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CHEMISTRY AND MOVEMENT OF GROUND WATER, NEVADA TEST SITE*

By

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ABSTRACT

Three chemical types of ground water are distinguished at the Nevada Test Site and vicinity. A sodium-potassium water is related to tuff (in part zeolitized) and to alluvium containing detrital tuff. A calcium-magnesium water is related to limestone and dolomite, or to alluvium containing detritus of these rock types. A mixed chemical type, containing about as much sodium and potassium as calcium and magnesium, may result from the addition of one of the first two types of water to the other; to passage of water first through tuff and then through carbonate rock, or vice versa; and to ion-exchange during water travel. Consideration of the distribution of these water types, together with the distribution of sodium in the water and progressive changes in the dissolved solids, suggests that the ground water in the Nevada Test Site probably moves toward the Amargosa Desert, not into Indian Spring Valley and thence southeastward toward Las Vegas. The low dissolved solids content of ground-water reservoirs in alluvium and tuff of the enclosed basins indicates that recharge is local in orgin.

INTRODUCTION

The chemical character of ground water depends to a large degree upon the character of the rock formations through which the water moves. The composition of the water is the result of several solutional and decompositional processes. Certain reactions, such as the solution of carbonate and the exchange of cations, are reversible. The chemical processes are affected by certain variables in the environment, among them the type of geologic environment, amount of vegetative cover, amount of water available, its rate of circulation, the activity of micro- and other organisms, temperature, and pressure.

The chemical constitution of a sample of ground water is a history of the underground experiences of the water. Yet, the deciphering of that history is often made impossible by sheer complexity. The longer the water is underground and the greater the number of geologic environments through which it passes, the more complicated and difficult to unravel is its history.

A large number of water samples from the Nevada Test Site and vicinity has been analyzed in the course of hydrologic investigations by the Geological Survey in behalf of the U.S. Atomic Energy Commission. Others have been analyzed in connection with investigations made in cooperation with the Nevada State Engineer. These analyses clarify some questions regarding the movement of ground water from the Test Site.

Purpose and scope

The purpose of this report is to determine if the chemical character of the ground water can be used to predict the direction of ground-water movement from the Nevada Test Site. The report describes the chemical variation of ground water in different basins and relates these variations to aquifer lithology and ground-water movement.

Acknowledgments

The writers wish to express their gratitude to their colleagues of the U.S. Geological Survey who have offered many helpful suggestions and criticisms. Special thanks are due J. D. Hem and R. C. Scott for constructive advice on geochemistry and for critical review of this report. None of these men, however, should be held responsible for the authors' interpretations and conclusions.

Location and area

The Nevada Test Site is an approximately rectangular area of about 1,130 square miles in southern Nye County, Nev., and is about 70 miles northwest of Las Vegas, Nev. The geologic map illustrating this report (fig. 1) extends beyond the boundaries of the Test Site on all sides and represents about 2,200 square miles. Places mentioned in this report but beyond the limits of figure 1 are shown in figure 2.

Topography and drainage

The Nevada Test Site is in the Basin and Range physiographic province. It contains two enclosed basins, Yucca Flat and Frenchman Flat, one basin having exterior drainage, Jackass Flats, and several mountain ranges.

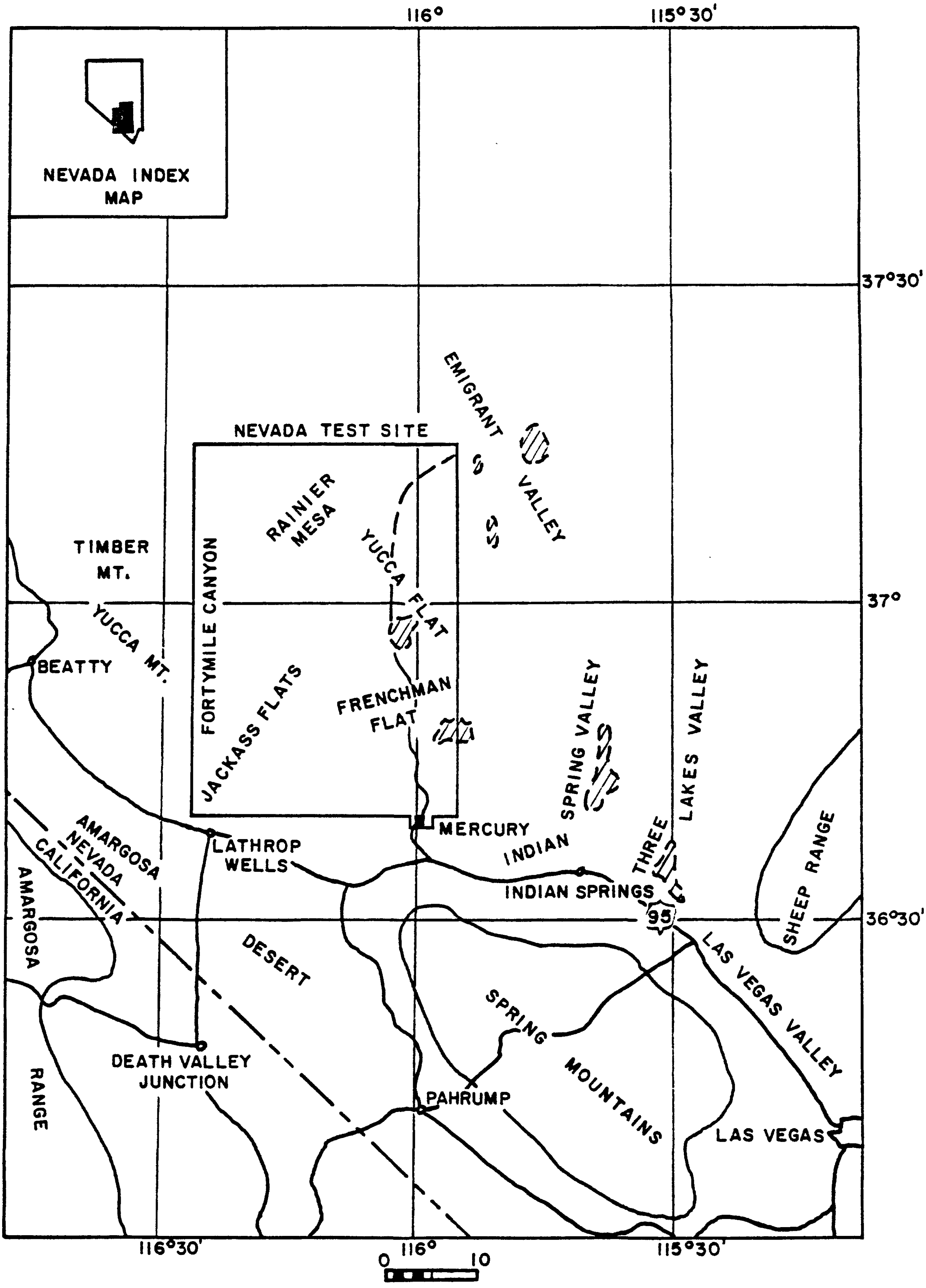


Figure 2.--Index map showing principal places discussed in this report. (Base from World Aeronautical Chart 363, Mt. Whitney.)

The western part of the Test Site is drained by Fortymile Canyon into Jackass Flats, which in turn is drained southward into the Amargosa Desert.

The Las Vegas Valley, an intermontane trough, trends southeastward from the southern end of the Test Site to Las Vegas. It is flanked on the southwest side by the Spring Mountains and on the northeast side by the southern ends of several mountain ranges. Only the southeast half of it is drained toward Las Vegas. The rest is drained into playa lakes in the southern ends of Indian Spring and Three Lakes Valleys.

General geology

The mountains are composed of sedimentary rocks of late Precambrian and Paleozoic age and of extrusive and minor sedimentary rocks of Tertiary or younger age. The rocks of Paleozoic age have been intruded by granitic rocks of Mesozoic age (Houser, F. N., written communication, 1963). Both the sedimentary rocks of Paleozoic age and the rocks of Tertiary or younger age have been intruded by mafic dikes of Miocene or younger age. The basins are partly filled with unconsolidated alluvial and lacustrine sediments. The upper parts of these sediments are of Quaternary age, but the lower parts at places may be of Tertiary age.

The total stratigraphic thickness of the late Precambrian and Paleozoic rocks is more than 35,000 feet, somewhat more than half of which is limestone and dolomite (Barnes, Harley, oral communication, 1963). The limestone and dolomite are especially important in both the circulation and the chemistry of the ground water. They will be referred to collectively hereafter as the carbonate rocks. The other principal rock types in the Paleozoic sequence are siltstone, argillite, and quartzite.

The rocks of Tertiary or younger age consist principally of tuff but include also flows of basaltic, andesitic, and rhyodacitic composition, together with minor amounts of sedimentary rocks. Their total aggregate thickness is not known, but it probably exceeds 10,000 feet (Healey and Miller, 1962, p. 9). The volcanic rocks have been penetrated in drill holes to a depth of more than 5,000 feet. Most of these rocks are rhyolitic (Houser, F. N., and Botinelly, T., oral communication, 1963). Despite considerable variation in physical appearance, they are a unit in their effect on the chemistry of the ground water. The zeolitized parts of the tuff are especially important because they influence the chemical character of the water through ion-exchange.

The valley fill (alluvium) is thick in some of the basins. The maximum known thickness of the fill is 1,870 feet, in south-central Yucca Flat, where it was penetrated in a test well. The well was not drilled to the bottom of the fill, however, and the complete thickness was not determined. The alluvium is composed of detritus from the adjacent mountains, and the character of the water in it depends on the kinds of rock materials in it.

The geologic structure is extremely complex. As stated by Healey and Miller, (1962, p. 10), "The Paleozoic rocks were extensively thrust faulted, probably during the Late Cretaceous (Johnson and Hibbard, 1957, p. 378). Many normal faults displace both the Paleozoic sedimentary rocks and the Tertiary volcanic rocks. Vertical displacements on the normal faults range from a few feet to several thousands of feet. The Las Vegas Valley shear zone (Longwell, 1960) has had profound influence on the present structure of the southeast part of the region. This major shear zone may be traced 100 miles northwestward from Boulder City, Nev. * * *. Horizontal movement along the shear zone has been estimated at 25 miles by Longwell (1960) and 27 miles by B. C. Burchfiel (written communication, 1961)."

General hydrology

The chemical character of ground water is the result of processes during the movement of the water from places of recharge to places of discharge. Ground water in the Basin and Range province is recharged from precipitation, principally on the flanks of the mountains. It then moves down into the valley fill, whence it discharges by evapotranspiration. The bedrock that makes up the mountains and underlies the fill was thought to be an impermeable barrier that prevents the movement of ground water from one basin to another. This seems not to apply to the basins of the Nevada Test Site and several other basins in southern Nevada. Winograd (1962a, p. 8; 1962b, p. C110) has shown that water levels in wells in the Tertiary tuff decline as the wells are deepened into the zone of saturation. The head in the tuff is higher than that in the underlying Paleozoic carbonate rocks at the same place. He concludes, "The movement of ground water in the valley fill and the tuffs beneath the bolsons of the Nevada Test Site is vertically downward into the Paleozoic carbonate rocks. The ground water moves laterally in the carbonate rocks, though probably circuitously, beneath all three basins toward the discharge areas, presumably to the southwest."

Eakin and others (1963) have shown that, in a region extending from the California state line northward nearly 90 miles beyond the Nevada Test Site, the ground water may move from north to south. The hydraulic potential, as represented by the water-level altitudes in selected wells, and the relations of discharge to recharge suggest that southward movement is not only possible but probable. Confirmation of this movement is suggested by the chemical character of the waters. The ground water probably is discharged in the Amargosa Desert and, in part, in Death Valley.

Previous investigations

Reference has been made in the preceding section to significant reports that have been published on regional hydrology. Other sources of information, especially data on chemical character of water, are mentioned below.

Chemical analyses of water samples collected in tunnels driven into Rainier Mesa at the northwest border of Yucca Flat were reported by Clebsch and Barker (1960), and those for waters from wells, test holes, and springs in and near the Nevada Test Site to 1960 were reported by Moore (1961, tables 3 and 5). Five of the analyses for the Nevada Test Site and several for water from surrounding areas were reported also by Scott and Barker (1962, p. 72-73). The analyses of water from the test wells drilled for the Geological Survey's hydrologic investigation of the Nevada Test Site have been reported in various Survey TEI reports summarizing the results from the individual wells, have been tabulated by Eakin and others (1963), and are repeated in appendix A of this report. The tritium age of ground water as related to the movement of the water in and near the Nevada Test Site was discussed by Clebsch (1961).

THIS INVESTIGATION

Most of the chemical analyses given in this report were made by the Quality of Water Branch, U.S. Geological Survey, Denver, Colo. A few analyses were made in other Survey laboratories, or in outside laboratories. The water samples were collected by many individuals, most of them Survey personnel.

The analyses were evaluated in relation to drilling methods and to conditions in the wells at the time of sampling, and eight that probably do not represent the formation water have been excluded from the maps and tables in this report. Among these are samples that have a pH of 9.9 to 11.5, which probably is due to cement that was used in the well. A few others represent samples that probably had been contaminated by, or consisted mainly of, drilling fluid.

The analyses were plotted for study as modified pie diagrams, which in the form adopted here facilitate the discrimination of borderline water types and represent fairly well the chemical concentration. These diagrams appear in several of the illustrations for this report. Nearly all those for well water appear on figure 1.

The water of springs and that from fractures intersected in the tunnels in Rainier Mesa are discussed in the text and tabulated in appendix B but are not illustrated by diagrams in figure 1. These water types are from perched zones of saturation and therefore do not represent regional ground-water trends. The spring water and some of the tunnel water is diagramed in figure 4.

Parallelogram diagrams also were used in the study of the chemical analyses, because these diagrams facilitate comparison of the water of one area with that of another (Piper, 1945). They may show progressive change in chemical composition in one direction or another, and thereby may suggest the direction of movement of the water. On these diagrams the percentage of sulfate, chloride, fluoride, and nitrate are plotted against bicarbonate and carbonate on one axis, and calcium and magnesium are plotted against sodium and potassium on the other axis. Parallelogram diagrams for ground water from several areas in and adjacent to the Nevada Test Site are shown in figure 5.

The analyses tabulated in appendices A and B of this report are stated in both parts per million (ppm) and equivalents per million (epm). The figures for epm are used in plotting the pie diagrams and in calculating percentages for the parallelogram diagrams.

Numbering system

Wells, test holes, and springs are identified in this report by location numbers based on the Nevada State coordinate system, central zone. Each number consists of at least two parts: the first two digits of the north coordinate, followed (after a hyphen) by the first two digits of the east coordinate. Where several wells are in the same 10,000-foot rectangle, a letter is added to the number for each well, beginning with "a." The well, test hole, or spring is always on or north of its north coordinate and on or east of its east coordinate.

The coordinates shown on the map (fig. 1) are 64(0,000) at the south to 94(0,000) at the north; and 56(0,000) at the west to 77(0,000) at the east. A location number that is low in both digits--73-58, for example--is in the southwestern part of the map. A location number that is high in both digits--91-74, for example--is in the northeastern part of the map.

Wells and springs in the Amargosa Desert have been numbered by the Ground-Water District Office, U.S. Geological Survey, Carson City, Nev., according to township, range, and section. This arrangement could not be extended into the Nevada Test Site because townships and sections have not been surveyed there. For uniformity in this report, therefore, the wells and springs of the Amargosa Desert have been assigned numbers based on the coordinate system, which for convenience has been extended arbitrarily into the California part of figure 6.

WATER TYPES

The ground water of the region is bicarbonate water with but few exceptions. Some of the water from the Test Site is sulfate water. One water has nearly as much sulfate as bicarbonate. The circumstances that seem to account for these and a few others are discussed in the section headed "Unusual water types."

Most of the water can be classified on the basis of cations alone as follows:

1. Sodium-potassium type--sodium predominates, potassium generally is minor to negligible and the two together are 60 percent or more of total cations.

2. Calcium-magnesium type--either calcium or magnesium may predominate, and the two together are 60 percent or more of total cations.

3. Mixed chemical type--neither cation pair amounts to as much as 60 percent of total cations; both pairs amount to more than 40 percent

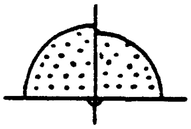
each, and either pair may predominate.

When plotted as modified pie diagrams, these three water types are fairly distinctive. The sodium and potassium are plotted together in the southeast quadrant, and opposite--in the northwest quadrant--the calcium and magnesium are plotted together. The bicarbonate and carbonate are plotted together in the northeast quadrant and the sulfate and chloride are plotted together in the southwest quadrant (fig. 3).

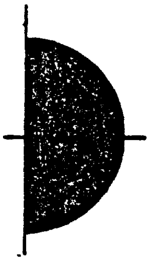
A sodium-potassium water approximates a semicircle in the east half of the diagram, but a calcium-magnesium water approximates a semicircle in the north half (fig. 3, wells 84-68 and 65-73, respectively). A water of mixed chemical type generally has a relatively large wedge in the northeast quadrant, and smaller, more or less equal, wedges in the northwest and southeast (fig. 3, well 75-73). If the mixture also includes sulfate and chloride in substantial proportions, there will be a wedge in the southwest, and the diagram will approach a circle.

The term, "mixed chemical type," is not intended to mean that turbulent mixing of waters has taken place. Turbulent mixing seems unlikely to occur underground except in special geologic situations, such as large solution openings. A water of mixed chemical type may be attributed to passage of the water through one kind of rock and then another, with opportunity for ion exchange or solution of different minerals.

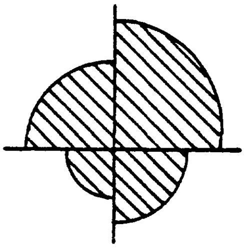
As suggested above, most of the water of the region is low in sulfate and chloride. Many of the pie diagrams show almost nothing in the quadrant assigned to these anions.



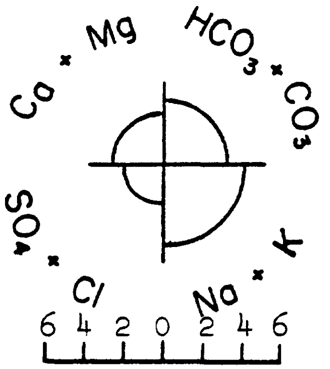
Calcium-magnesium water
(well 65-73)



Sodium-potassium water
(well 84-68)



Water of mixed chemical type
(well 75-73)



Plotting scheme
and scale (in equivalents per million)

Figure 3.--Chemical diagrams illustrating three types of water, Nevada Test Site and vicinity.

RELATION OF WATER CHEMISTRY TO ROCK TYPES

The relation of the chemical composition of the ground water to rock types is shown by figure 1, on which the chemical diagrams are placed adjacent to the symbols representing the source of the water, and the geology is represented by rock types rather than by geologic formations. Some wells tap strata other than and different from the rock at the surface, thus obscuring the relation of water to aquifer. Well 88-66 begins in alluvium but draws water from carbonate rock. Wells 73-66 and 87-62 tap both tuff and carbonate rock, and analyses for both water sources are shown. A letter adjacent to the chemical diagram indicates the lithology of the aquifer.

Water from tuff

Water from volcanic rocks--mainly tuff--is typically a sodium-potassium water that contains but little calcium, magnesium, sulfate, or chloride. The water collected from seeps in the tunnels in Rainier Mesa and the water from springs probably have traveled only or mainly through tuff and are considered to be typical of water from tuff (fig. 4). Some of this water contains small amounts of calcium, magnesium, sulfate and chloride, indicating that these constituents are not entirely lacking in the tuff. The water of some springs contain enough of these constituents so that they may be classed as of mixed type, but the total concentration of this water is so low that the relative proportions may not be meaningful. The same water after additional residence time in the rocks might dissolve relatively much more sodium than other constituents, thereby acquiring the

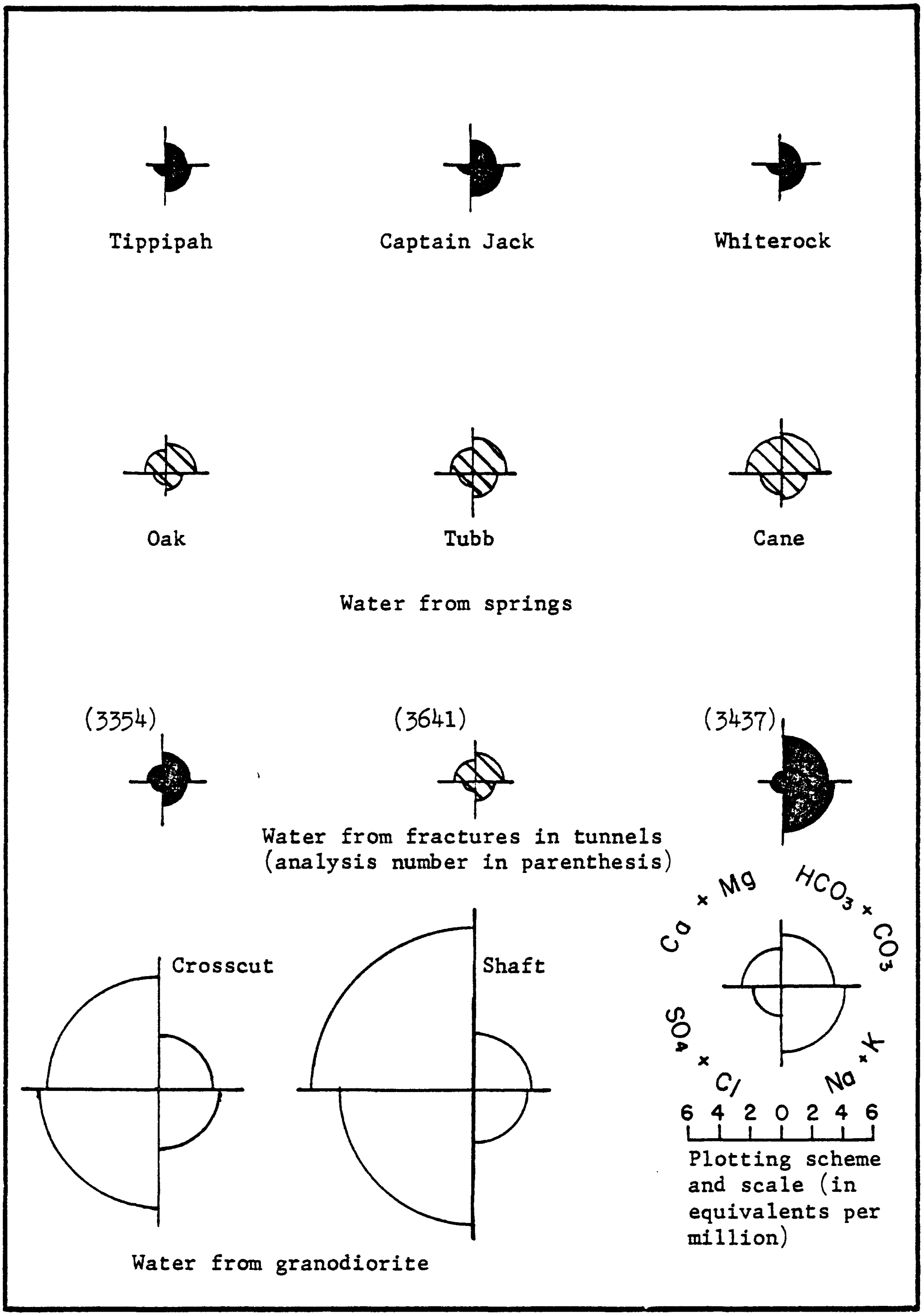


Figure 4.--Chemical diagrams representing water from springs and tunnels in tuff, and water from granodiorite.

character of a typical "tuff" water. The spring water is described further in the section entitled, "Water from springs and tunnels."

Water from carbonate rocks

Some of the water from the carbonate rocks is of the calcium-magnesium type, which makes a semicircle in the north half of the pie diagram, with almost nothing in the south half. The amount of magnesium in the water from test hole 90-67b is about three times the amount of calcium, and indicates that the water-bearing rock is dolomite, or at least is dolomitic. This inference is confirmed by Houser and Poole (1959, p. 11), who state that the composition of the rock penetrated in the hole is "dolomite from the surface to about 540 feet and limy dolomite from 540 to 951 feet." The magnesium in some other water is but slightly greater than, or is approximately equal to, the calcium; for example, well 88-66. The calcium predominates in other water; for example, well 67-68.

Not all the water from carbonate rocks is of calcium-magnesium type. Several are of mixed chemical type, among them the water from wells 87-62, 79-69a, and 75-73. The sodium in such water probably is due to contact of the water with tuffaceous materials; that is, passage of the water through tuff or through alluvium containing detrital tuff. The water may have entered carbonate rock and then have passed through tuffaceous materials and back into carbonate rock; or it may have entered tuffaceous materials first and then have moved into carbonate rock.

Water from alluvium

The chemical character of water in alluvium depends to a considerable degree on the kind of rock materials that make up the alluvium. It differs from place to place in accord with the character of the source rocks from which the alluvial detritus is derived. It also may depend on the relation of alluvium to the bedrock aquifer. Several situations affecting the chemical character of ground water at and near the Nevada Test Site are described below.

Water from alluvium containing detrital tuff is likely to resemble water from tuff but may contain relatively more calcium and magnesium than a typical "tuff" water. The alluvium in Frenchman Flat, as represented by well 74-70b (Hood, 1961, p. 44-48), contains detrital limestone, dolomite, quartzite, rhyolite, tuff, and argillite. The water from wells 74-70a and 74-70b is a sodium-potassium type much like some of the spring water that issues from tuff. Both water types contain a little calcium and magnesium, although the maximum is only 12 percent of total cations. In fact, the amount of calcium and magnesium in this water is surprisingly low in view of the prominence of limestone and dolomite in the descriptions of the well log.

By contrast, the water of well 83-68 seems to have more calcium and magnesium than would be expected from the description of the strata at the well. The well penetrates only alluvium, which contains relatively large percentages of various kinds of detrital tuff, together with somewhat smaller amounts of quartzite, chert, and argillite (Price and Thordarson, 1961, p. 18-29). Carbonate-rock detritus is insignificant, although carbonate rocks are exposed both east and west of the well.

Yet, the calcium and magnesium in the water are enough to put the water on the boundary between the sodium-potassium and mixed types.

Water from alluvium is usually chemically similar to the water from the carbonate rocks if carbonate-rock detritus is abundant, as in the case of well 65-73. This well penetrates alluvium "consisting principally of fine- to medium-grained dolomite and quartzite fragments in a calcareous-silt matrix" (Moore, 1962, p. 10). The dolomite fragments could have been derived from rock outcrops either north of the well in the Spotted Range or south of it in the Spring Mountains. The water from the well is a calcium-magnesium water, with magnesium slightly exceeding calcium; sodium, sulfate, and chloride are negligible.

The ground water in alluvium may not have any obvious relation to the lithology of the alluvium in some special geologic situations. Where water from bedrock aquifer is discharged into alluvium, the chemical character of a water sample collected near the place of discharge may be dominated by the influence of the bedrock aquifer; only with extended residence in the alluvium will the water acquire a chemical character compatible with its host. Such a situation could easily lead to uncertainty in interpretation of a chemical analysis, especially where subsurface conditions are but partly understood, or the subsurface discharge is not believed to occur. For example, water from a well ending in alluvium that taps water discharged into the alluvium from a carbonate-rock aquifer, in a locality where the nearest exposed rock is tuff, would seem anomalous.

Water from granodiorite

The Climax stock, which is at the north end of Yucca Flat, consists of granodiorite and quartz monzonite and probably contains water only locally. The water seems to occur where the rock is most fractured, in more or less isolated bodies. The water probably is replenished from precipitation on the immediate area. The fractures containing the water are poorly connected, and its movement is restricted so severely that each water body seems to have its own independent level (Walker, 1962, p. 36). It is doubtful that the water in the granite moves away in significant quantities into the surrounding Paleozoic rocks.

Samples from two closely spaced sites in the granodiorite stock, taken from different depths below the land surface, proved to be calcium-magnesium sulfate water (fig. 4). The sulfate content is notably high, especially in comparison with the amount of sulfate in water from other types of rock. The water in adjacent rocks contains much less sulfate indicating that not much water can be moving out of the stock. This inference is confirmed by the dissolved solids, which in both samples is much greater than in most samples from other sources in the vicinity. The nearest approach in terms of dissolved solids is the water from well 89-68. This well is about 2 miles southeast of the stock. It penetrates more than 4,200 feet of quartzite, argillite, quartzitic siltstone, and dolomite, of Paleozoic age, and the water from it is of mixed chemical type. The dissolved-solids content of the water is only 430 ppm, and the sulfate content is about 60 ppm--probably too low for any significant contributions of water to have come from the granodiorite.

UNUSUAL WATER TYPES

Some waters from the Nevada Test Site and vicinity seem to be anomalous..Possible explanations for some of them are suggested in the following paragraphs.

Water of mixed type from tuff

The water from well 81-67 (Yucca Flat) is of mixed type, not at all the sodium-potassium water to be expected from a well ending in tuff. Calcium and magnesium are nearly equal, and together they exceed slightly the sum of sodium plus potassium. The calcium and magnesium may be traceable to a buried north-south ridge of Paleozoic rock situated a few miles west of the well. This rock in a test hole about 3 miles northwest of well 81-67 is limestone and shale or siltstone (Moore, 1962, p. 38-39), and it begins only 72 feet below the land surface. Water coming to the well from the west, therefore, may have had a longer history in the carbonate rock than it had in tuff. The mixed chemical character may be due to mixing in or near the well of calcium-magnesium water from the west with sodium-potassium water coming from other directions.

Water high in sulfate

The water from well 73-61 is exceptional because in it the sulfate is five times the bicarbonate, whereas in most water of the Test Site the sulfate is monor or negligible. The aquifer tapped by the well is tuff. The nearest well showing a substantial amount of sulfate is number 73-66, which is about 8 miles to the east. There the sulfate was in water from carbonate rock and was somewhat less than the bicarbonate. The water at both wells may have been influenced by the same factors, although not equally.

The dominance of sulfate in the water at well 73-61 and the relative abundance of it in the water at well 73-66 may be traceable to the geologic process that caused extensive hydrothermal alteration of the volcanic rocks, and less extensively the Paleozoic carbonate rocks, in the hills bordering Jackass Flats on the north, 5 miles from well 73-61. Silicification, alunitization, and kaolinitization were intense enough to destroy much of the original texture of the volcanic rocks (E.J. McKay, written communication, 1962). Alunite is the basic hydrous sulfate of aluminum and potassium. Therefore, the ground water in this area may be expected to contain substantial amounts of sulfate. The sulfate in the water from the carbonate rocks at well 73-66 may be due to water that has come from the hydrothermally altered area.

Water high in sulfate and in dissolved solids

The water from well 68-69, which was drilled in Mercury Valley in search of water for Camp Desert Rock, contains more than 5,000 ppm of dissolved solids (table 1). This is nearly twice as much as in the next most mineralized water considered in this report, which is from a well in the southern part of the Amargosa Desert (Well 61-53), and six times as much as in the most mineralized water within the Test Site (Well 73-61). A chemical diagram for this water is not shown on figure 1 because if drawn to the same scale as the other diagrams it would obscure too many significant features of the map. The water is a sodium sulfate type-1,291 ppm of sodium (72 percent of total cations) and 3,599 ppm of sulfate (94 percent of total anions). The water-bearing strata at the well, as indicated by a broadly generalized driller's log (Moore, 1962, p. 26), may be interpreted either as alluvium or rhyolite, or both. The log offers

Table 1.--Analyses of water from wells 66-69 and 68-69, in parts per million and equivalents per million

	[a]Well 66-69 (Army 6A)		[b]Well 68-69 (Camp Desert Rock)	
	Parts per million	Equivalents per million	Parts per million	Equivalents per million
Silica (SiO_2)	9.3	------	22.6	------
Calcium (Ca)	24	1.20	281	14.02
Magnesium (Mg)	16	1.32	90	7.40
Sodium (Na)	222	9.66	1,291	56.16
Potassium (K)	11	.28	------	------
Bicarbonate (HCO_3)	486	7.97	98	1.61
Carbonate (CO_3)	0	.00	tr	------
Sulfate (SO_4)	169	3.52	3,599	74.93
Chloride (Cl)	23	.65	98	2.76
Fluoride (F)	.8	.04	------	------
Nitrate (NO_3)	4.1	.07	------	------
Phosphate (PO_4)	2.7	------	------	------
Dissolved solids Residue at 180° C.	703	------	------	------
Sum	718	------	5,416	------
Hardness as $CaCO_3$ Total	126	------	1,073	------
Non-carbonate	0	------	------	------
Specific conductance (Micromhos at 25° C.)	1,130	------	------	------
pH	8.0	------	8.1	------

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[a] Analysis by U.S. Geological Survey, Denver, Colo.

[b] Analysis by Smith Emery Co., Los Angeles, Calif.

no helpful explanation for the mineralization of the water. The water is so different from other waters of the region that unknown local factors must be the cause. Possibly the water in the alluvium at Camp Desert Rock is stagnant and has become highly mineralized as a result of long contact with rocks that include a source of sulfate material not recognized at the surface. Evaporite deposits included in the alluvium might be such a source. Concentration of the water by evaporation might have occurred under topographic and climatic conditions of the geologic past, but is unlikely under present conditions. The static water level at Camp Desert Rock, about 975 feet below the land surface, is too deep for evaporation. If the water entering the Mercury basin was a bicarbonate type, as is most of the water of the region, a mechanism for minimizing the bicarbonate and increasing the sulfate must have operated.

Another inference based on the unusual character of the water from well 68-69 is that the confining layer under the zone of saturation provides a relatively tight seal. The mineralized water seems not to appear in wells tapping other aquifers. The well is less than 3 miles "upstream" from well 67-68, which taps carbonate rock and has water containing only 330 ppm dissolved solids and 38 ppm sodium (28 percent of total cations). No more than a trickle of the mineralized water can be reaching the carbonate-rock aquifer at well 67-68.

High sodium in calcium-magnesium area

Well 66-69, known also as Army well 6A and as the Riess well (from the name of the Army's consultant), yielded a sodium-potassium water from a part of the area where other water, so far as they are represented by analyses, is of the calcium-magnesium type. The dissolved-solids content of the water was relatively (but not excessively) high, about 700 ppm; sodium was 222 ppm (78 percent of total cations), bicarbonate was 486 ppm (66 percent of total anions), and sulfate was 169 ppm (table 1). The log of the well (Moore, 1962, p. 17-19) shows the water-bearing strata to be quartzite, in which soluable sodium is improbable. The water sampled does not represent the formation water, perhaps because it was contaminated by the cement used in the well during drilling. J. D. Hem (written communication, 1963) pointed out that the bicarbonate content is high relative to the pH, making a system in which calcium probably would be precipitated as calcium carbonate. If a water having the characteristics shown by the analysis were to be mixed with a calcium carbonate type (possibly formation water), the final solution would contain relatively small amounts of calcium. Owing to doubt as to the validity of the sample, the analysis is not plotted on figure 1 nor considered further. It is mentioned chiefly because the history of the well and the results obtained from it are well known in southern Nevada.

Unlike water from adjacent wells

Wells 79-69a and 79-69b are only about 100 feet apart at the land surface, but the analyses of the water samples from them were not alike. Both wells (hereafter for convenience in these paragraphs simply wells "a" and "b") draw water in substantial quantities solely from fractured carbonate rocks, (Garber and Thordarson, 1962, p. 19 and 27), but the specific capacity [1] of well "a" is much greater than that of well "b." Both wells were drilled to a depth of about 1,700 feet, but well "b" after reaming and casing is effectively only 1,650 feet deep. The water samples seem to represent fairly the formation water from each well, for the following reasons.

Three water samples from well "a" were collected over an 8-month period during which the well was pumped regularly at 200 gallons per minute, or more. The analyses show only relatively small variations in the amounts of the principal anions and cations (appendix A). The relative constancy in chemical composition therefore suggests that water was being drawn from a large reservoir.

Only one sample was collected from well "b," but it was taken after about 6,000,000 gallons of water had been pumped out (R. A. Young, oral communication, 1963).

Averages of the principal ions for the three samples from well "a" may be compared in table 2 with the corresponding ions in one sample from well "b." The principal dissimilarities in the waters follow:

1. The water from well "b" was a sodium-potassium type having only a moderate proportion of calcium and magnesium, but the water from well "a" was of mixed chemical type, in which the calcium and magnesium is nearly equal to the sodium and potassium.

2. The water from "b" had only 0.75 as much dissolved solids as that from "a."

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[1] Specific capacity is the discharge, in gallons per minute, divided by the drawdown, in feet.

3. The calcium in the water of well "a" was 1.84 times as much as the magnesium, but in the water of well "b" the relation was reversed. In "b" the magnesium was 2.77 times as much as the calcium; only at well 90-67b, among wells at the Test Site, does the magnesium exceed the calcium by a greater amount, and there it is 3.1 times the calcium.

4. The calcium was only about one-fifth as much in the water from "b" as in the water from "a."

The greatest single difference between the two is in the calcium. The other ions in table 2 differ only by 5 to 15 percent, but the calcium in water from "a" is 4.5 times that in water from "b." Water similar to that from "b" could be made by removing about 3 epm of calcium carbonate from the water of well "a." This simple relation, together with the fact that the pH of the water from "a" was about 7, whereas that for "b" was over 8, led J. D. Hem (written communication, 1963) to suggest that calcium carbonate was being precipitated near well "b," probably in the rock openings adjacent to the well, and that the precipitates are in part responsible for the relatively low specific capacity of the well. The magnesium would not necessarily be precipitated along with the calcium.

Table 2.--Principal ions in water from wells 79-69a and 79-69b, in equivalents per million

	Well 79-69a (average of three analyses)	Well 79-69b (one analysis)
Calcium (Ca)	3.72	0.83
Magnesium (Mg)	2.02	2.30
Sodium (Na)	5.80	5.48
Potassium (K)	.34	.38
Bicarbonate (HCO_3)	9.36	6.33
Carbonate (CO_3)	.00	.20
Sulfate (SO_4)	1.45	1.27
Chloride (Cl)	.86	.99
Dissolved solids (residue on evaporation at 180° C., in ppm)	644	482

Hem's suggestion led to the collection of new water samples from both wells, and to a series of field measurements of the conductivity of the water for an hour preceding the sampling, after an initial conductivity of 880 micromhos at well "b," the conductivities at the two wells were similar within the narrow range of 980 to 1,000 micromhomos. The calcium and bicarbonate were similar to the original water samples from well "a" (table 3). Thus, the difference between the waters from the two wells seemed to have disappeared. This result led R.C. Scott (oral communication, 1963) to suggest that the water of both wells is and was the same chemically, and that the low calcium content of the first water sample from well "b" was due to precipitation of calcium bicarbonate while the sample was in transit or in storage.

Whether the foregoing chemical anomalies are due to precipitation in fractures of the aquifer or in the sample bottle, or to some other cause, remains a matter for speculation. It is worth mention that the first sample from well "b" was collected nearly 6 months after the collection of the last sample from well "a" that was completely analyzed and that the last two, partially analyzed samples were collected after both pumps had been shut down for an unreported period of time. Obviously the conditions in the aquifer were not the same on any two sampling dates. Just as obviously, the conditions that prevailed at collection of the first samples cannot be duplicated, if only because a large quantity of water then in the aquifer has since been pumped out. The nearest approach to a solution to this problem might consist of sampling for chemical analysis the discharge of both wells when both have been pumped continuously for a protracted time.

Table 3.--Calcium and bicarbonate in water from wells 79-69a and 79-69b

	Calcium (Ca) (epm)	Bicarbonate (HCO_3) (epm)
Well a		
Sept. 1, 1961	3.69	9.46
Jan. 19, 1962	3.49	9.18
Apr. 25, 1962	3.99	9.44
Averages	3.72	9.36
Mar. 19, 1963	3.99	9.31
Well b		
Oct. 10, 1962	.83	6.33
Mar. 19, 1963	3.94	9.34

WATER FROM SPRINGS AND FROM TUNNELS

Selected chemical analyses of waters from springs and tunnels are tabulated in appendix B and are illustrated by chemical diagrams in figure 4. The most recent analysis is given for each spring. Additional chemical analyses of water from springs and tunnels are given in reports by Moore (1961, table 5A) and Clebsch and Barker (1960, table 2A).

Eight springs are present within the boundaries of the Nevada Test Site, and all discharge water from perched zones of saturation in tuff and rhyolite. Their discharge ranges from less than 1 to 3 gallons per minute (Moore, 1961, p. 17). The water-bearing bed of six of them is zeolitized tuff in the lower member of the Indian Trail Formation. The water-bearing rocks of Cane and Topopah Springs are calcareous tuff and rhyolite, respectively. Topopah, Tippipah, Rainier, Captain Jack, and

Whiterock Springs yield water of the sodium-potassium type, closely resembling the water from wells in tuff in Frenchman and Yucca Flats. The sodium and potassium content of these waters ranges from 64 to 93 percent of total cations, and bicarbonate ranges from 64 to 79 percent of total anions.

Cane, Oak, and Tubb Springs yield water of the mixed chemical type. The sodium and potassium content (44 to 57 percent of total cations) is about equal to the calcium and magnesium content (43 to 56 percent of total cations). The source of the calcium and magnesium at Oak and Tuff Springs is not apparent. The calcium content (38 percent of total cations) of the water of Cane Spring apparently is due to the contact of the water with dacitic tuff, which has a higher calcium content than the rhyolitic tuff.

The dissolved-solids content of the spring water of the Test Site is relatively low, ranging from 123 to 362 ppm (appendix B), and the average (220 ppm) is about 65 ppm lower than the water in wells that tap tuff or tuffaceous alluvium in Emigrant Valley, and Yucca Flat, and 165 ppm lower than in Frenchman Flat. In contrast the dissolved-solids content of two springs in the Amargosa Desert, which are fed from the main zone of saturation, is substantially higher--468 and 500 ppm.

The tunnel samples were collected from seeps discharging from fractures in the tunnels in Rainier Mesa. They represent water from perched zones of saturation in zeolitized tuff, which are replenished by precipitation on the mesa. Almost all waters from the tunnels are of the sodium-potassium type. The sodium and potassium ions (65 to 98 percent of total cations) predominate in 23 to 26 samples. In the remaining samples the calcium and magnesium content is about equal to that of sodium and potassium. The high calcium content of these three water samples may have resulted from contact with calcareous tuff. No source of the magnesium is apparent. The chemical composition and the dissolved-solids content (91 to 334 ppm) of the tunnel waters is similar to that of the springs, if the calculated dissolved solids is accepted instead of residue on evaporation in analyses where the residue is much greater than the calculated solids (Appendix B; Clebsch and Barker, 1960, p. 15-18). In these analyses the residue may have contained suspended matter.

CHEMICAL CHARACTER OF GROUND WATER BY AREAS

The chemical character of ground water in Indian Spring Valley, Yucca and Frenchman Flats, Jackass Flats, and the Amargosa Desert is shown by parallelogram diagrams (fig. 5) and on maps by pie diagrams (figs. 1 and 6). The chemical composition of the water of these areas, in percentage of chemical equivalents of cations and anions, is summarized in tables 4 to 7.

Indian Spring Valley

The ground water from Indian Spring Valley is of the calcium-magnesium type. The calcium and magnesium range from 84 to 94 percent of total cations, and the bicarbonate ranges from 84 to 89 percent of total anions (table 4). The calcium and magnesium are nearly equal. Sodium and potassium are negligible and by their near absence suggest that the water has had little or no contact with tuffaceous rock.

Table 4.--Composition in percentages of chemical equivalents of cations and anions of water from Indian Spring Valley

			Percent of total cations				Percent of total anions		
Well or spring number	Name	Aquifer	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate + carbonate (HCO_3 + CO_3)	Sulfate (SO_4)	Chloride + fluoride + nitrate ($Cl+F+NO_3$)
65-73	Army 2	Alluvium	45	48	6	1	87	8	5
65-76	Army 3	Alluvium	40	50	9	1	88	7	5
66-75	Test well 4	Carbonate rock	46	38	16	0	84	9	7
66-77	Cactus Spring	Alluvium	49	45	6	0	89	6	5
66-79	Indian Spring	Carbonate rock	50	44	6	0	88	8	4

This seems to be true notwithstanding the fact that 450 feet of tuff was penetrated below the alluvium in well 65-76 (Moore, 1962, p. 14-16). The tuff has a calcareous matrix but has little or no zeolitic material; it is more likely to yield calcium than sodium, and probably would yield water much less freely than the alluvium. The principal aquifer is probably the alluvium, in which detrital carbonate rock is abundant, and the water sample consisted principally, if not entirely, of water from the alluvium.

The principal aquifers in Indian Spring Valley are dolomite and alluvium containing detrital dolomite. The chemical composition of the aquifers explains the predominance of calcium and magnesium in the water.

Frenchman and Yucca Flats

Ground water in Frenchman and Yucca Flats falls into all three of the principal chemical types discussed in this report.

The sodium-potassium water is from wells in tuff or wells in alluvium containing detrital tuff. The sodium-potassium content of six wells is high, ranging from 87 to 98 percent (table 5); at one well (83-68) it is 60 percent, barely enough so that the water may be classed as of the sodium-potassium type. The high sodium content of these waters is due in part to the solution of sodium minerals in the volcanic tuff and in part to ion exchange. The alluvium and tuff in Yucca and Frenchman Flats contain a large amount of zeolite and montmorillonite clay, both of which are ion-exchange minerals. As ground water containing calcium and magnesium moves through these materials, calcium and magnesium are replaced by sodium.

Table 5.--Composition in percentages of chemical equivalents of cations and anions of water from Frenchman and Yucca Flats

Well number	Name	Aquifer	Percent of total cations				Percent of total anions		
			Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate + carbonate (HCO_3+CO_3)	Sulfate (SO_4)	Chloride + fluoride + nitrate (Cl+F+NO_3)
73-70	5A	Tuff	1	1	96	2	85	8	7
74-70a	5B	Alluvium	9	4	82	5	59	24	17
74-70b	5C	Alluvium	3	1	94	2	84	9	7
75-73	Test well 3	Carbonate rock	32	21	45	2	69	22	9
79-69	Test well C	Carbonate rock	32	14	51	3	80	14	6
81-67	Well 3	Tuff	25	27	43	5	80	11	9
83-68	Test well A	Alluvium	27	13	55	5	82	11	7
84-68	Test hole 7	Tuff	1	1	96	2	92	1	7
84-69	Test well F	Tuff	2	0	96	2	84	9	7

Table 5.--Composition in percentages of chemical equivalents of cations and anions of water from Frenchman and Yucca Flats--Continued

Well number	Name	Aquifer	Percent of total cations				Percent of total anions		
			Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate + carbonate (HCO_3+CO_3)	Sulfate (SO_4)	Chloride + fluoride + nitrate (Cl+F+NO_3)
87-62	Test well 1	Tuff	6	0	93	1	73	13	14
Do---	--do--	Carbonate rock	29	26	43	2	70	21	9
88-66	Test well 2	Carbonate rock	29	40	27	4	80	12	8
89-68	UE15d	Carbonate rock	27	14	54	5	81	14	5
90-67b	ME-3	Carbonate rock	21	66	11	2	87	9	4

The calcium-magnesium water is present in wells 88-66 and 90-67b, both of which are in dolomite in the northern part of Yucca Flat. Calcium and magnesium total 69 and 87 percent of the total cations and bicarbonate is 80 and 87 percent of total anions, respectively. The water in these wells differs from others in Frenchman and Yucca Flats, apparently because it has been in contact mainly with carbonate rock and little or no mixing with tuff water has taken place. Their chemical composition closely resembles the water of Indian Spring Valley.

The mixed chemical type of water is principally from wells in carbonate rock, but one well in tuff (Well 81-67) also has water of mixed chemical character. (See section on unusual water types). Two water samples from carbonate aquifers have sodium and potassium exceeding calcium and magnesium. None of these water samples show a significant predominance of either sodium plus potassium or calcium plus magnesium. The content of sodium and potassium does not exceed 59 percent of total anions, and the content of calcium and magnesium does not exceed 55 percent.

Jackass Flats (including Rock Valley)

Ground water in Jackass Flats and Rock Valley falls into three chemical types, one of which is a sodium-calcium sulfate type unusual in the region. The others are the sodium-potassium and calcium-magnesium types that seem to be normal to the area.

The sodium-potassium water is from wells 73-58, 73-66, and 74-58, all of which tap tuff. Well 73-66 taps carbonate rock, also; and therefore is discussed in some detail in the following paragraph. Although sodium is the predominant cation (62 to 83 percent) in the sodium-potassium water of the Jackass Flats-Rock Valley area, the proportion of calcium also is substantial, ranging from 13 to 25 percent (table 6). Except for this higher calcium content, these waters are similar to the waters from wells in tuffaceous materials in Frenchman and Yucca Flats.

The calcium-magnesium water is from the carbonate aquifer in well 73-66, Rock Valley. This well penetrated 3,137 feet of tuff and 263 feet of underlying dolomite, and water samples from both the tuff and the dolomite were analyzed. The water from the tuff is perched and, as noted above is a sodium-potassium type; it contains only 15 percent calcium and magnesium. The water from the dolomite is of the calcium-magnesium type, with calcium and magnesium making up 66 percent of total cations--four times as much as in the water from the tuff. The sulfate content of the water from the dolomite (43 percent of total anions) is markedly higher than in the water of the tuff (14 percent), and is, in fact, abnormally high for the region.

The sodium-calcium sulfate water is from the tuff aquifer in well 73-61. The sodium is 53 percent and the calcium is 35 percent of total cations. The sulfate is 80 percent of total anions and is unusually high. By contrast the sulfate content in waters from two wells only 6 miles to the west is less than 17 percent. The only other water samples from the Nevada Test Site that had sulfate as the predominant anion are two from the granodiorite at the north end of Yucca Flat. Substantial proportions of sulfate are present in some of the water from localities outside the Test Site, notably the Amargosa Desert and Mercury Valley, but these probably are not related to those of the Jackass Flats-Rock Valley area. The significance of the sulfate in wells 73-61 and 73-66 is discussed further in the section on "Water high in sulfate."

Table 6.--Composition in percentages of chemical equivalents of cations and anions of water from Jackass Flats (including Rock Valley)

Well number	Name	Aquifer	Percent of total cations				Percent of total anions		
			Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate + carbonate (HCO_3+CO_3)	Sulfate (SO_4)	Chloride + fluoride + nitrate (Cl+F+NO_3)
73-58	J-12	Tuff	25	8	62	5	70	15	15
73-61	J-11	Tuff	35	9	53	3	14	80	6
73-66	Test well F	Tuff	13	2	83	2	64	14	22
Do--	--do--	Carbonate rock	38	28	31	3	52	43	5
74-58	Test well 6	Tuff	22	7	65	6	68	17	15

Amargosa Desert

The Amargosa Desert has been shown by Eakin and others (1963, p. 20-24) to be the most probable place for discharge of ground water moving out of the Nevada Test Site. Their conclusions are based on the hydraulic potential across the region, the relation of discharge to recharge in different basins, and the chemical character of the water. They have shown further that probably no more than 7½ percent of the discharge known to take place in the Amargosa Desert can be derived from recharge within the Nevada Test Site. Their inferences that are based on the chemical character of the ground water are amplified in the following paragraphs, which relate to the southwestern part of the desert beginning near Lathrop Wells (fig. 6).

Most of the water that has been sampled in the Amargosa Desert is from alluvial aquifers, but may not be native to them. Some water may have been discharged into them from underlying carbonate-rock or other aquifers. More than one hydraulic system seems to be represented, but distinctions cannot be made on the basis of data now available; therefore, only the gross features of the ground-water chemistry can be presented here.

Figure 6 and table 7 show that most of the water is the mixed chemical type. Those of the eastern side of the figure have somewhat more calcium and magnesium than sodium and potassium. The sodium and potassium increase westward, and they predominate in five water samples along the western margin of the desert.

As sodium and potassium increase, the calcium and magnesium decrease, and this (fig. 7) suggests that the eastern waters are in part derived

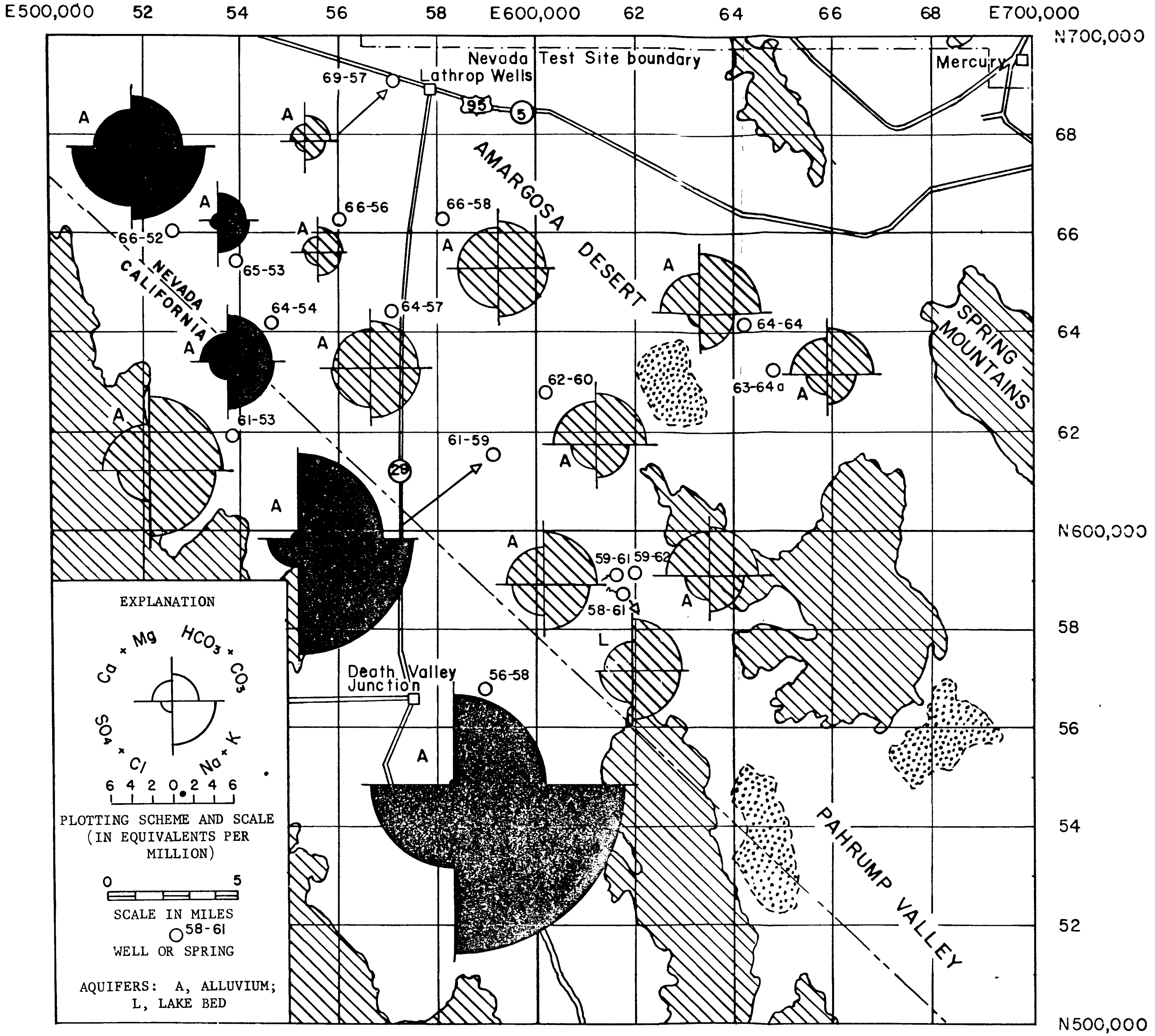

Figure 6.--MAP OF THE SOUTHWESTERN PART OF THE AMARGOSA DESERT SHOWING CHEMISTRY OF GROUND WATER. SODIUM-POTASSIUM TYPE, BLACK; MIXED TYPE, RULED.

Table 7.--Composition in percentage of chemical equivalents of cations and anions of water from the Amargosa Desert

Well or spring number	Name	Aquifer	Percent of total cations				Percent of total anions		
			Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate + carbonate (HCO_3+CO_3)	Sulfate (SO_4)	Chloride + fluoride + nitrate (Cl+F+NO_3)
56-58	------	Alluvium	1	2	95	2	51	31	18
58-61	------	Lake deposits	23	19	56	2	61	29	10
59-61	Big Spring	Alluvium	27	18	52	3	63	28	9
59-62	------	Alluvium	35	22	40	3	67	23	10
61-53	------	Alluvium	27	14	54	5	68	21	11
61-59	------	Alluvium	1	2	94	3	72	20	8
62-60	------	Alluvium	34	23	40	3	68	22	10
63-64a	Ray Van Horn well	Alluvium	27	29	41	3	70	20	10
64-54	------	Alluvium	28	10	58	4	69	14	17
64-57	------	Alluvium	28	16	52	4	53	34	13
64-64	White well	Alluvium	29	23	44	4	82	15	3

Table 7.--Composition in percentage of chemical equivalents of cations and anions of water from the Amargosa Desert--Continued.

Well or spring number	Name	Aquifer	Percent of total cations				Percent of total anions		
			Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate + carbonate (HCO_3+CO_3)	Sulfate (SO_4)	Chloride + fluoride + nitrate ($Cl+F+NO_3$)
65-53	------	Alluvium	13	2	80	5	73	16	11
66-52	------	Alluvium	28	6	63	3	46	35	19
66-56	------	Alluvium	36	7	52	5	62	29	9
66-58	------	Alluvium	28	17	51	4	54	34	12
69-57	------	Alluvium	37	6	53	4	70	20	10

from recharge in the Spring Mountains, which lie to the east and contain carbonate-rock formations. The water received as precipitation on the west slope of the mountains moves westward into the valley as a calcium-magnesium type. In this valley it mixes with sodium-potassium type arriving from another direction, or it picks up sodium in the alluvium by solution or ion exchange. The farther west it moves, the larger the proportion of sodium and potassium becomes.

The relation of recharge to water chemistry that is suggested in the preceding paragraph is seen also in Pahrump Valley, which is flanked on the east by the Spring Mountains. Pahrump Valley is, in fact, closer to the Spring Mountains recharge area than is the Amargosa Desert, and the ground water there is of the calcium-magnesium type and nearly free of sodium and potassium (Eakin and others, fig. 3).

The mixed character of the waters in the eastern and central part of the area shown on figures 6 and 7 may be due in part, also, to influx of water from the carbonate rocks of the Nevada Test Site, which has been shown elsewhere in this report to be of mixed character. Water from the western part of Indian Spring Valley also might move into the Amargosa Desert, acquiring a mixed character en route.

The five high-sodium water samples are aligned northwest-southeast along the western side of the desert, and the southeasternmost has the highest dissolved solids. Their alingment coincides with the general direction of the surface drainage, and probably also with the direction of movement of the ground water. The dissolved solids do not increase in a steady progression. The second and third water samples represented in figure 6 (beginning from the northwest) are less mineralized than the

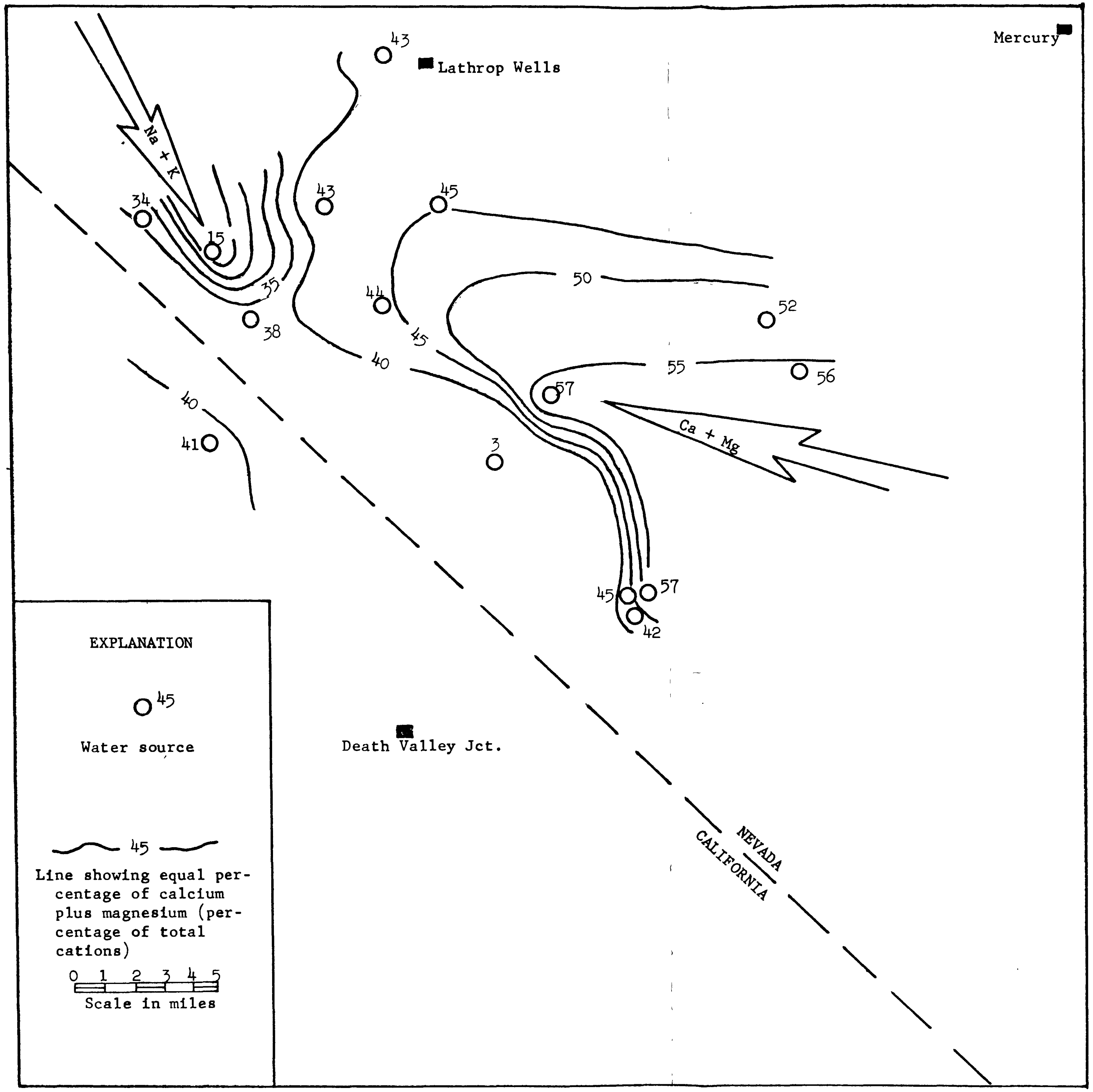

Figure 7.--Map of the southwestern part of the Amargosa Desert showing the distribution of calcium plus magnesium in ground waters, expressed as percentage of total cations. Area covered and water sources are the same as in figure 6.

first, but the overall increase is apparent. This increase may be due in substantial part to concentration by evapotranspiration at places of natural discharge, which are the places where samples were collected. However, the increase may also be due in part to solution of additional mineral matter during underground travel and together with the alingment suggests movement of sodium-potassium water from the northwest into the area. The increase in dissolved solids cannot be denied, but the alignment may be somewhat deceptive because the distinction between mixed types and high-sodium types is necessarily arbitrary. The more western of the mixed types have as much as 58 percent in sodium and potassium; the high-sodium water has only somewhat more than 60 percent. This arbitrary distinction may account for the fact that the water from well 61-53 breaks the alingment of high-sodium samples. Nevertheless, the percentage of sodium plus potassium is unquestionably higher along the western side of the area, and a general movement of sodium-potassium waters from the northwest seems to be a strong probability.

The high-sodium water shows a southeastward decrease in calcium and magnesium that may be significant. At wells 66-52 and 64-54 the calcium and magnesium total 34 and 38 percent, respectively, but at wells 61-59 and 56-58 they are only 3 percent. Wells 65-53 and 61-53 do not fit the progression, and, hence, may be presumed to be subject to other influences. If ground-water movement is from northwest to southeast, the decrease in calcium and magnesium may be due to ion exchange.

WATER MOVEMENTS INFERRED FROM DISSOLVED SOLIDS

The amount of dissolved solids in ground water depends on several variables, ranging from the quantity of carbon dioxide dissolved in the water to the kinds and solubility of the rocks and minerals, and it may suggest the direction in which the water has moved. The variables are such that small differences in the dissolved solids are likely to be meaningless, or at least not interpretable, but some of the larger differences seem to have meaning. For example, the waters from springs and those from tunnels in Rainier Mesa (Clebsch and Barker, 1960, table 2A; Moore, 1961, table 5a; this report, appendix B) seem to have had only relatively short contact with the rocks.

Some but by no means all the spring waters are low in dissolved solids (table 8). The springs are fed by perched zones of saturation in volcanic rocks, chiefly tuff. These zones of saturation probably are relatively small in areal extent, and the recharge to them is derived from the precipitation on nearby areas. The route of ground-water travel and the residence time therefore may be presumed to be short.

Seasonal variations in dissolved solids at Whiterock Spring are suggested by a series of five analyses (table 9). The analyses are not spaced closely enough nor regularly enough to show seasonal changes accurately. Rather, they show a wide range that is presumed to be seasonal because the static water level in a test hole adjacent to the spring, as recorded by a recording gage, fluctuates widely in response to precipitation in the immediate vicinity (Winograd, oral communication, 1963). The range in dissolved solids as shown by residue on evaporation was from 184 to 362 ppm, or about 1 to 2. If the calculated dissolved solids is considered instead, on the basis that some of the residues were erroneous because of turbidity of samples, the range is from 149 to 243 ppm, or about 1 to 1.6. In either case, the variations in dissolved solids suggest that some of the paths between the places of recharge and the spring are relatively short and direct.

Table 8.--Dissolved solids in spring water, Nevada Test Site, in parts per million

Number	Name of spring	Dissolved solids
88-64	Captain Jack	178
90-67	Oak	180
90-68	Tubb	185
83-63	Tippipah	159 - 194
79-61	Topopah	123 - 210
88-63	Rainier	250
74-66	Cane	288
89-65	Whiterock	184 - 362

Table 9.--Variations in dissolved solids at Whiterock Spring, Nevada Test Site, in parts per million

Date	Dissolved solids		Date	Dissolved solids	
	Res. on evap.	Calculated		Res. on evap.	Calculated
Sept. 18, 1957	184	184	May 19, 1959	208	168
Mar. 21, 1958	265	243	Jan. 29, 1960	352	149
			Nov. 10, 1960	362	184

The water samples from fractures intersected in the tunnels in Rainier Mesa are similar in dissolved-solids content to the spring water. The total solids in 25 samples range from 91 to 334 ppm (appendix B; Clebsch and Barker, 1960, p. 15-16), but the average is near the lower end of the range: 176 ppm. The dissolved solids in 18 of these samples was between 100 to 200 ppm. The sum of dissolved solids, rather than the residue on evaporation, is evaluated for seven of these samples because filtering failed to remove all the turbidity. The residue on evaporation is so much greater than the sum that suspended matter probably was included in the residue.

The "tunnel" water, like the spring water, passed mainly or solely through volcanic rock. They were from a perched zone, or zones, of saturation, or from fractures. The samples may be presumed to have been collected at points not far from the place or places of recharge, not only because of their low content of dissolved solids but also because of geologic and topographic relations. The source of recharge, therefore, may not be far away. This view is confirmed by the tritium analysis of one sample of water from a tunnel, which indicates a residence time underground of more than 0.8 year and less than 6 years (Clebsch, 1961, p. C-124).

The water from wells and test holes that penetrate the regional zone of saturation generally is more mineralized than the spring and "tunnel" water, yet few of them contain more than 500 ppm, the desirable limit recommended by the U.S. Public Health Service (1962) for dissolved solids in water to be used for human consumption. A few of the water samples from the Nevada Test Site are very low in dissolved solids. The water from the Paleozoic carbonate rock in well 87-62, in the depth interval from 3,700 to 4,206 feet, contains only 220 ppm dissolved solids. It compares favorably with the water from the uppermost perched aquifer in tuff in the same well (412 to 560 feet), which contains 240 ppm. The low dissolved-solids content of the water from the tuff suggests that the site of recharge to the tuff is near.

The ground water in Indian Spring Valley is notably low in dissolved solids. The three analyses for the valley that are represented on figure 1 range from 205 to 225 ppm in dissolved solids (wells 65-73, 65-76, and 66-75). Two others that are from sources a few miles beyond the east boundary of figure 1 contain 205 and 225 ppm, respectively (well 66-77 and spring 66-79). All are calcium-magnesium types, from carbonate rocks or from alluvium presumed to contain detritus of such rocks. By contrast, the nearest well to the west that taps a carbonate aquifer has half again as much dissolved mineral matter (well 67-68, in Mercury Valley, 330 ppm); and the nearest well to the north has about twice as much (well 75-73, in Frenchman Flat, 444 ppm). The only water from carbonate rocks that is comparable in dissolved solids to Indian Spring Valley is from well 87-62, which is discussed above, and well 88-66 (236 ppm). If the amount of dissolved solids is meaningful, the water of Indian Spring Valley might be moving westward into Mercury Valley or northward into Frenchman Flat, but a reverse movement in the opposite direction is unlikely.

If the water movement is westward or northward from Indian Spring Valley, the proportion of calcium and magnesium should decrease in the direction of movement and it does. Whereas the calcium and magnesium average 92 percent of total cations in the waters of Indian Spring Valley, they are but 70 percent at well 67-68 (Mercury Valley) and 53 percent at well 75-73 (Frenchman Flat).

Consideration of the dissolved solids in water from tuff and tuffaceous alluvium suggests that recharge to these aquifers in the Emigrant, Yucca, and Frenchman basins is local in origin; and, further, that direct movement of water between basins through these aquifers is unlikely. The waters from three wells in Emigrant Valley that tap tuff or tuffaceous alluvium are low in dissolved solids, averaging about 285 ppm. This average is 70 ppm higher than the average for eight springs from perched aquifers in tuff--actually, 100 ppm or more higher than the dissolved solids in five of the eight. The average is also about 100 ppm higher than the average for 25 water samples from tunnels in Rainier Mesa. These comparisons of average dissolved solids suggest that the three water samples from Emigrant Valley have traveled somewhat farther, or have been somewhat longer underground, than the spring and "tunnel" water.

The Emigrant Valley water and the water from three wells tapping tuff and tuffaceous alluvium in Yucca Flat (wells 83-68, 84-68, and 84-69) averages about the same in dissolved solids. The Yucca Flat water, therefore, probably has not moved underground from Emigrant Valley. If they had done so, they probably should contain more dissolved mineral matter than the Emigrant Valley water types. Omitted from consideration here is the water of Yucca Flat well 81-67, which is of mixed chemical type though it comes from tuff, and is therefore discussed in the section on "Unusual water types."

The average dissolved solids for the waters from three wells in Frenchman Flat that tap tuff or tuffaceous alluvium is about 385 ppm. This is about 100 ppm more than in the water from similar aquifers in Yucca Flat and Emigrant Valley, which are considered above. The water in Frenchman Flat might, on the basis of dissolved solids alone, be interpreted as having moved southward from Yucca or Emigrant Valleys. However, the movement of ground water in Yucca Flat has been shown by Winograd (1962a, b) to be not so much laterally through the alluvium and tuff as downward through these rocks into the underlying carbonate rocks and through those rocks to sites of discharge. The movement of ground water in Emigrant Valley is imperfectly known, but scanty evidence suggests that the water table in the vicinity of Groom Lake slopes southeastward, not southwestward toward Frenchman Flat. Hence, the transfer of substantial quantities of water between the three valleys, with movement taking place in the tuff and alluvium, seems unlikely. The higher dissolved-solids content of the Frenchman Flat water, therefore, is attributed to longer residence in the rock in that valley, or to a relatively greater supply of soluble minerals in the rock.

Each basin probably is recharged locally from precipitation on adjacent higher lands. The water received in this manner may move downward through tuffaceous rocks into the underlying carbonate rocks, as in Yucca Flat, but it probably does not move in large quantities from the tuff or tuffaceous alluvium of one of these three basins into similar rocks of an adjacent basin. The interbasin movement of ground water takes place in the carbonate rocks.

The water of wells 73-58 and 74-58, Jackass Flats, contains only 197 and 242 ppm, respectively, dissolved solids, and suggest a local source of recharge. Both wells tap volcanic rocks. The higher dissolved solids are from the well tapping the thicker section of saturated rock. Both wells are near the axis of Fortymile Canyon, where freshening by infiltrating stream water may be effective. The ground water at these two wells probably has not traveled far from the recharge site.

The water from wells 65-53, 66-56, and 69-57, near Lathrop Wells (fig. 6), has only 294, 310, and 233 ppm, respectively, in dissolved solids. Their dissolved-solids content is substantially below the average for water of the Amargosa Desert (about 465 ppm), but is somewhat higher than the dissolved solids in the waters from wells 73-58 and 74-58 in Jackass Flats (197 and 242 ppm), roughly 10 miles to the north. This water, may have enetered the rocks as recharge from runoff from Fortymile Canyon or as recharge in the high country of Yucca and Timer Mountains.

The ground water of the Amargosa Desert, as represented by available analyses, averages about 465 ppm dissolved solids. The dissolved solids in 8 to 15 water samples were between 400 and 600 ppm, and they exceeded 700 ppm in 2 samples. The average is twice that for water in Indian Spring Valley and substantially greater than the dissolved solids in most water of the Test Site. The maximum for the Amargosa Desert is the greatest in the region. The dissolved solids point to the Amargosa Desert, therefore, as the destination to which the ground water may be going, not as the place from which it comes.

WATER MOVEMENTS INFERRED FROM SODIUM DISTRIBUTION

The chemical character of water moving through rocks may be altered by ion exchange, a process in which one or more ions from the water solution are exchanged for other ions adsorbed on the rock. One of these reactions is the exchange of calcium and/or magnesium dissolved in the water for sodium or potassium from the rock (Hem, 1959, p. 221). It is suggested in another section of this report that the sodium content of the waters from tuff or tuffaceous alluvium is due in part to solution of sodium from the rock and in part to the exchange of calcium and magnesium for sodium. At any rate, the water that has been in or has passed through tuffaceous materials generally has a substantial proportion of sodium and may have but little calcium and magnesium.

The reaction outlined above may be reversible under some circumstances, but the conditions permitting such reversal seem not to exist in the vicinity of the Nevada Test Site. To reverse the reaction would require that the water contain a much greater concentration of sodium than has yet been found at or near the Test Site. The normal condition therefore seems to prevail and the sodium dissolved in ground water is likely to remain in solution. If water high in sodium moves out of tuffaceous materials into sodium-poor materials, such as the carbonate rocks, it may pick up calcium and magnesium in addition to the solids already in solution but it will not lose sodium to the rock. If a sodium-potassium water were to become mixed with a calcium-magnesium water, the result would be a water of mixed chemical character, perhaps similar to the water from wells 75-73 and 79-69a. Lack of sodium in water may be presumed to mean lack of contact of water with rock containing soluble sodium, tuff included.

The presence or absence of sodium in the waters of the Test Site and vicinity are clues to the ground-water movement. The distribution of sodium suggests the following conclusions:

1. The water in the Paleozoic carbonate rocks underlying the Test Site is in part recharged by percolation downward through tuff or through alluvium containing detrital tuff, or both. The water entering the carbonate rocks in this manner is generally a sodium-potassium type, which when added to the calcium-magnesium type already in the rocks yields a water of mixed chemical character.

2. The water in the carbonate rocks of the Test Site may be moving toward the Amargosa Desert, where the water generally is of mixed chemical character, have a generous amount of sodium, and are more concentrated than those within the Test Site. Not all the water reaching the Amargosa Desert, however, need come from the Test Site.

3. The water of Indian Spring Valley has had little opportunity for contact with tuff or tuffaceous alluvium, or with another rock material containing much soluble sodium. This water probably entered the rocks as recharge on the upper slopes of the Spring Mountains, which lie to the south. The mountains contain extensive outcrops of carbonate rocks, from which calcium and magnesium could be dissolved.

4. The water in the carbonate rocks is not moving southward from the Test Site to Indian Spring Valley. If it did so, the waters of Indian Spring Valley would contain more sodium, and also would probably be higher in dissolved solids.

5. The ground water in Indian Spring Valley may move northward toward Frenchman Flat or westward toward Mercury Valley and the Amargosa

Desert. This inference, based solely on the chemical character of the water, is confirmed by studies of the hydraulic potential, which have shown the water table to be higher in Indian Spring Valley than in Mercury Valley or Frenchman Flat (Eakin and others, 1963).

SUMMARY AND CONCLUSIONS

Sodium-potassium water is found at the Nevada Test Site in aquifers in tuff and in alluvium containing detrital tuff. They are found in Yucca, Frenchman, and Jackass Flats, and in Emigrant Valley. The water from springs and those from fractures intersected in tunnels is notably low in dissolved solids, and this fact suggests nearness of the recharge areas. However, the dissolved solids in water from tuffaceous aquifers tapped by deep wells are not much higher than in the spring and "tunnel" waters; from this it is inferred that water in such aquifers generally has not progressed far in their underground travels. Their chemical history is relatively uncomplicated.

The water from tuffaceous aquifers in Yucca Flat averages the same in dissolved solids as the water from similar aquifers in Emigrant Valley. This fact suggests that movement underground of large quantities of water from Emigrant Valley into Yucca Flat through these aquifers does not take place.

The water from tuffaceous aquifers in Frenchman Flat averages higher in dissolved solids than those in Yucca Flat and Emigrant Valley, and therefore could have come from those valleys, water chemistry alone being considered. However, movement of ground water in tuffaceous rock is downward into the underlying carbonate rocks and it is concluded that recharge to the tuffaceous aquifers is derived chiefly from local precipitation in each basin.

Calcium-magnesium water is found in limestone and dolomite (carbonate rocks) and in alluvium containing, or presumed to contain, detritus of such rocks. The waters in Indian Spring Valley are typical calcium-magnesium type. A typical calcium-magnesium water low in dissolved solids, like a typical sodium-potassium water low in dissolved solids, probably has had only a relatively uncomplicated chemical history.

Water having the characteristics of both the preceding types is termed water of mixed chemical type. These may be water from tuffaceous aquifers that have moved into carbonate rocks (or alluvium with carbonate-rock detritus) and there have picked up calcium and magnesium in addition to solids already in solution. They may be water from carbonate rocks that have come in contact with tuff--or, more probably, detrital tuff in alluvium--and have picked up sodium by solution or through ion exchange. They may also be the result of mixing of calcium-magnesium with sodium-potassium water, but such mixing is probably rare.

Water of mixed chemical type is found in some of the carbonate rocks tapped by wells within the Nevada Test Site, and suggest that some of the water recharged to the carbonate rocks passes first through tuffaceous rocks.

Water of mixed chemical type predominates in the Amargosa Desert. In general, also, the water of this desert is the most mineralized of the region. These facts suggest, therefore, that this water has traveled farther and has a more complicated chemical history than others, and that the Amargosa Desert is a destination for moving ground water. It is a discharge area.

The virtual lack of sodium in the waters of Indian Spring Valley is especially significant because sodium dissolved in water generally remains in water. Lacking substantial sodium, the water of Indian Spring Valley has not come from the tuff and tuffaceous alluvium, or even from the carbonate rocks, within the Nevada Test Site. More probably they have been derived from recharge on the upper slopes of the Spring Mountains, where carbonate rocks crop out. Their low content of dissolved solids (average 215 ppm) supports this hypothesis.

Recharge water may also move from the Spring Mountains westward into the Amargosa Desert. The calcium and magnesium content of the water, in percent of total cations, decreases progressively westward from the mountains in a manner that suggests a meeting with water from the northwest.

Low total solids in three samples from the northern margin of the Amargosa Desert, near Lathrop Wells, suggest influx of water recharged nearby, possibly in the high country of the Yucca Mountain-Timber Mountain area or from surface water in Fortymile Canyon.

In conclusion, the ground water of the Nevada Test Site seems to be moving into the Amargosa Desert, but not into Indian Spring Valley. Only a fraction of the water reaching the Amargosa Desert is from the Test Site. Large contributions appear to be coming from the Spring Mountains and from localities to the northwest.

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APPENDIX B.--SELECTED CHEMICAL ANALYSES OF WATERS FROM SPRINGS AND TUNNELS, IN PARTS PER MILLION AND EQUIVALENTS PER MILLION (IN PARENTHESES), BY THE U.S. GEOLOGICAL SURVEY

Chemical analyses for waters of springs in and near the Nevada Test Site, including repetitive analyses as available, were reported by Moore (1961, table 5a). The table below includes only the latest analysis for each spring. This is the only analysis for some springs, and therefore is a repetition of the analysis published previously, but for others it is an analysis made since the previous publication. In all cases the analysis given below is the one on which the chemical diagram shown in this report is based; in no case does the latest analysis differ greatly from previous analyses of water from the same source. Analyses representing a few springs in the Amargosa Desert and Indian Spring Valley are included.

Chemical analyses for waters from fractures intersected in the U-12-b tunnel in Rainier Mesa and from drill holes in the tunnel were reported by Clebsch and Barker (1960, table 2A). Only six additional samples from such sources have been analyzed subsequently, and these are reported below.

The springs in the Nevada Test Site are fed by perched zones of saturation and therefore do not represent directly the regional relationships that are the subject of this paper. Accordingly, they are omitted from figure 1 in the interest of simplicity. Their locations can be determined approximately from the numbers assigned to them, which consist of the first two digits of the north coordinate followed, after a hyphen, by the first two digits of the east coordinate. (See the section on "Numbering system" for further explanation.)