounding desert pavement. This appears to be due to transport of salts to the surface of the tread from the layer just below it, because at some steps there is only half as much salt at a depth of 2–4 inches as there is at greater depth and under the surrounding desert pavement.

White spots of "alkali" are not confined to steps, for they occur also on the gravel benches along the rims of washes and as linear belts elongate with the slope. Their areas range from 1 square foot to 300 square feet. The large ones develop an irregular surface, suggestive of salt heaving. Many have a depression, suggesting a sinkhole, at the center. At all the spots, desert varnish is flaking from the stones, and silt shows through the pavement. Some of the spots are distinctly circular and form a variety of sorted circle in the desert pavement. The spots seem to be most abundant on north-facing slopes, but this observation is not offered with certainty.

The salts deposited on the surface include a high percentage of magnesium sulfate and of sodium carbonate, but many more analyses are needed to confirm that the salts on the surface and in the tread are layered in an orderly way with respect to their solubilities.

Steps occur also on the upper Pleistocene gravel beach bars of Lake Manly age. Unlike the fan gravels these beach deposits are rather homogeneous shingle gravel (Hunt and others, 1965). There are few fine particles, but where the steps occur, the salt content is high. In part, these steps may be minor beach terraces that have been accentuated by mass wasting.

To provide a basis for estimating the present rate of movement on the steps, two lines of wood dowels were installed on sorted steps on a slope of 15° a quarter of a mile above Park Village. The dowels, which were 6 mm in diameter and 20 mm long, were inserted to a depth of 10 mm. Precision of the original alinement was within about 3 mm. After nearly 4 years (January 1957 to November 1960) total movement of the tops of the dowels was as shown in table 53.

TABLE 53.—*Apparent displacement of two lines of dowels on sorted steps at Park Village during the period January 1957 to November 1960*

Station 1		Station 2	
Dowel	Apparent displacement of top of dowels (in mm), direction N or S	Dowel	Apparent displacement of top of dowels (in mm), direction N or S
1	0	1	15 NE (diagonal downhill)
2	1 S (uphill)	2	8 N (downhill)
3	1 S	3	1 N
4	0	4	2 S(uphill)
5	2 S	5	0
6	1 S	6	1 N
7	1 S	7	1 N
8	2 N (downhill)	8	3 N
9	1 N	9	4 N
10	0	10	5 N
11	1 S	11	2 N
12	1 S	12	3 N
13	2 S	13	1 N
14	2 S	14	½ N
15	½ N	15	2 N
16	1 N	16	2 S
17	2 N	17	3 N
18	4 N	18	0
19	1 N	19	2 N
20	1 N	20	1 S
21	2 N	21	1 N
		22	1 N
		23	2 N
		24	½ S
		25	1 N

The dowels were measured several times during the 4-year period. Comparison of measurements suggested slight irregular tilting but no movement of their bases, and since the final dowel positions were within the limits of observational error, the tilting may be spurious. Moreover, the possible tilting, if real, could be adjustment to the strains created when the dowels were driven into the gravel. Further evidence that the steps are moving very little, if at all, under the present environment is provided by trails more than 50 years old that cross the steps without signs of deformation by creep. The breakdown of some steps by gullying also suggests that they are static. However, the white alkali spots associated with some steps and the fact that many treads have but little desert varnish suggest some continuing activity.

It is concluded that the steps and terracettes in this area are probably less active under the present environment than formerly and that they probably originated in an environment with somewhat more moisture and more frequent and deeper wetting and drying of the ground than occurs now. Such conditions prevailed during the Recent pluvial period when there was a sufficient excess of moisture over evaporation to create a lake 30 feet deep in Death Valley. The steps and terracettes may date from that time.

STRIPES

On gravel-fan surfaces with desert pavement, trains of flakes, slabs, and blocks extend downslope from disintegrating boulders. On some younger gravels that are without desert pavement, natural levees of cobbles or boulders along the sides of shallow washes also give a striped effect, but the natural levees are due chiefly to fluvial processes.

Trains of boulders like those developed in other western mountains also have developed on the mountains bordering Death Valley. They occur on steep slopes above about 4,000 feet altitude, particularly where the Precambrian Stirling Quartzite crops out. In the mountains, solifluction may be an important part of the process by which the trains developed; on the gravel fans, however, the trains are due chiefly to sheet floods and rill wash on the desert pavement redistributing fragments that have collected around the base of disintegrating boulders. Creep is believed to be a less important factor in view of the excellent preservation of hillside trails abandoned more than 50 years ago (see Hunt and others, 1965) and the lack of appreciable movement of the steps with the dowels.

POLYGONS AND NETS ON THE SALT-CRUSTED TERTIARY FORMATIONS

Sorted and nonsorted polygons are strikingly developed on hilltops and on slopes as steep as 37° on saliferous Tertiary formations like those in the vicinity of Mustard Canyon and on the hills northeast of there. The polygons are sorted where gravel deposits thin out against the Tertiary formations; the polygons have the same dimensions and basic structure, but they are nonsorted where the ground is entirely fine-grained sediment of the Tertiary formations.

The saliferous Tertiary formations in the vicinity of Mustard Canyon are fine-grained playa deposits containing considerable salts of many different kinds. The deposits are covered by a crust of rock salt a foot or so thick that conforms to the topography, and the polygons are due to cracking of this crust (fig. 68).

The largest polygons tend to be six sided; but the length of the sides varies greatly, and the shapes and sizes are correspondingly irregular. Diameters range from 6 to 16 feet. The cracks outlining the polygons meet in threes—some at equal angles, but some at angles that vary greatly. Width of the cracks ranges from a hairline to one-sixteenth inch, except where widened by solution where they may be as much as 3 inches across. Some cracks are at least 1 foot deep. The cracks are irregular in detail along a band about 1 inch wide; they wind in broad arcs, some 2 feet long in a band about 6 inches wide. The cracks widen upward into a U-shaped eroded trough about 1 inch wide.

Near the edge of the gravel deposits, stones collect in the depressions along the polygonal cracks, forming sorted polygons.

The gravel overlying the salt-crusted Tertiary formations is a transported mantle that rests on the

FIGURE 68.—Polygonally cracked salt crust on hillside of a Tertiary formation at Mustard Canyon. The polygonal slabs are as much as 16 feet in diameter; the salt crust is about 1 foot thick.

surface rather than in it, as in desert pavement, and many of the stones are on edge. Those along the cracks are edgewise (fig. 69), and they fill cracks 2 inches wide. The gravel in the cracks is not cemented. At a depth of 10 inches the gravel-filled crack is a quarter of an inch wide, and this thins to a hairline at 21 inches. The following cross section was measured along one of the cracks (fig. 69).

Surface.

Depth (inches)	
0–1	Layer of scattered stones 1 stone thick.
1–21	Loose gravel in crack 2 in. wide at surface; ¼ in. wide 10 in. below surface; hairline width at base of this unit; walls consist of cobbles and pebbles in a silt matrix.
21–24	Loose gravel; crack ends downward at top of this layer.
24–24½	Layer of salt (probertite) extends across position of the crack.
24½–26	Well-bedded silt; beds continuous across the projected position of the crack.
26–26½	Noncemented granules.

Base of Pleistocene.

26½–47	Fine-grained playa sediment, Pliocene(?)

Base of excavation.

The dip of the cracks in the salt crust is vertical where the cracks are oriented up and down the slopes; but it is at right angles to the surface where the cracks are transverse to the slopes, a feature strikingly illustrated in Mustard Canyon where the canyon walls are steep. The dip of transverse cracks into the hillside is approximately the complement of the angle of slope of the hillside. Some measurements, for example, are—

Slope of hillside	*Dip of crack*
24°	66°
29°	65°
32°	55°
37°	47°

In general, salt has accumulated along the cracks to form ramparts a few inches high and as much as 10 inches wide on their upslope side as illustrated on figure 70. Downhill from the cracks, salt has accumulated as vertical walls as much as 20 inches high facing the canyon; but this is a secondary feature not directly related to the polygons, and may be due in part to redeposition of salt dissolved from the projecting edges of salt in the cracks that angle into the hillsides. In places the polygons are strikingly accentuated because the ramparts serve to retard erosion by slope wash. Erosion of the vertical walls of salt produces pedestal rocks like those found in badlands.

The polygonal cracking of the crust of rock salt on the Tertiary formations in the Mustard Canyon area probably is due to the same process as that causing the

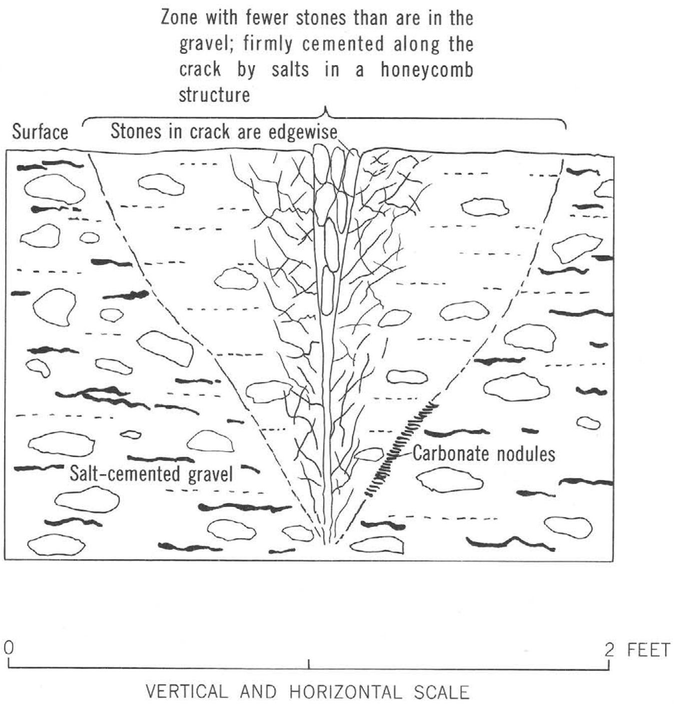

FIGURE 69.—Section along crack at edge of sorted polygon in gravel overlying a salt-crusted Tertiary formation near Mustard Canyon. Along the crack is a wedge-shaped zone containing fewer pebbles than are in the surrounding salt-cemented gravel.

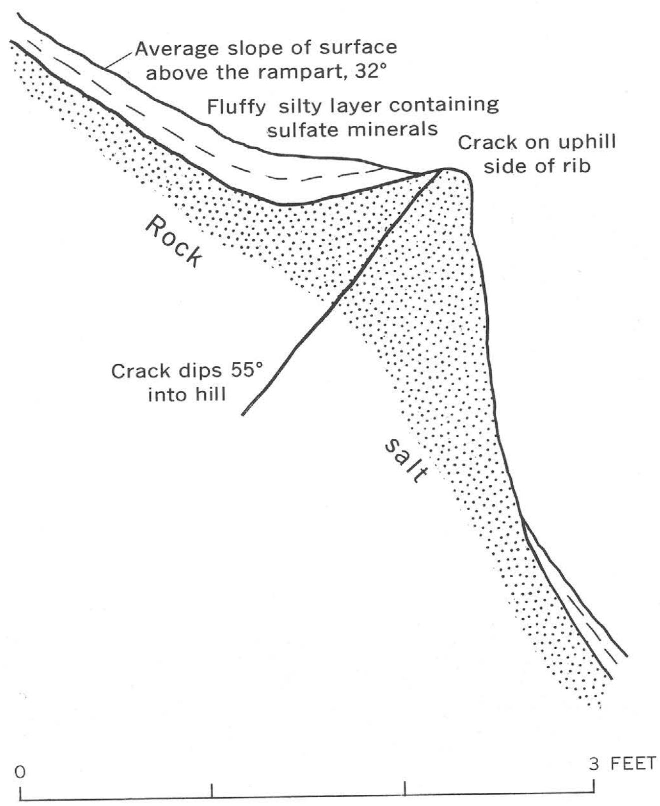

FIGURE 70.—Section of salt rampart along crack dipping into steep hillside along Mustard Canyon.

cracking of rock salt in the chloride zone on the saltpan. The favored explanation is that volume changes are caused by the extreme thermal changes to which this ground is subject.

The surfaces of the polygons are very irregular, with a relief of 4–8 inches in 1–2 square feet. The irregularities are due partly to heaving and partly to solution pitting. The result is a net superimposed on the polygonal pattern near the edges of the gravel deposits. Where stones collect in the depressions, the nets are sorted (fig. 71).

The hummocks of the net pattern seem largely independent of the cracks; each crosses the other, but there is a slight tendency for the hummocks to be alined along the sides of the cracks in a band 6–12 inches wide. The largest solution pits generally are in the interior of the polygons rather than along the edges. Areas of these pits range from 1 inch by 3 inches to 7 by 12 inches. Solution holes at the bottom of the pits are less than 2 inches in diameter.

Over much of the salt is a capping layer of silt less than 1 inch thick, and this layer is cracked into little polygons 2–5 inches in diameter. On the hummocks the cracks in this layer gape as much as ⅛ inch, but in the depressions they are less than 1/32-inch wide and many are closed. Solution pits ⅛–½ inch in diameter are common along these cracks and are elongated along them. The cracks end downward at the salt and evidently are due to desiccation.

A different kind of sorted polygon from that at Mustard Canyon has formed on the hills 1 mile northeast where the ground is silty, lightly covered with stones, and not crusted with salt. Small-scale desiccation cracks develop in the silt, and stones accumulate in the depressions (fig. 72), presumably as the result of repeated opening of cracks and of slope wash.

At one locality, along Furnace Creek opposite the mouth of Corkscrew Canyon, a hillside has developed sorted stripes. The hillside is on a Tertiary formation; at the top of the hill is gravel. The ground is silty, stony, and saliferous but not crusted with salt. On gentle slopes the ground develops sorted nets 1–2 feet in diameter, owing to accumulation of stones in the depressions between hummocks. The stripes are where the slope exceeds 10°. They consist of troughs about 7 inches wide containing stones separated by equally wide ridges of silt resembling the hummocks at the nets. In contrast to the striped effect produced in places by debris trains from disintegrating boulders and by natural levees, these sorted stripes are true patterned ground.

PATTERNS ON OLD SPRING DEPOSITS

Old spring deposits of loose fluffy marl, like some near Nevares Springs, develop small hummocks, and where there are pebbles, these collect in the surrounding depressions and form sorted nets. Where the pebble layer is nearly continuous, small isolated hummocks of fine-grained sediments are domed upward through the pebbles producing sorted circles.

The domes near Nevares Springs are 6–12 inches in diameter, 1.5 inches higher than the surrounding surface. The fracture pattern at the center of the hummocks consists of cracks that radiate from the centers in threes and seems to reflect the doming. At one dome that was excavated, the cracked surface layer, 3 inches thick, was firm. This was underlain by a powdery layer 2–2.5 inches thick, whitened with sulfate salts. Below this was a firm layer, 6 inches thick, cemented with calcium carbonate and divided by cracks that did not extend upward and that had been widened by solution. Below this was loose stony ground.

The centers of many domes are collapsed, forming a depressed area 2.5 inches deep; this surface is coated with sodium carbonate, sodium sulfate, and magnesium sulfate.

The sorted nets of this locality are on a maximum slope of about 6°. Where the slope steepens to about 7°, sorted stripes are present, and the patterns are very similar to those at the Furnace Creek locality opposite Corkscrew Canyon.

POLYGONAL CRACKS IN THE SILT LAYER UNDER DESERT PAVEMENT

On the old gravel deposits, where desert pavement is well developed, polygonal cracks develop in the silty layer that directly underlies the surface layer of cobbles and boulders forming the pavement. The polygonal cracks are spaced 2–3 inches apart. This spacing may be a function partly of the texture of the sediment in which the cracks developed and partly a function of the thickness and extent of the overlying cobble or boulder. The ground between the cracks is highly porous, being honeycombed with openings about 1 mm wide (fig. 73). Kindle (1918, p. 480–481) reported that such cavities are characteristic of saliferous mud; however, cavities of similar size occur also in mud subject to freezing and thawing.

DESICCATION CRACKS ON MUDFLOWS

The surfaces of mudflows, especially those on Furnace Creek fan and around Artists Drive, have well-developed mud cracks in silt that clearly are due to desiccation. The cracks end downward at the first change in lithology and are usually no more than 1 foot deep. In ground of a given texture, the width of the cracks and the size of the polygonal blocks increase with the increase in thickness of the cracked layer (see also Segerstrom, 1950, p. 115). In Death Valley where the cracked layer is 6 inches deep, for example, the cracks are 2½

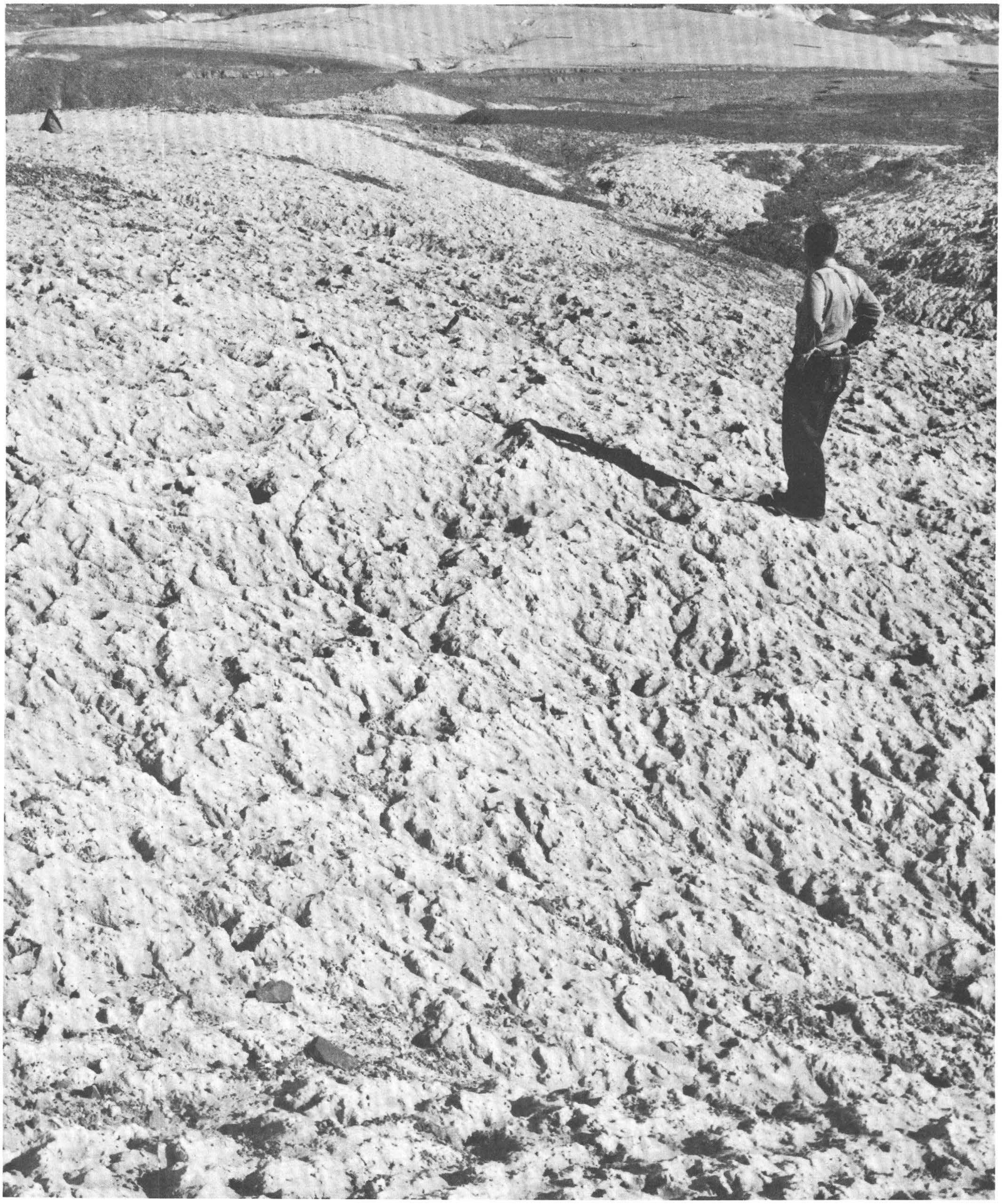

FIGURE 71.—Nets in polygonally cracked silty rock salt on a hillside of a saliferous Tertiary formation near Mustard Canyon. On level ground the hummocks are irregular in shape; on hillsides like this they are elongate parallel to the contour and have their steep sides facing uphill.

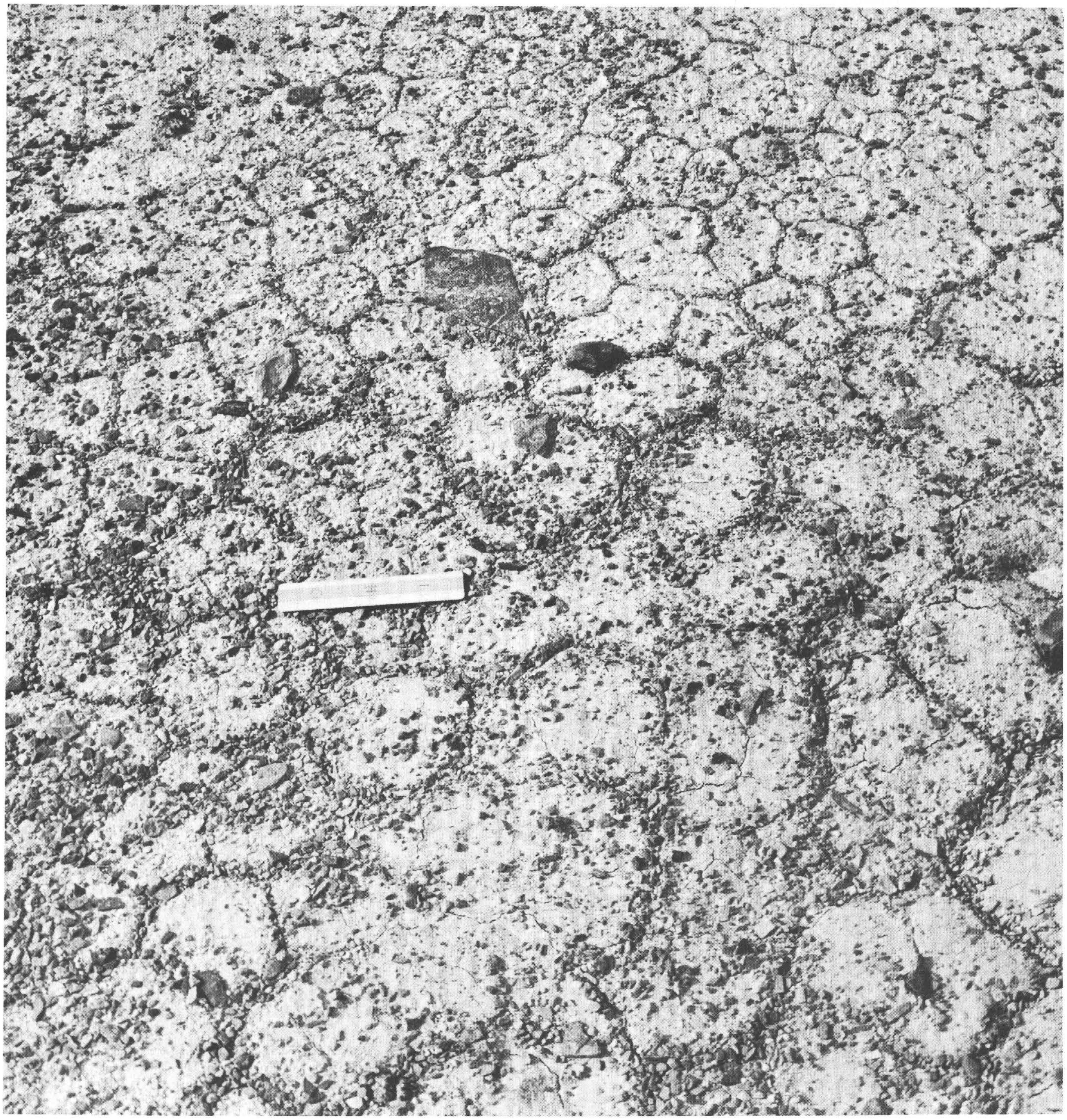

FIGURE 72.—Sorted polygons about 1 mile northeast of Mustard Canyon. Six-inch rule as scale.

inches wide and the polygonal blocks are 1½–2 feet in diameter. Where the cracked layer is 2 inches thick, the cracks are only half an inch wide and the polygonal blocks are 4–6 inches in diameter.

The pattern of cracking is irregular. Many cracks are curved, and the intersections tend to be at right angles.

CIRCLE PATTERNS OVER COLLAPSE STRUCTURES

Circle patterns over collapse structures, analogous to those at the salt pools on the saltpan (p. B112), have developed on the hills of Tertiary playa deposits that include high percentages of salts. Removal of the salts by solution develops caverns in the Tertiary formations, and the circle patterns at the surface

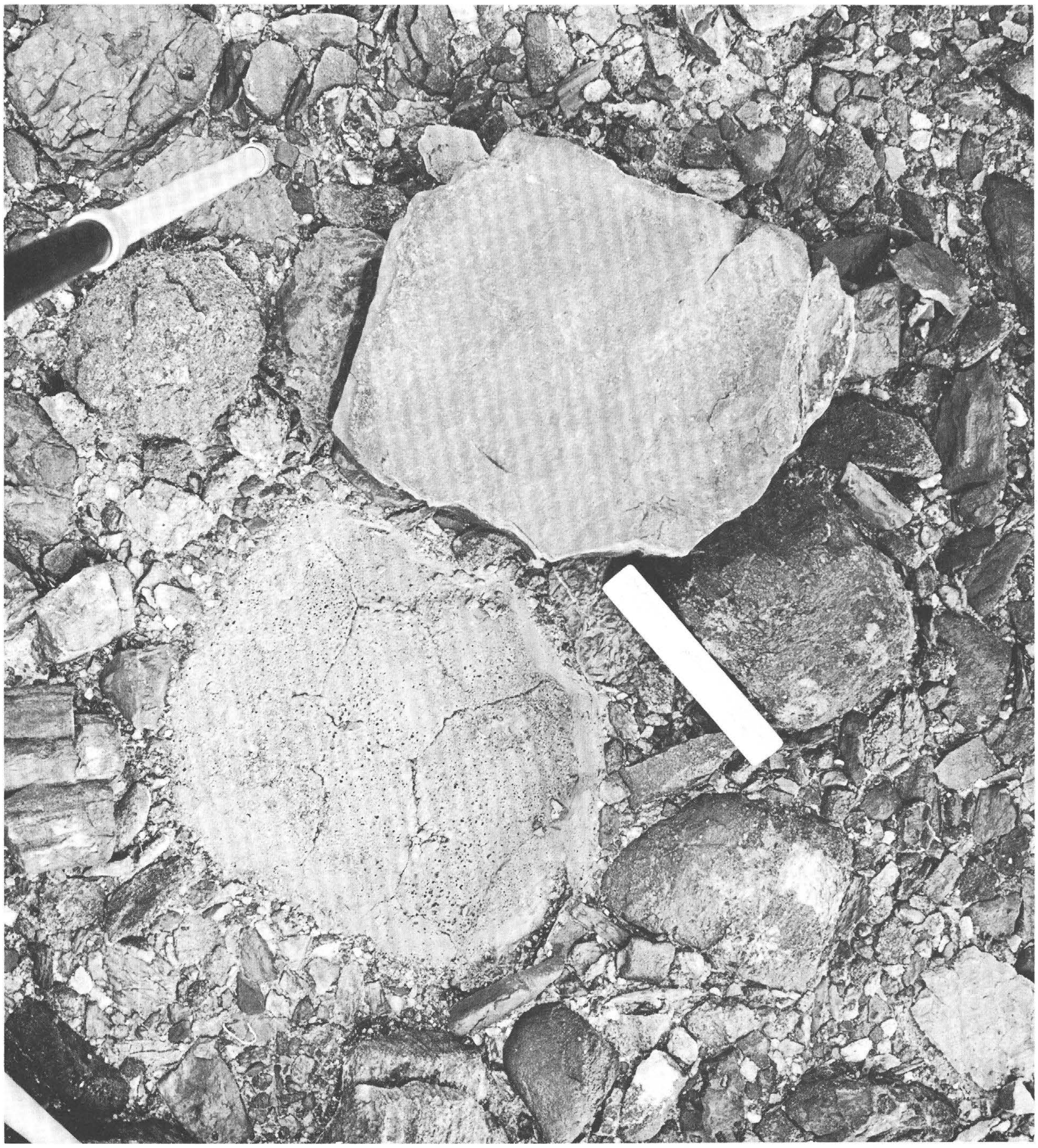

FIGURE 73.—Polygonal cracks in porous silt under a cobble that forms part of the desert pavement on a gravel formation; 6-inch rule as scale. Photograph by John R. Stacy.

develop when the beds above the cavern begin to collapse into it. The circle patterns are most strikingly developed where the Tertiary formations are capped by thin gravel and have barely started to subside into the underground solution channel. The circle pattern, though, evolves into true karst topography with depressions as much as 100 feet in diameter and 35 feet deep.

FACTORS CONTROLLING PATTERNED GROUND IN DEATH VALLEY

The development of patterned ground in Death Valley has been controlled by many variable factors. The patterns, other than the stripes, are especially well developed where fine-grained sediment and salts occur in situations where they are subject to changes in volume.

Volume changes and ground movement in the surface and near-surface layers of the ground, in this area, may be due to—

1. Physical changes resulting from wetting and drying;
2. Chemical and mineralogical changes due to wetting and drying—for example, growth of salts to cause heaving;
3. Physical changes resulting from temperature changes; and
4. Chemical and mineralogical changes due to temperature changes—for example, changes in state of hydration of minerals.

The differences in kinds of patterned ground and their degree of development on various parts of the flood plain correlate closely with the susceptibility of the different parts to wetting and drying. Where wetting occurs often enough and in a way to prevent accumulation of salts, ephemeral desiccation cracks develop. Where wetting and drying cause salts to be deposited, patterned ground develops; the kind of pattern is controlled by the frequency of the wetting and drying and whether the water is on the surface or only in the ground. Salts deposited by surface water form a polygonally cracked crust; salts deposited in the capillary fringe form net patterns.

Possibly too, volume changes result from the deliquescent properties of the salts, for the salts can absorb moisture from humid air as well as from wet ground.

A special form of volume change occurs, and circular collapse fractures result, when salts are removed by solution, as seems to have occurred at the Salt Pools and where karstlike features have developed on the saliferous Tertiary formations.

The range in surface temperatures in Death Valley is extreme, both diurnally and seasonally. Simple volume changes due to heating and cooling probably account for the polygonal cracking of the thick layers of rock salt, such as occur in the chloride zone or at the edge of the saltpan and on hillsides of some of the Tertiary formations. The thermal coefficient of linear expansion of rock salt per 1°C at 40°C is 40.4×10^{-6} which approaches that of ice, 47.4×10^{-6} (Hodgman 1960, p. 2243; Dorsey, 1940, p. 473). In view of the large fluctuations of temperature in Death Valley and the fact that thermal contraction and expansion is commonly accepted as the origin of frost-crack and ice-wedge polygons (Washburn, 1956, p. 850–852), where ice constitutes but a fraction of the ground as contrasted to the monomineralic nature of rock salt polygons, thermally induced volume changes seem to be an adequate explanation for the latter too.

The extremes of temperature, with, or possibly without, the benefit of moisture, also produce mineralogic changes and develop features like the caprock of bassanite and anhydrite on the deposits of massive gypsum which, in turn, influence the patterned ground on those surfaces.

Even on the gravel fans the presence of fine-grained sediments or of salt has favored the development of patterned ground, like the sorted steps on the gravel deposits characterized by desert pavement with its layer of silt under the pavement layer. The younger gravel deposits that do not contain much salt or fine-grained sediments are without patterned ground. The only exception to this generalization is the occurrence of steps on the sides of some beach bars. These steps contain no fine-grained sediments; but they may contain salts, although the fact was not determined. Elsewhere in the valley, wherever the surface or near-surface layer contains much salt or fine-grained clastic sediments, patterned ground of one kind or another is well developed.

The direct effect of the salts has been severalfold. Differences in texture and thickness of mud, which affects width, spacing, and depth of penetration by cracks, are produced by differences in the coarseness and amount of the salt disseminated through the mud. Salts that accumulate in desiccation cracks widen and accentuate them. Crusts of salt deposited on the muds retard evaporation from the mud and thus favor transport of salts upward in the capillary fringe. Deposition of salt in the capillary fringe or from vadose water produces a hummocky-type of heaving that results in net patterns.

The local topography has a direct effect in controlling the development of rectangular rather than polygonal patterns in salt crusts in narrow channels.

The climate obviously has been an important factor since it controls the relative role of surface water and water in the ground. If the climate were wetter than at present, the mass wasting of the gravel fans would probably be accelerated by increased heaving and collapse of salts as the result of alternate wetting and drying in somewhat the same manner that freezing and thawing promote creep. However, if the climate were humid enough to result in leaching of the salts, they would be less concentrated and correspondingly less important. In general, direction of exposure has had little effect on the occurrence of the patterned ground. Exceptions are the uniformly oriented lace-like salt growths on the massive rock salt, the north ward shingling of the salt saucers, the probably somewhat greater abundance of "alkali" spots on the north-facing slopes than on the south-facing slopes of the gravel fans, and the occurrence of some sorted polygons on south-facing slopes.

From the point of view of patterned ground salt and ice are similar. As already noted, their coefficients of linear expansion are of the same order of magnitude. The pressure effects of crystal growth are probably similar: in saliferous deposits subject to wetting and and drying and to upward movement of salts by capillarity, the concentration gradient, other things being equal, would be at right angles to the evaporating surface; with continuing evaporation, therefore, the progress of crystallization and the accompanying pressure effects would also be at right angles to this surface. The development of ice is oriented by the freezing surface, and the predominant stress resulting from ice-crystal growth is demonstrably at right angles to the freezing surface (Taber, 1929, p. 477–450; 1930). Thus, with both salt and ice the respective control surfaces are usually parallel to the ground surface, and the growth of crystals can cause heaving of the ground. Also, their respective control surfaces become warped and tend to parallel any cracks in the ground, so that stress from crystal growth tends to have a lateral component that can cause thrusting adjacent to the cracks.

Clearly, there are close parallels between stresses in highly saliferous ground of a hot desert and those in ground characterized by intense frost action. In both environments the ground is subject to contraction cracking as the result of desiccation and of thermal changes, and in both environments crystal growth can cause heaving and thrusting. It is logical, therefore, that the stresses should result in similar forms of patterned ground in spite of the widely different climates involved.

The length of time the processes have operated seems to be less significant than the other factors. Mass wasting, fundamental to the development of steps and terracettes, is exceedingly slow in Death Valley under the present climate, as indicated by trails abandoned more than 50 years ago but showing no signs of downslope displacement and by rows of dowels that showed no significant movement attributable to mass wasting in a 4-year period. Under a pluvial climate, however, the steps and terracettes may have formed quickly. Death Valley last had a pluvial climate about 2,000 years ago when there was sufficient moisture to produce a lake 30 feet deep.

On parts of the flood plain on the saltpan where considerable mositure is available, some patterned ground forms seasonally. On slightly elevated parts of the saltpan which are protected against floods, the patterned ground may be old. Much of it antedates trails and floods that are 50 years old, and antedates much of the erosion of the thick salt crusts.

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STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

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[Letters designate the separately published chapters]