Title

hydrogeologic and hydrochemical framework, SouthCentral Great basin, nevada/California, with special reference to the Nevada Test Site. Hydrologic setting in stratigic graphic unit. Technical reference document.

Author

Winograd, Isaac J. and William Thordason

100979

Document Date

1/1/75

ERC Index number

05.09.023

Document Type

Published Article

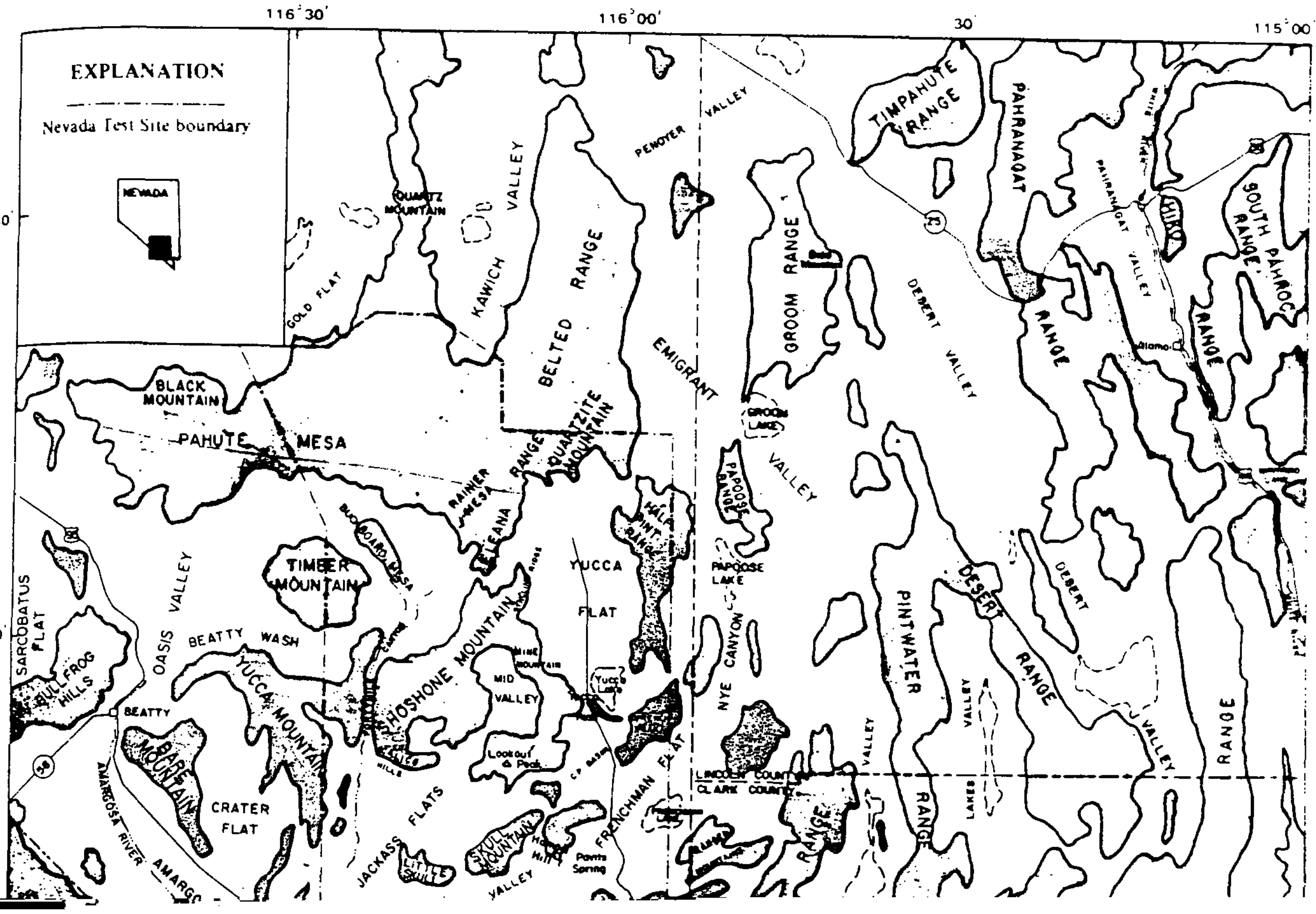
Box Number

1684-1

Recipients

Atomic Energy Commission

Hydrogeologic and


116°30'
116°00'
30'
115°00'
37°30'
37°00'
EXPLANATION
Nevada Test Site boundary
NEVADA
TIMPAHUTE RANGE
PAHRANAGAT
PAHRANAGAT VALLEY
SOUTH PAHROC RANGE
QUARTZ MOUNTAIN
KAWICH VALLEY
BELTED RANGE
PENOYER VALLEY
GOLD FLAT
EMIGRANT
GROOM RANGE
DESERT VALLEY
RANGE
Alamo
BLACK MOUNTAIN
PAHUTE MESA
QUARTZITE MOUNTAIN
RAINIER MESA
ELEANA RANGE
GROOM LAKE
PAPOOSE RANGE
VALLEY
HALFPINT RANGE
TIMBER MOUNTAIN
OASIS VALLEY
YUCCA FLAT
PAPOOSE LAKE
SARCOBATUS FLAT
BEATTY WASH
BULLFROG HILLS
BEATTY
YUCCA MOUNTAIN
SHOSHONE MOUNTAIN
MID VALLEY
NYE CANYON
PINTWATER RANGE
DESERT RANGE
DESERT VALLEY
LINCOLN COUNTY
CLARK COUNTY
BARE MOUNTAIN
CRATER FLAT
AMARGOSA RIVER
JACKASS FLATS
SKULL MOUNTAIN
FRENCHMAN FLAT
Lookout Peak
Pavits Spring
VALLEY
LAKES VALLEY
RANGE
95
58
25

No large perennial or intermittent streams are found in the region. Several of the prominent perennial springs near the base of the Spring Mountains periodically flow a few thousand feet to 1 mile or so from their orifices before being diverted or seeping into alluvial fans. The Amargosa River may be intermittent in a short reach in the vicinity of Beatty, Nev.

ECONOMIC DEVELOPMENT

One major and three minor population centers are within or immediately adjacent to the study area. The city of Las Vegas and its suburbs are the major center, having a population of about 240,000 people (Nevada Chamber of Commerce, 1965). The minor population centers are Indian Springs in Clark County and Mercury and Beatty in Nye County. The 1965 population of these villages was about 2,000, 1,200 and 500 people, respectively. The population of these small communities fluctuates with the level of activity at the Nevada Test Site. Tourism is the major industry in Las Vegas and at Beatty, but a sizeable part of the income in both communities comes from expenditures of the U.S. Atomic Energy Commission and the National Aeronautics and Space Administration at the Nevada Test Site, and of the U.S. Air Force at Nellis Air Force Base north of Las Vegas.

Except for several thousand acre-feet of water piped into Las Vegas from Lake Mead, ground water was the sole source of water for the entire region of study in 1967. The pumpage for the city of Las Vegas amounted to about 42,000 acre-feet in 1964.

CLIMATE

The study area lies principally within the most arid part of Nevada, the most arid State in the Union. The average annual precipitation on the valleys ranges from 3 to 6 inches and on most of the ridges and mesas averages less than 10 inches. The potential annual evaporation from lake and reservoir surfaces was estimated by Meyers (1962) to range from 60 to 82 inches, or roughly 5 to 25 times the annual precipitation. The diurnal relative humidity of much of the region — as indicated by records at Las Vegas — ranges from 10 to 30 percent during the summer and from 20 to 60 percent in winter. The mean daily maximum temperature at Las Vegas (sta. alt, 2,162 ft) ranges from 13.0°C (Celsius) in January to 40.5°C in July; the mean daily minimum temperature for the same months ranges from 0.5°C to 24.5°C; temperatures in the higher valleys, such as in central Yucca Flat (sta. alt, 4,076 ft), are as much as 3.0° to 8.5° lower. In Death Valley, in the southwest corner of the study area, temperatures greater than 49.0°C are common during the summer months. Annual rainfall in this valley averages about 1.7 inches, and annu[illegible] evaporation is about 150 inches per year (Hun[illegible] others, 1966).

A significant exception to the general aridity [illegible] region is the subhumid climate of the Sheep Rang[illegible] the Spring Mountains. The precipitation on these m[illegible]tains generally ranges from 10 inches on the lower s[illegible] to 30 inches on the highest peaks of the Spring M[illegible]tains; possibly as much as one-third of this precipit[illegible] is snowfall. Thus, the climate of the region ranges [illegible] arid on the valley floors to subhumid on the crests [illegible] highest mountains.

Variations in precipitation and temperature c[illegible] marked differences in plant life. Creosote bush, [illegible] bush, and a variety of yuccas, which dominate the [illegible]jadas below 4,000 feet, give way to blackbrush [illegible] joshua trees at slightly higher altitudes. Juniper, p[illegible] pine, and sagebrush dominate above 6,000 feet and [illegible] in turn replaced by white fir and yellow pine (*P[illegible] ponderosa*) above 7,500 feet (Bradley, 1964).

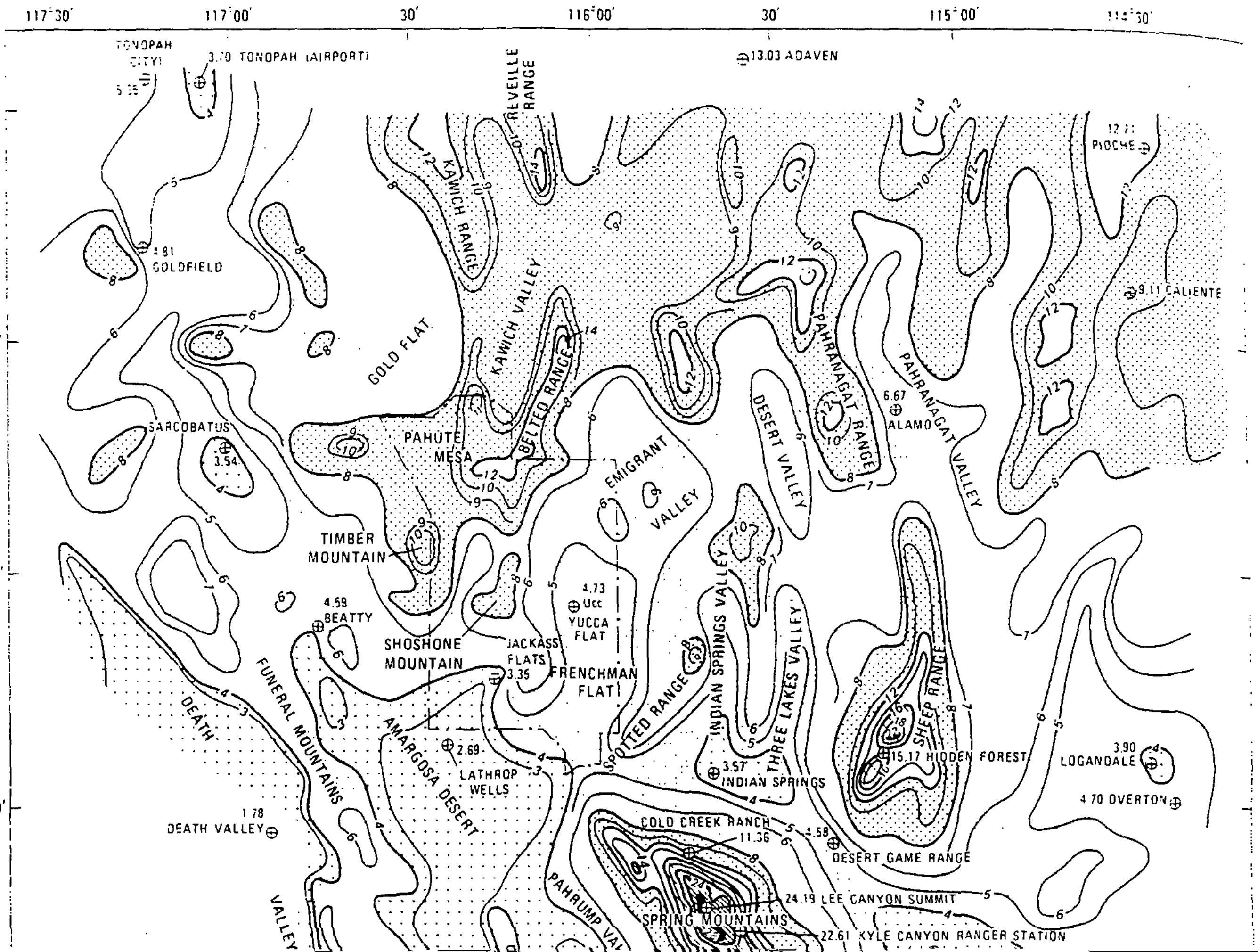
Precipitation varies markedly with the season. [illegible] most precipitation falls during winter and summer. [illegible] monthly precipitation at Las Vegas and at the Nev[illegible] Test Site is illustrated in figure 2. The mean ann[illegible] precipitation is shown in figure 3.

Winter precipitation, originating from the west, [illegible] usually associated with transitory low-pressure syste[illegible] and, therefore, moves over large areas (Quiring, 196[illegible] The summer precipitation, on the other hand, occ[illegible] predominantly as convective storms which can be [illegible]tense over a few square miles and which vary in locati[illegible] from one storm to the next. Summer moisture genera[illegible] originates from the southeast or south.

Recent studies by Weedfall (1963) and Quiri[illegible] (1965) showed that precipitation within the study area [illegible] a function of altitude and of longitudinal positi[illegible] Generally, stations east of long 115°45′ receive from [illegible] to 2.5 times more precipitation than stations at simil[illegible] altitudes but west of long 116°45′. Stations between the[illegible] longitudes receive intermediate or transitional amoun[illegible] of precipitation at any given altitude. Reasons for th[illegible] longitudinal control were outlined by Quiring (1965).

The net effect of the longitudinal and the altitude con[illegible]trols of precipitation is a marked precipitation defici[illegible] within the region bounded by lat 36°30′ and 37°15′ an[illegible] long 115°30′ and 116°15′. Topographically, this area i[illegible] the lowest part of the study area; moreover, most of i[illegible] falls within the transition zone outlined by Quirin[illegible] (1965, fig. 1). Precipitation in this area ranges from 4 t[illegible] 10 inches and, except for the Amargosa Desert and Death Valley, is the lowest for the region.

Geological, botanical, ecological, and paleontological studies indicate that the entire region at one time had a much wetter climate. As a whole, the evidence suggests


117°30'
117°00'
30'
116°00'
30'
115°00'
38°00'
30'
37°00'
30'
TONOPAH CITY
3.70 TONOPAH (AIRPORT)
REVEILLE RANGE
13.03 ADAVEN
PIOCHE
KAWICH RANGE
KAWICH VALLEY
3.81 GOLDFIELD
GOLD FLAT
9.11 CALIENTE
PAHRANAGAT RANGE
PAHRANAGAT VALLEY
6.67 ALAMO
BELTED RANGE
PAHUTE MESA
SARCOBATUS
3.54
EMIGRANT VALLEY
DESERT VALLEY
TIMBER MOUNTAIN
4.73 Ucc YUCCA FLAT
4.59 BEATTY
SHOSHONE MOUNTAIN
JACKASS FLATS
3.35
FRENCHMAN FLAT
SPOTTED RANGE
INDIAN SPRINGS VALLEY
THREE LAKES VALLEY
SHEEP RANGE
15.17 HIDDEN FOREST
3.90 LOGANDALE
4.70 OVERTON
DEATH
FUNERAL MOUNTAINS
AMARGOSA DESERT
2.69 LATHROP WELLS
3.57 INDIAN SPRINGS
1.78 DEATH VALLEY
VALLEY
COLD CREEK RANCH
11.56
4.58
DESERT GAME RANGE
PAHRUMP VAL
24.19 LEE CANYON SUMMIT
SPRING MOUNTAINS
22.61 KYLE CANYON RANGER STATION

GEOLOGIC SETTING

The Nevada Test Site region is geologically complex. It lies within the miogeosynclinal belt of the Cordilleran geosyncline, in which 37,000 feet of marine sediments accumulated during the Precambrian and Paleozoic Eras. Except for a few small intrusive masses, no rocks of Mesozoic age are found within the study area. The region is also within a Tertiary volcanic province in which extrusive rocks, locally more than 13,000 feet thick, were erupted largely from caldera centers. Quaternary detrital sequences, largely alluvium, fill most of the low-lying areas in the region.

Two major periods of deformation affected the region. The first orogeny occurred in late Mesozoic and perhaps early Tertiary time and resulted in folding and thrust faulting of the Precambrian and Paleozoic rocks. During middle to late Cenozoic time the region underwent normal block faulting, which produced the Basin and Range topography. Displacements along major strike-slip faults, measured in miles, occurred during both periods of deformation.

The description of stratigraphy and structure which follows pertains chiefly to the Nevada Test Site but is applicable in general terms to most of the area of figure 1. Where differences in the general geology of a specific part of figure 1 and that at the Nevada Test Site exist, they are noted at appropriate places in the text. The outline of stratigraphy and structure presented below is taken from the following sources: Albers (1967); Harley Barnes (U.S. Geol. Survey, written commun., 1965); Barnes and Poole (1968); Burchfiel (1964, 1965); Ekren (1968); Ekren, Rogers, Anderson, and Orkild (1968); Fleck (1970); Hinrichs (1968); Longwell (1960); Longwell, Pampeyan, Bowyer, and Roberts (1965); Noble (1968); Orkild (1965); Poole, Carr, and Elston (1965); Ross and Longwell (1964); Secor (1962); Stewart (1967); and Vincelette (1964).

PRECAMBRIAN AND PALEOZOIC STRATIGRAPHY

During Precambrian and Paleozoic time, 37,000 feet of marine sediments were deposited in the study area. The region was then part of an elongated subsiding trough, the Cordilleran geosyncline, which covered most of westernmost North America. The eastern part of this trough, dominated by carbonate and mature clastic sediments, is called the miogeosyncline. The miogeosynclinal sediments throughout the Nevada Test Site and the surrounding region have been divided into 16 formations. Names, thicknesses, and gross lithologic character of these formations are summarized in table 1. For detailed stratigraphic descriptions the reader is referred to Burchfiel (1964).

Because of the generally uniform miogeosynclinal sedimentation, 15 of the 16 formations of table 1 (excluding the Devonian and Mississippian rocks) are probably representative of the lithology and the relative thickness of Precambrian and Paleozoic strata in the region extending several tens of miles beyond Nevada Test Site.

In addition to the uniform lithologic character of the formations throughout the study area, the vertical distribution of clastic and carbonate lithologies within the 37,000-foot sequence is significant. The Precambrian to Middle Cambrian strata, 10,000 feet thick, are predominantly quartzite and siltstone; the Middle Cambrian through Upper Devonian strata, 15,000 feet thick, are chiefly limestone and dolomite, the Devonian and Mississippian rocks of the Yucca Flat area, about 8,000 feet thick, are chiefly argillite and quartzite; and the Pennsylvanian and Permian rocks about 4,000 feet thick, are chiefly limestone. Thus, the Precambrian and Paleozoic sedimentation was marked by two major sequences of clastic and carbonate sedimentation. Minor clastic rocks — the Dunderberg Shale Member of the Nopah Formation, the Ninemile Formation, and the Eureka Quartzite — occur within the lower carbonate sequence.

A lateral variation in lithology and thickness of Devonian and Mississippian rocks contrasts with the lithologic uniformity of other parts of the stratigraphic section. In western Yucca Flat, Jackass Flats, and areas to the west and northwest, the Devonian and Mississippian strata are composed chiefly of clastic rocks (quartzite, siltstone, argillite, and conglomerate), as much as 8,000 feet in thickness, called the Eleana Formation (table 1). However, in the Spotted Range and the Indian Springs Valley, rocks of equivalent age are predominantly carbonate, and they aggregate about 1,000 feet in thickness. Preliminary work by Poole, Houser, and Orkild (1961) indicated that the southeastward transition from clastic to carbonate lithology was probably gradational, but that postdepositional thrust or strike-slip faulting may have obscured the transition.

For this report the clastic Eleana Formation will be considered representative of the Devonian and Mississippian rocks in Yucca Flat, Jackass Flats, and northwestern Frenchman Flat. The predominantly carbonate Monte Cristo Limestone and part of the Bird Spring Formation of the Spring Mountains are tentatively considered representative of time-equivalent rocks in the Spotted Range and Indian Springs Valley.

No major unconformities occur within the miogeosynclinal column. Several disconformities are present but are not marked by deep subaerial erosion of the underlying rocks.

MESOZOIC STRATIGRAPHY

Rocks of Mesozoic age in the study area consist of

TABLE 1. — *Stratigraphic and hydrogeologic units at Nevada Test Site and vicinity*

System	Series	Stratigraphic unit	Major lithology	Maximum thickness (feet)	Hydrogeologic unit	Water-bearing characteristics and extent of saturation
Quaternary and Tertiary	Holocene, Pleistocene, and Pliocene	Valley fill	Alluvial fan, fluvial, fanglomerate, lakebed, and mudflow deposits	2,000	Valley-fill aquifer	Coefficient of transmissibility ranges from [illegible] to 35,000 gpd per ft; average coefficient of interstitial permeability ranges from 5 to 70 gpd per sq ft; saturated only beneath structurally deepest parts of Yucca Flat and Frenchman Flat.
Tertiary	Pliocene	Basalt of Kiwi Mesa	Basalt flows, dense and vesicular.	250	Lava-flow aquifer	Water movement controlled by primary (cooling) and secondary fractures and possibly by rubble between flows; intercrystalline porosity and permeability negligible, estimated coefficient of transmissibility ranges from 500 to 10,000 gpd per ft; saturated only beneath east-central Jackass Flats.
Tertiary	Pliocene	Rhyolite of Shoshone Mountain	Rhyolite flows.	2,000		
Tertiary	Pliocene	Basalt of Skull Mountain	Basalt flows.	250		
Tertiary	Pliocene	*Piapi Canyon Group*, Timber Mountain Tuff: Ammonia Tanks Member	Ash-flow tuff, moderately to densely welded; thin ash-fall tuff at base.	250	Welded-tuff aquifer	Water movement controlled by primary (cooling) and secondary joints in densely welded part of ash-flow tuff; coefficient of transmissibility ranges from [illegible] to 100,000 gpd per ft; intercrystalline porosity and permeability negligible; unwelded part of ash-flow tuff, where present, has relatively high interstitial porosity (35-50 percent) and modest permeability (2 gpd per sq ft) and may act as leaky aquitard; saturated only beneath structurally deepest parts of Yucca, Frenchman, and Jackass Flats
Tertiary	Pliocene	*Piapi Canyon Group*, Timber Mountain Tuff: Rainier Mesa Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff at base.	600		
Tertiary	Miocene	*Piapi Canyon Group*, Paintbrush Tuff: Tiva Canyon Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff near base.	300-350		
Tertiary	Miocene	*Piapi Canyon Group*, Paintbrush Tuff: Topopah Spring Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff near base.	890		
Tertiary	Miocene	*Piapi Canyon Group*, Paintbrush Tuff: Bedded tuff (informal unit)	Ash-fall tuff and fluvially reworked tuff.	1,000	Bedded-tuff aquifer	Coefficient of transmissibility ranges from 200 to 1,000 gpd per ft; saturated only beneath structurally deepest parts of Yucca Flat, Frenchman Flat, and Jackass Flats; Occurs locally below ash-flow tuff members of Paintbrush Tuff and below Grouse Canyon Member of Indian Trail Formation
Tertiary	Miocene	Wahmonie Formation	Lava-flow and interflow tuff and breccia; locally hydrothermally altered.	4,000	Lava-flow aquitard	Water movement controlled by poorly connected fractures; interstitial porosity and permeability negligible; coefficient of transmissibility estimated less than 500 gpd per ft; contains minor perched water in foothills between Frenchman Flat and Jackass Flats.
Tertiary	Miocene	Wahmonie Formation	Ash-fall tuff, tuffaceous sandstone, and tuff breccia, all interbedded; matrix commonly clayey or zeolitic.	1,700	Tuff aquitard	Coefficient of transmissibility ranges from 100 to 200 gpd per ft; interstitial porosity is as high as 40 percent, but interstitial permeability is negligible (6 × 10[illegible] to 6 × 10[illegible] gpd per sq ft); owing to poor hydraulic connection of fractures, interstitial permeability probably controls regional ground-water movement; perches minor quantities of water beneath foothills flanking valleys; fully saturated only beneath structurally deepest parts of Yucca Flat, Frenchman Flat, and Jackass Flats; Grouse Canyon and Tub Spring Members of Indian Trail Formation may locally be aquifers in northern Yucca Flat.
Tertiary	Miocene	Salyer Formation	Breccia flow, lithic breccia, and tuff breccia, interbedded with ash-fall tuff, sandstone, siltstone, claystone, matrix commonly clayey or calcareous.	2,000		
Tertiary	Miocene	(?)				
Tertiary	Miocene	Indian Trail Formation: Grouse Canyon Member	Ash-flow tuff, densely welded.	200		
Tertiary	Miocene	Indian Trail Formation: Tub Spring Member.	Ash-flow tuff, nonwelded to welded.	300		
Tertiary	Miocene	Indian Trail Formation: Local informal units	Ash-fall tuff, nonwelded to semiwelded ash-flow tuff, tuffaceous sandstone, siltstone, and claystone; all massively altered to zeolite or clay minerals; locally, minor welded tuff near base; minor rhyolite and basalt.	2,000		
Tertiary	Miocene	(?)				
Tertiary	Miocene	Rhyolite flows and tuffaceous beds of Calico Hills	Rhyolite, nonwelded and welded ash flow, ash-fall tuff, tuff breccia, tuffaceous sandstone; hydrothermally altered at Calico Hills; matrix of tuff and sandstone commonly clayey or zeolitic.	>2,000		
Tertiary	Miocene and Oligocene	Tuff of Crater Flat	Ash-flow tuff, nonwelded to partly welded, interbedded with ash-fall tuff; matrix commonly clayey or zeolitic.	300		
Tertiary	Miocene and Oligocene	Rocks of Pavits Spring	Tuffaceous sandstone and siltstone, claystone; fresh-water limestone and conglomerate; minor gypsum; matrix commonly clayey, zeolitic, or calcareous.	1,400		
Tertiary	Oligocene	Horse Spring Formation	Fresh-water limestone, conglomerate, tuff.	1,000		

TABLE 1. — *Stratigraphic and hydrogeologic units at Nevada Test Site and vicinity* — Continued

System	Series	Stratigraphic unit	Major lithology	Maximum thickness (feet)	Hydrogeologic unit	Water-bearing characteristics and extent of saturation[1]
Cretaceous to Permian		Granitic stocks	Granodiorite and quartz monzonite in stocks, dikes, and sills.		(A minor aquitard)	Complexly fractured but nearly impermeable.
Permian and Pennsylvanian		Tippipah Limestone	Limestone.	3,500	Upper carbonate aquifer	Complexly fractured aquifer; coefficient of transmissibility estimated in range from 1,000 to 100,000 gpd per ft; intercrystalline porosity and permeability negligible; saturated only beneath western one-third of Yucca Flat.
Mississippian and Devonian		Eleana Formation	Argillite, quartzite, conglomerate, conglomerite, *limestone*.	7,800	Upper clastic aquitard	Complexly fractured but nearly impermeable; coefficient of transmissibility estimated less than 500 gpd per ft; interstitial permeability negligible but owing to poor hydraulic connection of fractures probably controls ground-water movement; saturated only beneath western Yucca Flat and Jackass Flats.
Devonian	Upper	Devils Gate Limestone	Limestone, dolomite, minor quartzite.	+1,380	Lower carbonate aquifer	Complexly fractured aquifer which supplies major springs throughout eastern Nevada; coefficient of transmissibility ranges from 1,000 to 1,000,000 gpd per ft; intercrystalline porosity and permeability negligible; solution caverns are present locally but regional ground-water movement is controlled by fracture transmissibility; saturated beneath much of study area.
	?					
	Middle	Nevada Formation	Dolomite.	1,525		
Devonian and Silurian		Undifferentiated	Dolomite.	1,415		
Ordovician	Upper	Ely Springs Dolomite	Dolomite.	305		
	Middle	Eureka Quartzite	Quartzite, minor limestone.	340		
	?	Pogonip Group: Antelope Valley Limestone	Limestone and silty limestone	1,530		
	Lower	Pogonip Group: Ninemile Formation	Claystone and limestone, interbedded.	335		
		Pogonip Group: Goodwin Limestone	Limestone.	900		
Cambrian	Upper	Nopah Formation Smoky Member	Dolomite, limestone.	1,070		
		Halfpint Member	Limestone, dolomite, silty limestone.	715		
		Dunderberg Shale Member	Shale, minor limestone.	225		
	Middle	Bonanza King Formation Banded Mountain Member	Limestone, dolomite, minor siltstone.	2,440		
		Papoose Lake Member	Limestone, dolomite, minor siltstone.	2,160		
		Carrara Formation	Siltstone, limestone, interbedded. Upper 1,050 feet predominantly limestone; lower 950 feet predominantly siltstone.	1,050		
				950	Lower clastic aquitard[3]	Complexly fractured but nearly impermeable; supplies no major springs; coefficient of transmissibility less than 1,000 gpd per ft; interstitial porosity and permeability is negligible, but probably controls regional ground-water movement owing to poor hydraulic connection of fractures; saturated beneath most of study area.
	Lower	Zabriskie Quartzite	Quartzite.	220		
		Wood Canyon Formation	Quartzite, siltstone, shale, minor dolomite.	2,285		
Precambrian		Stirling Quartzite	Quartzite, siltstone.	3,400		
		Johnnie Formation	Quartzite, sandstone, siltstone, minor limestone and dolomite.	3,200		

[1]Coefficient of transmissibility has the units gallons per day per foot (gpd per ft) width of aquifer; coefficient of permeability has the units gallons per day per square foot (gpd per sq ft) of aquifer.

[2]The three Miocene sequences occur in separate parts of the region. Age correlations between them are uncertain. They are placed vertically in table to save space.

[3]The Noonday(?) Dolomite, which underlies the Johnnie Formation, is considered part of the lower clastic aquitard.

several small granitic stocks. No Mesozoic sedimentary rocks occur within the study area. Several thousand feet of Triassic and Jurassic rocks crop out in the southeastern one-third of the Spring Mountains and in the ridges east and northeast of Las Vegas; however, these strata are not known to underlie the Nevada Test Site or its immediate surrounding area.

CENOZOIC STRATIGRAPHY

Cenozoic volcanic and sedimentary rocks are widely distributed in the region. Tertiary volcanic and associated sedimentary rocks aggregate as much as 6,000 feet in thickness in Yucca Flat, 8,500 feet in western Frenchman Flat and eastern Jackass Flats, more than 5,000 feet in western Jackass Flats, and more than 13,500 feet beneath Pahute Mesa. The volcanic rocks are of both pyroclastic and lava-flow origin and include several rock types. The most common rock types, in order of decreasing abundance, are ash-flow tuff, ash-fall tuff, rhyolite lavas, rhyodacite lavas, and basalt. The tuffs are commonly of rhyolitic and quartz-latitic composition. The Tertiary sedimentary rocks associated with the volcanic strata include conglomerate, tuffaceous sandstone and siltstone, calcareous lacustrine tuff, claystone, and fresh-water limestone. The Tertiary rocks are largely of Miocene and Pliocene age, but some are Oligocene. The Quaternary strata generally aggregate less than 2,000 feet in thickness and consist of valley-fill deposits and minor basalt flows.

The Cenozoic strata at Nevada Test Site have been divided into 12 formations and numerous members. These strata are listed in table 1, which also provides information on their thickness, lithologic character, and areal extent. The formations and members are representative of the Cenozoic rocks beneath Yucca Flat, Frenchman Flat, and Jackass Flats; the table is not representative of the volcanic rocks in the Pahute Mesa and Timber Mountain areas of the Nevada Test Site. Yucca Mountain, Pah Canyon, and Stockage Wash Members of the Paintbrush Tuff have been omitted from table 1 because of their limited areal extent and probable absence within the zone of saturation. The table is based on the work of Harley Barnes (written commun., 1965), Orkild (1965), and Poole, Carr, and Elston (1965). The terminology for the pyroclastic rocks described in this report is that of Ross and Smith (1961) and Poole, Elston, and Carr (1965).

Several general characteristics of the Cenozoic pyroclastic rocks, lava flows, and associated sediments are summarized as follows:

1. Areal extent, thickness, and physical properties of each of the Cenozoic volcanic formations vary widely. This irregularity is characteristic of volcanic rocks and is a function of their modes of emplacement, prevailing wind directions, and the topographic relief at the time of their extrusion. Accordingly, the descriptions of lithology and thickness of the Cenozoic formations in table 1 are considered representative only of Yucca Flat, Frenchman Flat, and Jackass Flats.
2. Tertiary rocks generally overlie Precambrian and Paleozoic rocks with angular unconformity. A conglomerate or breccia commonly lies at the base of the Tertiary section on a weathered surface of older rocks. Locally, joints in the older rocks are filled with detritus derived from the overlying basal Tertiary rocks. Evidence of the development of karst terrane on the carbonate rocks beneath the unconformity is absent.
3. The oldest Tertiary rocks were deposited upon a paleotopographic surface of moderate relief developed upon Precambrian and Paleozoic strata. Harley Barnes (written commun., 1965) reports that this erosion surface had a maximum relief of about 2,000 feet. By partly filling the topographic lows, the oldest Tertiary rocks reduced the relief of the area. By late Miocene time, the relief was co siderably reduced, as evidenced by the widespre distribution of ash flows of the Paintbrush Tuf
4. The Miocene and Oligocene rocks up through t basal Wahmonie Formation are of both pyroclast and sedimentary origin and consist principally nonwelded ash-flow tuff, ash-fall tuff, tuff brecci tuffaceous sandstone and siltstone, claystone, ar freshwater limestone; lava and welded ash-flo tuff are of minor importance in the area considere The Pliocene and Miocene rocks above th Wahmonie Formation, in contrast, consist chief of welded ash-flow tuff. Nonwelded ash-flow tuf ash-fall tuff, and tuffaceous sandstone ar relatively minor in these younger rocks.
5. The bulk of the Miocene and Oligocene sedimentar rocks appears to be restricted to Frenchman Fla eastern Jackass Flats, Rock Valley, and Mercur Valley. These strata make up the Rocks of Pavit Spring and the Horse Spring Formation and als are present in the Salyer Formation. Miocene and Oligocene sedimentary rocks are of minor oc currence in Yucca Flat and western Jackass Flats although the entire section of Tertiary strata in the latter valley has yet to be explored by drilling.
6. The Miocene and Oligocene rhyolitic tuffaceous rocks up through the Wahmonie Formation are generally massively altered to zeolite (clinoptilolite, mordenite, and analcime) or to clay minerals; a vertical zonation of the zeolite minerals in these rocks was described by Hoover (1968). The Miocene and Pliocene rhyolitic tuffs above the Wahmonie Formation, by contrast, either are glassy or have devitrified to cristobalite and feldspar, but they are less commonly altered to zeolite or clay.

STRUCTURAL GEOLOGY

The structural geology of the region is complex, and details on the general tectonic setting of the study area are available in only a few published reports cited above. About half of these papers are devoted primarily to a single structural feature of the region, the Las Vegas Valley shear zone. The outline of structural geology presented below provides the information needed for subsequent discussions of the disposition of the aquifers and aquitards and the hydraulic barriers within the principal aquifers.

Harris (1959) demonstrated that a large positive area (Sevier Arch) probably existed in much of southeastern Nevada and western Utah from late Jurassic to early Late Cretaceous; thus, Jurassic and Cretaceous strata were probably never deposited within most of the study area.

The Precambrian and Paleozoic miogeosynclinal rocks were first significantly deformed during late Mesozoic and perhaps early Tertiary time. The deformation was marked by uplift and erosion and subsequent folding, thrusting, and strike-slip faulting that made the region mountainous.

Beginning with the Miocene volcanism and continuing through the Quaternary, large-scale normal block faulting has disrupted the Tertiary volcanic and sedimentary strata as well as the previously deformed Precambrian and Paleozoic rocks. The normal faulting caused the Basin and Range structure reflected by the topography in the region today. In late Tertiary and Quaternary time, the resulting valleys have been largely filled by detritus aggregating several hundred to a few thousand feet. Currently active normal faulting is indicated by fault scarps cutting alluvial fans and by the absence of extensive unfaulted pediments. Some evidence indicates that strike-slip faulting occurred during Tertiary time, some time after deposition of early Miocene tuff (Ekren and others, 1968). This faulting may possibly reflect periodic rejuvenation of strike-slip faults formed during the late Mesozoic orogeny.

Widespread erosion of the miogeosynclinal rocks occurred during and after the late Mesozoic orogeny but before block faulting. Before the first deformation of the region, the Precambrian and Lower Cambrian clastic rocks were buried at depths of at least 15,000 feet in the eastern half of the study area and about 27,000 feet in the western half. Today, these strata are exposed in several areas. They form the bulk of the northwest one-third of the Spring Mountains, a significant part of the Groom and Desert Ranges, and the bulk of the Funeral Mountains. Their distribution, a function of geologic structure and depth of erosion, exercises significant control over the regional movement of ground water. Plate 1 shows the areal extent of dominantly clastic pre-Tertiary strata and the relation of these strata to some major thrust faults and folds.

In contrast to the miogeosynclinal rocks, the postdepositional distribution of Tertiary rocks has been controlled principally by fairly simple block faulting and erosion. The northwestern part of the area is a faulted and eroded volcanic plateau of which Pahute and Rainier Mesas (fig. 1) are remnants. In the remainder of the area, ridges of pre-Tertiary rocks interrupt the continuity of the once extensive ash-flow sheets.

Thrust faults are perhaps the most spectacular of the tectonic features of the region. Thrust faulting displaced the pre-Tertiary rocks laterally a few thousand feet to several miles. Locally, imbricate thrusting repeatedly stacked the miogeosynclinal strata upon one another. Some major thrust faults, though folded, crossfaulted, and eroded can be followed in outcrop or reconstructed for miles (pl. 1).

Some workers (Burchfiel, 1965; Secor, 1962) believe that the major thrust faults, which commonly have dips of 35°–50°, flatten with depth and follow less competent strata, specifically the shales of the Carrara Formation; that is, the thrusting is of the décollement type, where the sedimentary rocks slide over the crystalline basement. Vincelette (1964) and Fleck (1970) rejected the décollement hypothesis; they presented evidence that the relatively steep dip of the major thrust faults remains unchanged with depth.

Strike-slip faults and shear zones cut and offset the thrust faults in several places within the region. The best documented of these is the Las Vegas Valley shear zone (Longwell, 1960). This zone (structural feature 13 on pl. 1) is expressed topographically by a valley that extends from Las Vegas nearly to Mercury, a distance of about 55 miles. The amount and the direction of movement along this shear zone has been estimated from structural and stratigraphic evidence to be 15 to 40 miles. Other strike-slip zones, most of which are of smaller displacement than the Las Vegas Valley shear zone, have been mapped in Death Valley, the Spring Mountains, and the Amargosa Desert and at the Nevada Test Site. Some of these faults may be structurally related to the Las Vegas Valley shear zone (E. B. Ekren, written commun., May 1966).

Normal faults, numbering in the thousands within the study area, are the most common tectonic features of the region. Generally the displacement along these faults is less than 500 feet, but it is thousands of feet on some. The normal faults are responsible for the characteristic Basin and Range topography of the region.

Several large anticlines and synclines occur within the area (Longwell and others, 1965; Tschanz and Pampeyan, 1961). Approximate axes of some of these folds are shown on plate 1. These broad folds were formed before the beginning of extensive sedimentation and volcanism in the Miocene; they parallel other features of the late Mesozoic deformation and probably formed during that episode.

Thrust, strike-slip, and normal faults and the folds that may influence the regional movement of ground water are shown on plate 1. Most of the structures shown were taken directly or by inference from the geologic maps of Clark and Lincoln Counties (Longwell and others, 1965; Tschanz and Pampeyan, 1961), from unpublished data on the Amargosa Desert by R. L. Christiansen, R. H. Moench, and M. W. Reynolds (U.S. Geol. Survey), and from unpublished data on the Yucca Flat area by Harley Barnes (U.S. Geol. Survey).

PRINCIPAL AQUIFERS AND AQUITARDS

Ground-water hydrology of the region can be most advantageously discussed by grouping the numerous

TABLE 3. — *Pumping-test data for aquifers in Nevada Test Site and vicinity*

Well	Stratigraphic unit	Depth interval (feet)	Thickness (feet)	Estimated penetration of aquifer (percent)	Hydraulic setting	Depth to static water level (feet)	Specific capacity (gpm per foot of drawdown)	Coefficient of transmissibility (gpd per ft): Estimated from specific capacity	Calculated from drawdown curve	Calculated from recovery curve	Remarks
					Lower carbonate aquifer						
79-69a	Carrara Formation (upper half).	1,540-1,701	161	---	Unconfined	1,540	530	900,000	----	----	Well 79-69a is 100 ft northwest of well 79-69. During two pumping tests neither drawdown nor recovery could be measured owing to very high aquifer transmissibility and low pumping rates (60 and 212 gpm). Carrara Formation tapped by well is probably part of upper plate of low-angle thrust fault that crops out a few miles west of well.
79-69	---do-------	1,540-1,650	110	----	---do-----	1,540	6.2	6,000	(1)	(1)	Step-drawdown analysis indicates specific capacity of 11.7 gpm per foot of drawdown and water entry chiefly from interval 1,607-1,623 ft. Carrara Formation tapped by well is probably part of upper plate of low-angle thrust fault that crops out a few miles west of well.
67-73	Bonanza King Formation (Banded Mountain Member).	1,020-1,301	281	5	Confined	839	4.8	8,000	20,000	53,000	Step-drawdown analysis indicates specific capacity of 11.3 gpm per foot of drawdown.
67-68	Bonanza King(?) Formation. Nopah(?) Formation	1,333-1,946 785-1,168	613 383	20	---do----- Unconfined	785	6.0	6,000	39,000	86,000	Step-drawdown analysis indicates specific capacity of 16.7 gpm per foot of drawdown.
66-75	Nopah Formation (Smoky Member).	737-1,490	753	10	---do-----	737	4.5	4,000	11,000	27,000	Step-drawdown analysis indicates specific capacity of 10.8 gpm per foot of drawdown.
88-66	Pogonip Group	2,550-3,422	872	10	Confined	2,055	.4	700	1,300	5,300	Water yielded principally from interval 3,176-3,412 ft.
75-73	---do-------	1,103-1,853	750	10	Unconfined	1,103	.7	600	3,800	----	----
73-66	Silurian(?) dolomite.	3,137-3,400	263	<5	Confined	1,735	30±	60,000	----	----	Density changes in water column, due to anomalously high water temperature, completely masked water-level fluctuations due to pumping. Air-line measurements permitted approximation of specific capacity.
87-62	Devils Gate Limestone and Nevada Formation, undifferentiated.	3,700-4,198	498	<20	---do-----	1,968	.8	1,000	----	3,500	----
84-68d	Devonian(?) dolomite and calcareous quartzite.	2,821-3,026	205	<5	---do-----	1,626	.4	700	2,400	----	----
					Bedded-tuff aquifer						
81-67	Bedded tuff(?) of Piapi Canyon Group.	1,685-1,800	115	----	Confined	1,569	0.9	1,000	1,300	2,100	See Hood (1961) for pumping-test details; aquifer is probably bedded tuff or nonwelded ash-flow tuff.
90-74	---do-------	490- 670	180	----	Unconfined(?)	490	.4	200	----	----	Constant-rate pumping test not made; specific capacity based on measurements made after 90 min. pumping; aquifer is probably bedded tuff or nonwelded ash-flow tuff.
90-75	---do-------	896-1,091	195	----	---do-----	896	.6	400	----	----	Constant-rate pumping test not made; specific capacity reported after 30 min. of pumping; aquifer is probably bedded tuff or nonwelded ash-flow tuff.
					Welded-tuff aquifer						
73-58	Topopah Spring Member of Paintbrush Tuff.	741- 887	146	40	Confined(?)	741	56	100,000	See remarks.	See remarks.	Drawdown of 6.9 ft measured with air line and test pressure gage in first 3 min. of pumping test at rate of 567 gpm; additional drawdown not detectable in subsequent 57 min. of pumping test.
74-57	---do-------	928-1,475	547	100	---do-----	928	22	40,000	68,000	----	Step-drawdown analysis suggests considerable head losses at face of bore; losses are probably due to poor gun perforation of casing.
81-69	---do-------	1,507-1,675	168	100	---do-----	1,507	.1	200	See remarks.	50	Well tested by bailing; data on recovery of water level given by Moore and Garber (1962).

TABLE 3. — *Pumping-test data for aquifers in Nevada Test Site and vicinity* — Continued

Well	Stratigraphic unit	Depth interval (feet)	Thickness (feet)	Estimated penetration of aquifer (percent)	Hydraulic setting	Depth to static water level (feet)	Specific capacity[1] (gpm per foot of drawdown)	Coefficient of transmissibility[2] (gpd per ft): Estimated from specific capacity	Calculated from drawdown curve	Calculated from recovery curve	Remarks
					Lava-flow and welded-tuff aquifers						
[illegible]	Basalt of Kiwi Mesa	1,039-1,150	111	100	Unconfined	1,039	2.5	4,000	28,000	----	Combined test of lava-flow and welded-tuff aquifers. Measurements made with test pressure gage and air line.
	Topopah Spring Member of Paintbrush Tuff.	1,150-1,329	179	15	Confined						
					Valley-fill aquifer						
[illegible]	Valley fill	689-1,200	511	60	Unconfined	689	1.7	1,000	2,400	2,500 1,700	See Hood (1961) for pumping-test details. Value of 1,700 gpd per ft from recovery during 133-day shutdown; other values from 48-hr pumping test.
[illegible]	---do-------	683- 900	217	15	---do-----	683	4.0	3,000	7,700	11,000	See Hood (1961) for pumping-test details.
[illegible]	---do-------	714- 870	156	....	---do-----	714	1.3	800	----	----	Specific capacity and static water level reported by driller.
[illegible]	--do-------	1,605-1,870	264	80-100	---do-----	606	1.9	1,000	13,200	12,200	See Price and Thordarson (1961) for pumping-test details.
[illegible]	---do-------	107- 371	264	100	---do-----	107	12	10,000	----	33,500	Specific capacity after about 21 hr of pumping; driller's log indicates mostly clay below 235 ft.
[illegible]	---do-------	114- 542	428	100	---do-----	114	30	30,000	----	----	Specific capacity and static water level reported by driller; driller's log suggests chief aquifer in depth interval 114-200 ft.

[1] Specific capacity computed at 100 min. of pumping.

[2] See text for discussion of methods of computation of coefficient of transmissibility, in gallons per day per foot (gpd per ft), and time-drawdown curves (figs. 10-17 and 22-29) for pertinent construction data and length of pumping tests.

[3] Time-drawdown curves (fig. 14) indicate a positive boundary of very high transmissibility at 35 min.; the "zone" of high transmissibility is probably that tapped by adjacent well 76-69a.

several tens to hundreds of feet thick, surrounding the bore; or (3) crowding of flow lines, within several tens to a few hundred feet of the bore, due to small cross-sectional flow area in the water-bearing fractures tapped by the bore. Any of these three flow conditions would result in abnormally high time-dependent pressure losses near the bore, which would be reflected by the steep initial limb of the time-pressure curves.

Near a partially penetrating well, the flow lines converge on the bore not only radially but also spherically ; this convergence, or crowding, of the flow lines results in head losses that greatly exceed those for radial flow. For example, Muskat (1937, fig. 77) indicated that only 40 percent of the head loss of radial flow occurs within 5 feet of the bore, but as much as 95 percent of the head loss of spherical flow (near zero penetration) occurs within 5 feet; intermediate head losses (not illustrated by Muskat) occur for penetrations between 0 and 100 percent. Muskat's figure 77, when replotted on semilog paper, closely resembles the dual-limb time-pressure curves of the carbonate aquifer. The steep initial limb reflects the abnormal head losses near the bore, whereas the secondary limb reflects aquifer conditions farther from the bore, where flow is more nearly radial. A dimensionless semilog plot for partial penetration presented by Hantush (1964, fig. 11) also closely resembles the plots for the lower carbonate aquifer. Hantush's illustration indicates that after a certain time has elapsed, the slope of the gentle, or second limb of the curve approaches that for a fully penetrating well, except where well penetration is nearly zero. Time-pressure curves by Nisle (1958) for a partially penetrating well tapping a confined aquifer also closely resemble those for the lower carbonate aquifer. From Nisle's mathematical study he concluded that the standard modified nonequilibrium approach of Jacob (1950) could be used to compute aquifer transmissibility directly from the second limb of the curve. Nisle's study is of particular importance because the time-pressure curves he presented are for the pumped well, whereas Hantush's curves present time-pressure behavior for observation wells only. Geologic sections through each well test pumped at Nevada Test Site suggest that the wells penetrate 5 to 20 percent of the aquifer (table 3).

A zone of reduced transmissibility adjacent to the bore is a second possible cause for the dual-limb time-pressure curves. Loucks and Guerrero (1961) presented many semilogarithmic curves showing the effect of varying the radius of a zone of reduced transmissibility and of changing the ratio of the transmissibility of the aquifer and of the zone adjacent to the bore. They assumed radial-flow geometry. Their curves closely resemble those for the lower carbonate aquifer. The steep initial limb of their curves reflects the low level. Thus, the water table beneath this playa is 20 feet lower than the water table beneath the playa in northern Stewart Valley and is 130 feet lower than that beneath the playa in northwestern Pahrump Valley. The water table in the valley-fill aquifer in northern Stewart Valley and in northwestern Pahrump Valley thus stands well above levels in the same aquifer to the south-southeast and to the northwest. This difference in altitude and saturation of the valley fill nearly to the surface beneath the playas in Stewart and western Pahrump Valleys suggest that the ground water in these areas is ponded by some impermeable boundary, namely, the lower clastic aquitard. Such ponding does not preclude underflow of small magnitude. In contrast, the playa in southwestern Pahrump Valley is bordered on the southwest by the Nopah Range, which is composed predominantly of the lower carbonate aquifer. Malmberg's (1967) potentiometric contours for the valley-fill aquifer reproduced on plate 1 of this report indicate that ground water in this aquifer is moving toward (and into) the Nopah Range.

In summary, the preceding evidence indicates that at most only a few percent of the Ash Meadows discharge can be derived from either Stewart Valley or western and northwestern Pahrump Valley.

SOURCES OF RECHARGE TO THE LOWER CARBONATE AQUIFER

Within the basin boundary delineated on plate 1, the lower carbonate aquifer is recharged principally by precipitation in areas of high rainfall and favorable rock type and secondarily by downward leakage of water from the Cenozoic hydrogeologic units. Underflow into the basin from the northeast may also constitute a major source of recharge.

PRECIPITATION

Recharge from precipitation is probable beneath and immediately adjacent to the highly fractured Paleozoic carbonate rocks of the Sheep Range, northwestern Spring Mountains, southern Pahranagat Range (south of State Highway 25; fig. 1), and, to a lesser extent, beneath the Pintwater, Desert, and Spotted Ranges. The approximate average annual precipitation within the Ash Meadows basin is about 320,000 acre-feet on the Sheep Range, about 100,000 acre-feet on the northwestern Spring Mountains, and about 90,000 acre-feet on the southern Pahranagat Range (fig. 3). For these mountains, the 8-inch isohyetal contour roughly corresponds with the lowest outcrop of Paleozoic bedrock. Precipitation on the lower Desert, Pintwater, and Spotted Ranges was estimated only for those parts of the ranges receiving 8 inches or more rainfall. This amounted to about 60,000 acre-feet.

Thus, a total of about 570,000 acre-feet of precipitation falls annually within the basin on prominent ridges and mountains that are composed principally of the lower carbonate aquifer. This quantity is an approximation at best: precipitation that falls on carbonate-rock outcrops at low altitudes in the Spotted, Pintwater, or Desert Ranges or on the other minor hills and ridges in the region was not included; conversely, some of the precipitation included in the tabulation falls on the valley fill bordering the mountains, or on clastic rock, and not on the lower carbonate aquifer; it should be subtracted from the total. The preceding estimate could have been refined by planimetering the area of carbonate-rock outcrop for select altitude zones and by applying Quiring's (1965) altitude-precipitation curves of the region; however, such precision is unwarranted because of the approximate nature of the basin boundary.

Precipitation falling on the valley floors underlain by carbonate rocks was not estimated because recharge to either the lower carbonate aquifer or the younger aquifers beneath such areas seems improbable under present climatic conditions. Moreover, recharge to carbonate rocks beneath the valleys is controlled by the tuff aquitard.

Assuming that the spring discharge at Ash Meadows is derived principally from precipitation falling on carbonate-rock uplands within the boundaries of the Ash Meadows basin (pl. 1) and that steady-state conditions exist in the ground-water basin, the percentage of rainfall that infilitrates to the carbonate aquifer beneath the ranges can be estimated. Using the 17,100 acre-feet of measured spring discharge (average of two values given in table 7) and the precipitation estimate of roughly 570,000 acre-feet, about 3 percent of the rainfall falling on areas of carbonate-rock outcrop may infiltrate to the zone of saturation. The cited percentage of infiltration is in error in proportion to (1) the magnitude of underflow into the basin from the northeast, (2) underflow out of the basin at Ash Meadows, and (3) evapotranspiration in Ash Meadows discharge area in excess of that supported by recycled spring discharge.

UNDERFLOW FROM THE NORTHEAST

Geologic and hydrologic evidence presented in the section "Areal Extent of the Ground-Water Basin" indicates that the Ash Meadows ground-water basin may receive underflow from the northeast, but this evidence does not permit estimation of the quantity of underflow. A comparison of the deuterium content of ground water in Pahranagat Valley, along the flanks of the Spring Mountains and Sheep Range, and at Ash Meadows indicates that possibly as much as 35 percent (about 6,000 acre-ft annually) of the Ash Meadows discharge may enter the basin from the northeast. The deuterium data beneath the central Amargosa Desert), and downward leakage from the valley-fill aquifer beneath the central and south-central Amargosa Desert. Water in the valley-fill aquifer may have been derived from spring runoff at Ash Meadows, from Jackass Flats, or from northwestern Amargosa Desert. Important quantities of water from the valley-fill aquifer could leak downward only if the head in the valley fill beneath the central and south-central Amargosa Desert were higher than that in the underlying carbonate aquifer and if the lower carbonate aquifer and valley fill were in direct hydraulic continuity near buried structural highs where the Tertiary aquitard may not have been deposited or may have been removed by erosion prior to deposition of the valley fill. Data on the head relation between the two aquifers beneath the central and south-central Amargosa Desert are not available.

The minimum area of the Ash Meadows basin is about 4,500 square miles and the minimum discharge is about 17,000 acre-feet. In contrast, the superficial watershed tributary to the springs in Death Valley is 150 square miles (Pistrang and Kunkel, 1964), and the discharge exceeds 4,000 acre-feet. In addition, the Ash Meadows ground-water basin encompasses two of the highest mountain ranges in southern Nevada, whereas the Death Valley catchment area is the most arid in the Nation. Because of this relation and the foregoing hydrogeologic information, the authors suggest that most of the spring discharge in the very arid Furnace Creek Wash–Nevares Springs area (possibly more than 95 percent) originates outside of Death Valley.

Hunt, Robinson, Bowles, and Washburn (1966) suggested that the spring discharge in Death Valley comes principally from Pahrump Valley, either directly or through Ash Meadows. The present authors have previously considered that movement of significant quantities of ground water from Pahrump or Stewart Valleys to Ash Meadows is unlikely. (See section, "Relation to Pahrump Valley Ground-Water Basin.") Direct movement to Death Valley from Pahrump Valley also appears unlikely because the Resting Spring Range, which borders Stewart Valley and Chicago Valley on the west, is composed chiefly of the lower clastic aquitard (pl. 1).

GROUND-WATER CHEMISTRY, HYDROCHEMICAL FACIES, AND REGIONAL MOVEMENT OF GROUND WATER

Chemical analyses are available for ground water from 147 sources: 74 wells, 49 springs, and 24 water-bearing fractures in underground workings. Forty of the wells are in the immediate vicinity of or are within Nevada Test Site, and the aquifer or aquitard sampled is known beyond a reasonable doubt. Many of these 40 wells were sampled 2 or more times. In several of the test holes drilled specifically for hydrologic data, water samples were obtained from more than one aquifer or from two or more depths within a single aquifer. The authors use water chemistry to (1) define parts of the boundary of the Ash Meadows ground-water basin, (2) determine the direction of ground-water movement in the lower carbonate aquifer in the basin, (3) estimate the magnitude of downward leakage of semiperched ground water from the Cenozoic rocks into the lower carbonate aquifer, and (4) speculate on the depth of circulation within the lower carbonate aquifer.

The chemical analyses used are chiefly from the following sources: Maxey and Jameson (1948), Clebsch and Barker (1960), J. E. Moore (1961), Malmberg and Eakin (1962), Walker and Eakin (1963), Schoff and Moore (1964), and Pistrang and Kunkel (1964). In addition, analyses for the Pahrump Valley were obtained from the files of the U.S. Geological Survey in Carson City, Nev. Post-1963 analyses of ground water by W. A. Beetem and his associates, though not yet published, are on file at the U.S. Geological Survey offices in Denver, Colo.

PREVIOUS INTERPRETATION OF GROUND-WATER CHEMISTRY

Schoff and Moore (1964) presented the following observations and conclusions on the regional flow of ground water at the Nevada Test Site:

1. They recognized three types of ground water at Nevada Test Site and vicinity: (a) sodium and potassium bicarbonate; (b) calcium and magnesium bicarbonate; and (c) mixed. The sodium and potassium bicarbonate type is found in tuff aquifers and aquitards, and in the valley-fill aquifer in Emigrant Valley, Yucca Flat, Frenchman Flat, and Jackass Flats. The calcium and magnesium bicarbonate type is found in Paleozoic carbonate aquifers, as well as in valley-fill aquifers that are composed chiefly of carbonate-rock detritus. Schoff and Moore (1964) recognized such water only in southern Indian Springs Valley. They (1964, p. 62) defined mixed water as water having characteristics of both the preceding types. They believed that such water may have formed in one of three ways: (a) movement of water from tuffaceous into carbonate rocks (or alluvium with carbonate-rock detritus), followed by dissolution of carbonate minerals; (b) movement of water from carbonate rocks into tuff (or tuffaceous alluvium), followed by acquisition of sodium either by solution or by ion exchange of calcium for sodium; or (c) mixing of calcium and magnesium bicarbonate water with sodium and potassium bicarbonate water. They noted further that water of mixed chemical type is found in some of the carbonate

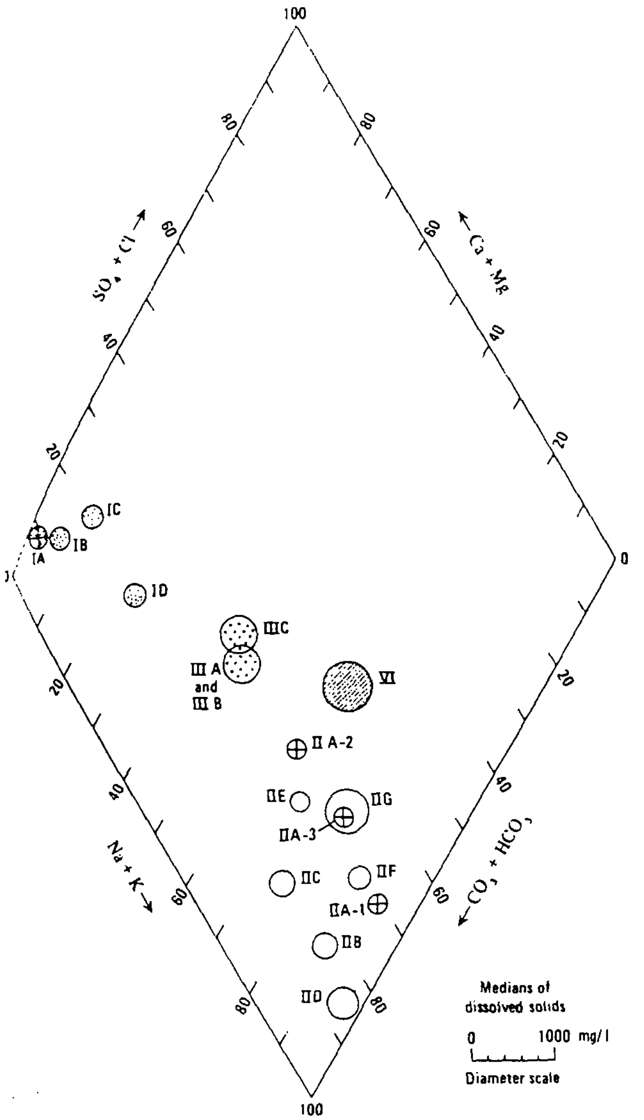


FIGURE 38. — Chemical types of the ground water at Nevada Test Site and vicinity. Roman numerals refer to map numbers and areas listed in table 8 and shown on pl. 3; circles with crosses represent populations of perched water; patterns in circles next to map numbers facilitate visual grouping of the hydrochemical facies.

in central Yucca Flat), it is also found in thin carbonate strata within the upper clastic aquitard.

Water of mixed chemical character, noted by Schoff and Moore (1964) in the Nevada Test Site (area IIIC) and the east-central Amargosa Desert (IIIA and IIIB), is designated the calcium magnesium sodium bicarbonate facies in this report. This water occurs within the lower carbonate aquifer between Ash Meadows and eastern Nevada Test Site. As noted by Schoff and Moore (1964), water from two wells tapping Cenozoic rocks in Yucca Flat (well 83–68 tapping the valley-fill aquifer and well 81–67 tapping the bedded-tuff aquifer) also is of mixed character (pl. 3). The dissolved-solids content of water from these wells is, however, 100 mg/l (milligrams per liter) less than that of the mixed water in the lower carbonate aquifer. Schoff and Moore's explanation of the anomalous water in well 81–67 appears reasonable; namely, that water tapped by this well is derived from Paleozoic strata, which occur about 1 mile west of the well (pl. 2*B*). However, this explanation is not applicable to the anomalous water from well 83–68; nor, for that matter, is it consistent with the sodium potassium bicarbonate water from well 84–67, which taps thin carbonate strata within the upper clastic aquitard.

Two other facies are suggested by plate 3: a playa facies (area V), which appears restricted to the "wet" playas (playas from which ground water is discharged by evapotranspiration) or to shallow wells in discharge areas; and a sodium sulfate bicarbonate facies, which appears to be restricted to the springs in the Furnace Creek Wash–Nevares Springs area (area VI) and to a few wells in the west-central Amargosa Desert. The chemistry of the playa facies is highly variable, dependent in part on the depth of the sampling well; a formal definition of this facies is not attempted in this report.

Analyses of water from selected wells in western Pahrump and Stewart Valleys were excluded from the statistical summary presented in table 8. These wells are less than 100 feet deep and are generally on or along the periphery of the playas in northwestern Pahrump and Stewart Valleys, where the water table is shallowest, less than 20 feet below the surface. Most of the excluded wells are less than 40 feet deep. The water from some of these wells is more highly mineralized than the water from most deeper wells in Pahrump Valley. Choice of the 100-foot depth limitation was arbitrary. Generally, the highest mineralization was found in wells drilled to depths of 35 feet or less on or along the playa in Stewart Valley. The generally higher mineralization of water from these shallow wells is probably due to accumulation of solutes in water within the fine-grained salt-incrusted sediments that characterize valley-fill deposits in the vicinity of wet playas. Ground water in such sediments in areas of upward movement of water is neither hydrologically nor chemically similar to that of the deeper wells tapping the valley-fill aquifer in Pahrump Valley. Water from the deeper wells is of the calcium magnesium bicarbonate facies (pl. 3), whereas water from many of the shallow wells belongs to the playa facies. Water of the playa facies is also found in shallow wells along the periphery of Alkali Flat at the south end of the Amargosa Desert (north of Eagle Mountain, fig. 34).

Along the margins of the study area, in Pahranagat Valley and at Furnace Creek Wash in Death Valley, only analyses from major springs discharging from the lower carbonate aquifer at valley level were used in the tabulation. Chemical quality of discharge from the major springs should be an average of the chemical quality of water in the lower carbonate aquifer, whereas water from low-yield springs (for example, Daylight and Keane Wonder Springs in the Funeral Mountains) or from wells of unknown construction may represent local recharge, recycled water, or water from several aquifers.

TABLE 9. — *Classification of hydrochemical facies at the Nevada Test Site and vicinity*

Hydrochemical facies	Percentage range of milliequivalents per liter of major constituents[1]			
	Ca+Mg	Na+K	HCO_3+CO_3	SO_4+Cl
Calcium magnesium bicarbonate	75-100	0-25	80-90	10-20
Sodium potassium bicarbonate	5- 35	65-95	65-85	15-35
Calcium magnesium sodium bicarbonate	50- 55	45-50	70	30
Sodium sulfate bicarbonate	30	70	60	40

[1] Minor constituents such as Li, Sr, NO_3, and F are not included in cation-anion percentages; percentages are taken from median values in table 8 and rounded to nearest 5 percent.

VARIATIONS OF DISSOLVED-SOLIDS CONTENT WITH DEPTH IN THE LOWER CARBONATE AQUIFER

Qualitative information on the vertical variation of dissolved solids in the lower carbonate aquifer is derived from several wells at Nevada Test Site, three oil-test wells drilled northeast of Nevada Test Site, and a comparison of the water from wells at Nevada Test Site with discharge from the springs at Ash Meadows.

Well 89-68 was drilled to a depth of 6,000 feet in northern Yucca Flat (pl. 2). Between 1,773 and 5,290 feet, the bore penetrated the lower clastic aquitard (Stirling Quartzite, 1,773-2,360 ft; Johnnie Formation, 2,360-5,290 ft; and the Noonday(?) Dolomite, 5,290-6,000 ft). A major permeable fault zone was found between the Johnnie Formation and the Noonday(?) Dolomite. Analyses of water samples from two intervals (1,785-1,940 and 1,785-6,000 ft) are given in table 10. The two analyses indicate little change in chemical quality with depth. The upper interval was sampled when the well was 1,940 feet deep. The drill-stem test data indicate that most of the water of the second sample came from depths greater than 2,170 feet and that a significant quantity of it, probably more than half, may have come from the permeable fault zone at a depth of about 5,290 feet. Heads measured during drill-stem testing indicate that the second sample does not reflect water that moved downward along the bore from upper to lower zone during or after drilling. The analyses suggest that the water quality in the lower clastic aquitard is relatively uniform to depths of several thousand feet. The absence of a significant change in the chemistry of water within the lower clastic aquitard suggests that the water in the lower carbonate aquifer may also be relatively uniform chemically to depths of several thousand feet.

TABLE 10. — *Chemical analyses of water from test wells 89-68 and 67-68, Yucca Flat and Mercury Valley, Nye County*

[Values for chemical constituents are in milligrams per liter. Analyses by U.S. Geol. Survey, Denver, Colo]

	Well 89-68		Well 67-68	
Depth interval (ft)	1,785-1,940	1,785-6,000	786-1,050	[illegible]
Silica (SiO_2)	8.5	17	20	[illegible]
Calcium (Ca)	45	41	46	[illegible]
Magnesium (Mg)	11	13	21	[illegible]
Sodium (Na)	98	96	38	[illegible]
Potassium (K)	16	15	4.9	[illegible]
Bicarbonate (HCO_3)	357	384	254	[illegible]
Carbonate (CO_3)	0	0	0	[illegible]
Sulfate (SO_4)	65	54	58	[illegible]
Chloride (Cl)	17	11	17	[illegible]
Specific conductance (μmhos per cm at 25°C)	715	720	483	[illegible]
pH	7.7	7.8	7.5	[illegible]

Test hole 67-68 was drilled to a depth of 1,946 feet in southern Mercury Valley (fig. 33). In the zone of saturation, carbonate rocks of the Nopah Formation (table 1) are between 786 and 1,168 feet, the Dunderberg Shale Member of the Nopah Formation between 1,168 and 1,333 feet, and the carbonate rocks of the Bonanza King (?) Formation between 1,333 and 1,946 feet. Through use of two strings of cemented casing and packers, the Nopah Formation and the Bonanza King (?) Formation were test pumped separately. At the conclusion of each test, a water sample was collected and analyzed. The results of these analyses are shown in table 10. Drill-stem tests of the Nopah Formation indicated that the sample for this formation actually came from the interval 786-1,050 feet. The drill-stem tests also indicated that the head in the Bonanza King (?) Formation was possibly as much as 4 feet higher than that in the upper aquifer.

A comparison of the chemical analyses of the water from the Nopah and Bonanza King(?) Formations indicates that the water in the two formations is practically identical. The near identical nature of the chemical quality of water from both aquifers may reflect natural upward crossflow through the Dunderberg Shale Member, which separates the two carbonate aquifers at the well site. Such crossflow is possible because of the 4-foot head differential that may exist and because the Dunderberg, a thin clastic unit, is rarely continuous areally, owing to normal faulting and its tendency to be pinched out along major faults and tight folds. If crossflow in the region of well 67-68 is upward and is principally responsible for the similarity in water chemistry noted for the two sampled intervals, then water of relatively low mineralization probably occurs in the lower carbonate aquifer at depths even greater than that penetrated by the well.

Specific conductance of water swabbed from two other test holes, wells 88-66 in Yucca Flat (pl. 2) and 66-75 (fig. 33) in southern Indian Springs Valley, suggests no increase in dissolved-solids content in the upper 800 feet of the lower carbonate aquifer. However, these data, obdrilled in the narrow valley between southern Sheep Range and southern Desert Range, at about the latitude of Sheep Peak. Downhole photography in the first hole might aid in an evaluation of the fracture porosity and therefore in the computation of average velocity beneath the Specter Range, whereas the head and hydrochemical data from the second and third holes might help to better define the eastern and northern boundaries of the Ash Meadows ground-water basin.

Hydraulic characteristics and water chemistry of the Cenozoic aquifers and aquitard should also be determined in the three proposed holes, if they are penetrated within the zone of saturation. Representative samples of water from the base of the tuff aquitard will be difficult to obtain because of the very low permeability of the rocks, but such samples are of major importance for estimating downward crossflow from the tuff aquitard into the carbonate aquifer.

3. Cuttings and water samples should be collected, and water level and depth of well should be recorded routinely for all new wells drilled along the periphery of Nevada Test Site. Collection of such data is relatively inexpensive, and some of it may help to better define the regional hydrogeology.

SUMMARY

The Nevada Test Site, a U.S. Atomic Energy Commission nuclear testing facility encompassing an area of about 1,400 square miles, has been the site of a detailed study of ground-water geology and hydrology. The test site lies within the miogeosynclinal belt of the Cordilleran geosyncline, where 37,000 feet of marine sediments accumulated during the Precambrian and Paleozoic Eras, and within a Tertiary volcanic province where as much as 13,000 feet of rocks were erupted from caldera centers. Except for a few small intrusive masses, Mesozoic rocks are absent. Quaternary and Tertiary detritus as much as 2,000 feet thick underlies the valleys.

The region has experienced two major periods of deformation. The first, in late Mesozoic and early Cenozoic time, resulted in both broad and tight folds and thrust faults in Precambrian and Paleozoic rocks. During middle to late Cenozoic time, block faulting produced the Basin and Range structure of the region. Displacements along major strike-slip faults measured several miles during both periods of deformation.

Precambrian to Middle Cambrian strata are predominantly quartzite and siltstone 10,000 feet thick. The Middle Cambrian to Upper Devonian strata are chiefly limestone and dolomite 15,000 feet thick. Upper Devonian and Mississippian rocks are chiefly argillite and quartzite about 8,000 feet thick. Pennsylvanian and Permian rocks are chiefly limestone about 4,000 feet thick. No major unconformities or disconformities marked by deep subaerial erosion of underlying rocks occur within this miogeosynclinal section.

The Tertiary volcanic rocks are ash-flow tuff, ash-fall tuff, rhyolite, rhyodacite, and basalt; the tuffs are commonly of rhyolitic and quartz-latitic composition. Sedimentary rocks associated with the volcanic strata include conglomerate, tuffaceous sandstone and siltstone, calcareous lacustrine tuff, claystone, and freshwater limestone. The Tertiary rocks are largely of Miocene and Pliocene age, although Oligocene rocks are present. Extent, thickness, and physical properties of the Tertiary rocks vary widely within and between the intermontane valleys.

Precambrian and Paleozoic miogeosynclinal rocks, Tertiary volcanic and sedimentary rocks, and Quaternary and Tertiary valley fill are grouped into 10 hydrogeologic units. The grouping is based on similar hydraulic properties, lithologic character, and stratigraphic position. The hydrogeologic units, in order of decreasing age, are: Lower clastic aquitard, lower carbonate aquifer, upper clastic aquitard, upper carbonate aquifer, tuff aquitard, lava-flow aquitard, bedded-tuff aquifer, welded-tuff aquifer, lava-flow aquifer, and valley-fill aquifer. The lower clastic aquitard, the lower carbonate aquifer, and the tuff aquitard control the regional movement of ground water.

The coefficient of transmissibility of the lower clastic aquitard is less than 1,000 gpd per ft. The effective interstitial porosity of 20 cores ranges from 0.6 to 5 percent and has a median value of 1.9 percent. The coefficient of permeability of 18 cores ranges from 0.0000007 to 0.0001 gpd per sq ft and has a median value of 0.000002. Although the clastic strata are highly fractured throughout the study area, regional movement of water through these rocks is probably controlled principally by interstitial permeability rather than fracture transmissibility because (1) the argillaceous strata have a tendency to deform plastically, (2) fractures in the brittle quartzite sequences tend to be sealed by interbedded micaceous partings or argillaceous laminae, and (3) the clastic rocks have low solubility.

The highly fractured to locally brecciated lower carbonate aquifer consists of limestone and dolomite. On the basis of pumping tests of 10 wells and regional flow analysis, the coefficient of transmissibility of the aquifer ranges from 600 to several million gallons per day per foot. Core examination indicates a fracture porosity of a fraction of 1 percent. The effective intercrystalline porosity of 25 cores ranges from 0.0 to 9.0 percent and has a median value of 1.1 percent. The coefficient of permeability of 13 cores ranges from 0.00002 to 0.1 gpd per sq ft and has a median value of 0.00008.

The water-bearing fractures are probabl[illegible] modified joints, fault zones, and breccia. Drill-stem tests in eight holes suggest that the water-bearing fractures are few and widely spaced, are present to depths of at least 1,500 feet beneath the top of the aquifer and as much as 4,200 feet below land surface, do not increase or decrease with depth, and are no more abundant or permeable immediately beneath the Tertiary–pre-Tertiary unconformity than elsewhere in the aquifer.

The lower carbonate aquifer contains several solution caverns in outcrop. One of the caverns, Devils Hole, reportedly extends at least 300 feet vertically into the zone of saturation. The caverns probably do not constitute a hydraulically integrated network of solution openings, except possibly near major discharge areas; variations in fracture transmissibility control the regional movement of ground water through the aquifer.

The upper clastic aquitard consists principally of argillite (about two-thirds of unit) and quartzite (about one-third of unit). Unlike the lower clastic aquitard and the lower carbonate aquifer, which are thousands of feet thick, of relatively uniform lithology, and widely distributed, the upper clastic aquitard is of hydrologic significance only beneath western Yucca Flat and northern Jackass Flats. In much of the area, it is represented by time-equivalent carbonate rocks, has been removed by erosion, or occurs well above the water table. The coefficient of transmissibility of this aquitard is probably less than 500 gpd per ft; interstitial permeability is negligible.

The tuff aquitard consists primarily of nonwelded ash-flow tuff, ash-fall (or bedded) tuff, tuff breccia, tuffaceous sandstone and siltstone, claystone, and freshwater limestone. Despite the widely differing origins of these strata, they generally have one feature in common: their matrices consist principally of zeolite or clay minerals, which are responsible in part for the very low interstitial permeability of these relatively porous rocks. Strata composing the aquitard have moderate to high interstitial effective porosity (median values ranging from 10 to 39 percent), negligible coefficient of permeability (median values ranging from 0.00006 to 0.006 gpd per sq ft), and very low coefficient of transmissibility (less than 200 gpd per ft). Evidence from several miles of tunnels indicates that the regional movement of ground water through the tuff aquitard is probably controlled by interstitial permeability rather than by fracture transmissibility.

The welded-tuff aquifer consists of moderately to densely welded ash-flow tuff. The coefficient of transmissibility of the aquifer at four well sites ranges from 200 to more than 100,000 gpd per ft and is probably controlled principally by interconnected primary (cooling) and secondary joints; interstitial permeability is negligible.

The valley-fill aquifer consists of alluvial-fan, mudflow, fluvial deposits, and lake beds. The coefficient of transmissibility of the valley-fill aquifer at six well sites ranges from 800 to about 34,000 gpd per ft; average interstitial permeabilities range from 5 to 70 gpd per sq ft.

Owing to the complex structural and erosional history of the area, the subsurface distribution and the saturated thickness of the hydrogeologic units differ from unit to unit and place to place. The structural relief on the pre-Tertiary hydrogeologic units commonly ranges from 2,000 to 6,000 feet within distances of a few miles and locally is as much as 500 feet within distances of 1,000 feet. Thus, the lower carbonate aquifer, which is generally buried and fully saturated at depths of hundreds to thousands of feet below most valley floors, is only partly saturated along flanking ridges. In contrast, in areas where the lower clastic aquitard occurs in structurally high positions, the lower carbonate aquifer either has been largely removed by erosion or occurs entirely, or largely, above the zone of saturation. Also, because of complex pre-early Tertiary deformation and deep erosion, only a fraction of the 15,000-foot aggregate thickness of the carbonate aquifer is usually present in the zone of saturation. In general, because of its great thickness, several thousand feet of the lower carbonate aquifer lies within the zone of saturation beneath most ridges and valleys of the study area.

Vertical displacement, ranging from hundreds to thousands of feet along block faults, affects the subsurface disposition and saturated thicknesses of the tuff aquitard and the welded-tuff and valley-fill aquifers. Beneath valleys that have deep (700–1,900 ft) water tables, the depth to water also affects the saturated thickness of the tuff aquitard and the welded-tuff and valley-fill aquifers. In Yucca Flat, the valley-fill aquifer is saturated only beneath a 10-square mile area where the aquifer thickness exceeds 1,600 feet. Similarly, the welded-tuff aquifer is only partly to fully saturated beneath the central part of that valley; it is unsaturated beneath margins of the valley, even though it is buried at depths of hundreds of feet.

Both intrabasin and interbasin movement of ground water occurs in the region. Intrabasin movement of ground water from welded-tuff and valley-fill aquifers to the lower carbonate aquifer occurs beneath several of the intermontane valleys of the study area. The volume of flow between the Cenozoic hydrogeologic units and the lower carbonate aquifer is usually small, because the aquifers are separated by the thick and widespread tuff aquitard. In Yucca and Frenchman Flats, water leaks downward at a rate less than 100 acre-feet per year in each valley. In east-central Amargosa Desert and on the upgradient side of major hydraulic barriers cutting the lower carbonate aquifer, intrabasin movement is upward from the lower carbonate aquifer into the younger hydrogeologic units. Interbasin movement characterizes flow through the lower carbonate aquifer underlying most of the valleys and ridges of south-central Nevada. Within the Nevada Test Site, water moves south and southwestward beneath Yucca and Frenchman Flats, Mercury Valley, and the east-central Amargosa Desert toward a major spring discharge area, Ash Meadows, in the Amargosa Desert. The hydraulic gradient ranges from 0.3 to 5.9 feet per mile. Interbasin movement through the carbonate rocks is significantly controlled by geologic structure. In the vicinity of major structures, the lower carbonate aquifer is compartmentalized either through its juxtaposition against the lower or upper clastic aquitard along major normal or thrust faults, by the occurrence of the lower clastic aquitard in structurally high position along major anticlines, or by gouge developed along major strike-slip faults. The water levels in the lower carbonate aquifer on opposite sides of such structures differ as much as 500 feet in a single valley and as much as 2,000 feet between valleys, although the hydraulic gradient within each aquifer compartment or block is only a few feet per mile.

Hydraulic, geologic, isohyetal, hydrochemical, and isotopic data suggest that the area hydraulically integrated by interbasin water movement in the lower carbonate aquifer is no smaller than 4,500 square miles and includes at least 10 intermontane valleys. This hydrologic system, the Ash Meadows ground-water basin, may, in turn, be hydraulically connected to several intermontane valleys northeast of the study area from which it may receive significant underflow. The principal discharge from the basin, about 17,000 acre-feet annually (about 10,600 gpm) occurs along a prominent fault-controlled spring line 10 miles long at Ash Meadows. The discharge of individual springs is as much as 2,800 gpm. Underflow beneath the spring line into the central Amargosa Desert is probable, but its magnitude cannot be estimated. Pahrump and Stewart Valleys, proposed as the major source of the spring discharge at Ash Meadows by earlier workers, contribute at most a few percent of the discharge. The major springs in east-central Death Valley (Furnace Creek Wash–Nevares Springs area) are probably fed by interbasin movement of water from central and south-central Amargosa Desert, but not from Pahrump Valley.

Five hydrochemical facies of ground water in and adjacent to the study area have been distinguished by percentages of major cations and anions. Ground water that has moved only through the lower carbonate aquifer or through valley fill rich in carbonate detritus is a calcium magnesium bicarbonate type. Water that has moved only through rhyolitic tuff or lava-flow terrane, or through valley-fill deposits rich in volcanic detritus, is a sodium potassium bicarbonate type. Water in the lower carbonate aquifer, in areas of downward crossflow from the Cenozoic aquifers and aquitards, is a mixture of these two types and is designated the calcium magnesium sodium bicarbonate type. It is characterized by about equal quantities of the cation pairs calcium plus magnesium and sodium plus potassium. Water in east-central Death Valley, probably a mixture of water of the third type and water from Oasis Valley, is a sodium sulfate bicarbonate type. Shallow ground water, such as that beneath saturated playas, is informally designated as the playa type. The chemistry of this water (dissolved-solids content as high as 50,000 mg/l) varies widely and depends in part on the depth of the sampling point. Major inferences pertinent to the ground water regimen, made on the basis of hydrochemical data, are as follows:

1. Ground water beneath the Nevada Test Site moves towards the Ash Meadows area.
2. Chemistry of water in the lower carbonate aquifer may not change markedly to depths as great as 10,000 feet.
3. Leakage of water from the tuff aquitard into the lower carbonate aquifer is probably less than 5 percent of the spring discharge at Ash Meadows.
4. Underflow into the Ash Meadows basin, from Pahranagat Valley, may amount to as much as 35 percent of the spring discharge at Ash Meadows.

The estimated velocity of ground water moving vertically through the tuff aquitard into the lower carbonate aquifer in Yucca Flat ranges from 0.0005 to 0.2 foot per year; values toward the lower end of the range are more probable.

The estimated velocity of water in the lower carbonate aquifer beneath central Yucca Flat ranges from 0.02 to 2.0 feet per day. Velocity in the carbonate aquifer beneath the Specter Range ranges from 2 to 200 feet per day. The spread of two orders of magnitude in estimated velocities in the carbonate aquifer in each area is due principally to uncertainty about the fracture porosity of the aquifer.

REFERENCES

Albers, J. P., 1967, Belt of sigmoidal bending and right-lateral faulting in the western Great Basin: Geol. Soc. America Bull., v. 78, no. 2, p. 143-156.

Ammann, C. B., 1960, Case histories of analyses of characteristics of reservoir rock from drill-stem tests: Jour. Petroleum Technology, v. 12, no. 5, p. 27-36.

Back, William, 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: U.S. Geol. Survey Prof. Paper 498-A, 42 p.

Baker, W. J., 1955, Flow in fissured formations: Fourth World Petroleum Cong. Proc., sec. II, p. 379-393.

Barnes, Harley, Christiansen, R. L., and Byers, F. M., 1965, Geologic map of the Jangle Ridge quadrangle, Nye and Lincoln Counties, Nevada: U.S. Geol. Survey Geol. Quad. Map GQ-363.

Barnes, Harley, Houser, F. N., and Poole, F. G., 1963, Geologic map of the Oak Spring quadrangle, Nye County, Nevada: U.S. Geol. Survey Geol. Quad. Map GQ-214.

RECEIVED
APR 16 1995