Summary of Hydrogeologic Controls on Ground-Water Flow at the Nevada Test Site, Nye County, Nevada

By Randell J. Laczniak, James C. Cole, David A. Sawyer, *and* Douglas A. Trudeau

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ABSTRACT

The underground testing of nuclear devices has generated substantial volumes of radioactive and other chemical contaminants below ground at the Nevada Test Site (NTS). Many of the more radioactive contaminants are highly toxic and are known to persist in the environment for thousands of years. In response to concerns about potential health hazards, the U.S. Department of Energy, under its Environmental Restoration Program, has made NTS the subject of a long-term investigation. Efforts supported through the U.S. Department of Energy program will assess whether byproducts of underground testing pose a potential hazard to the health and safety of the public and, if necessary, will evaluate and implement steps to remediate any of the identified dangers.

Test-generated contaminants have been introduced over large areas and at variable depths above and below the water table throughout NTS. Evaluating the risks associated with these byproducts of underground testing presupposes a knowledge of the source, transport, and potential receptors of these contaminants. Ground-water flow is the primary mechanism by which contaminants can be transported significant distances away from the initial point of injection. Flow paths between contaminant sources and potential receptors are separated by remote areas that span tens of miles. The diversity and structural complexity of the rocks along these flow paths complicates the hydrology of the region. Although the hydrology has been studied in some detail, much still remains uncertain about flow rates and directions through the fractured-rock aquifers that transmit water great distances across this arid region. Unique to the hydrology of NTS are the effects of underground testing, which severely alter local rock characteristics and affect hydrologic conditions throughout the region.

Any assessment of the risk must rely in part on the current understanding of ground-water flow, and the assessment will be only as good as the understanding itself. This report summarizes what is known and inferred about ground-water flow throughout the NTS region. The report identifies and updates what is known about some of the major controls on ground-water flow, highlights some of the uncertainties in the current understanding, and prioritizes some of the technical needs as related to the Environmental Restoration Program.

An apparent deficiency in the current understanding is a lack of knowledge about flow directions and rates away from major areas of testing. Efforts are necessary to delineate areas of downgradient flow and to identify factors that constrain and control flow within these areas. These efforts also should identify the areas most critical to gaining detailed understanding and to establishing long-term monitoring sites necessary for effective remediation.

INTRODUCTION

Background

Since the early 1950's, the Nevada Test Site (NTS) has been the primary continental location for testing of nuclear weapons by the United States and for conducting experiments related to the peaceful application of nuclear explosions. The site, which occupies 1,350 mi^2 of south-central Nevada (fig. 1), was chosen by the Atomic Energy Commission (predecessor to the U.S. Department of Energy) primarily because of its remoteness from population centers and because of Federal control over much of the land (U.S. Department of Energy, 1993, p. 1). Initially, nuclear tests were detonated at or above land surface, but as the concerns over atmospheric fallout intensified during the late 1950's, more and more tests were detonated below ground in tunnels and shafts. Since July 1962, and in accordance with the Limited Test Ban Treaty of 1963, all tests at NTS have been detonated beneath land surface (Office of Technology Assessment, 1989, p. 11-27; U.S. Department of Energy, 1994).

Activities at NTS over the past 40 years have generated a substantial amount of hazardous waste, both at the surface and underground (fig. 2). The largest volume of contaminants was produced as a direct consequence of nuclear testing (Bryant and Fabryka-Martin, 1991). At NTS, 828 underground nuclear tests have been detonated (U.S. Department of Energy, 1994), most of which (more than 95 percent) were at Yucca Flat, Rainier Mesa, and Pahute Mesa (fig. 2). No tests have been detonated since October 1992. These nuclear devices were emplaced deep in the earth to contain their explosive force and radioactive byproducts within the subsurface, thus avoiding the release of radioactivity to the atmosphere. Even though water levels in the NTS region are generally more than 800 ft below land surface, many of the intermediate and larger yield tests were detonated at depths near or below the water table to ensure the subsurface containment of radioactive byproducts (fig. 2). These tests have resulted in the introduction of radioactive and chemical contaminants into the regional ground-water flow system.

Individual test-generated contaminants differ considerably in terms of physical and chemical behavior and toxicity, and the after-shot distribution is difficult to define, in part because of dispersal by the test explosion itself (Borg and others, 1976). Contaminants produced by the detonation remain in the subsurface for many years. Where ground water contacts these contaminants, the potential for their migration is increased and their movement becomes dependent primarily on the rate and direction of ground-water flow. Thus, a knowledge of ground-water flow paths is essential to determine subsurface distributions and potential receptors of these test-generated byproducts.

The NTS is centrally located within the Death Valley ground-water flow system (fig. 3), one of the major hydrologic subdivisions of the southern Great Basin. It is estimated that more than 70,000 acre-ft of ground water are transmitted annually through this geologically diverse region (Blankennagel and Weir, 1973; Winograd and Thordarson, 1975; Harrill and others, 1988; Dettinger, 1989). In general, water moves southward through thick sequences of carbonate and volcanic rocks, away from areas of major recharge in central Nevada, toward areas of surface discharge at Ash Meadows, Oasis Valley, Alkali Flat, and Death Valley (fig. 1). Along these pathways, rain and snow on some of the intermediate mountain ranges and higher mesas contributes thousands of acre-feet of water into the underlying aquifers. Local communities and the numerous commercial and Federal facilities located throughout the area must rely on ground water for a large part of their water supply because surface water is limited in this arid region. Presently, wells throughout the flow system provide for agricultural, livestock, industrial, and domestic water needs, as do springs, which also support a diversity of wildlife and native vegetation.

A potential receptor of test-generated contaminants is the NTS workforce. More than 10 major water wells have been developed at NTS to provide water for drinking, industrial, and waste uses. Many of these wells, along with other drill holes on the NTS (fig. 2), have been sampled routinely for many years by the U.S. Department of Energy (USDOE) and the U.S. Environmental Protection Agency (USEPA). Samples have been tested for radioactive and other chemical constituents (Office of Technology Assessment, 1989; U.S. Environmental Protection Agency, 1991). No fission products have been detected in these samples, but tritium has been measured at concentrations greater than background (but not exceeding USEPA regulations for safe drinking water) in several of these wells. As a result of the USDOE practice of regularly monitoring drilling fluids at NTS, tritium and fission products have been detected in ground water at locations within the testing areas where none were expected (Borg and others, 1976; Hawkins and others, 1988, 1989; Nimz and Thompson, 1992). Although the concentrations of these contaminants generally have been low, tritium has been detected in excess of USEPA maximum permissible concentrations in a few samples at Yucca Flat (Crow, 1976) and at Pahute Mesa (Erikson, 1991; Nimz and Thompson, 1992).

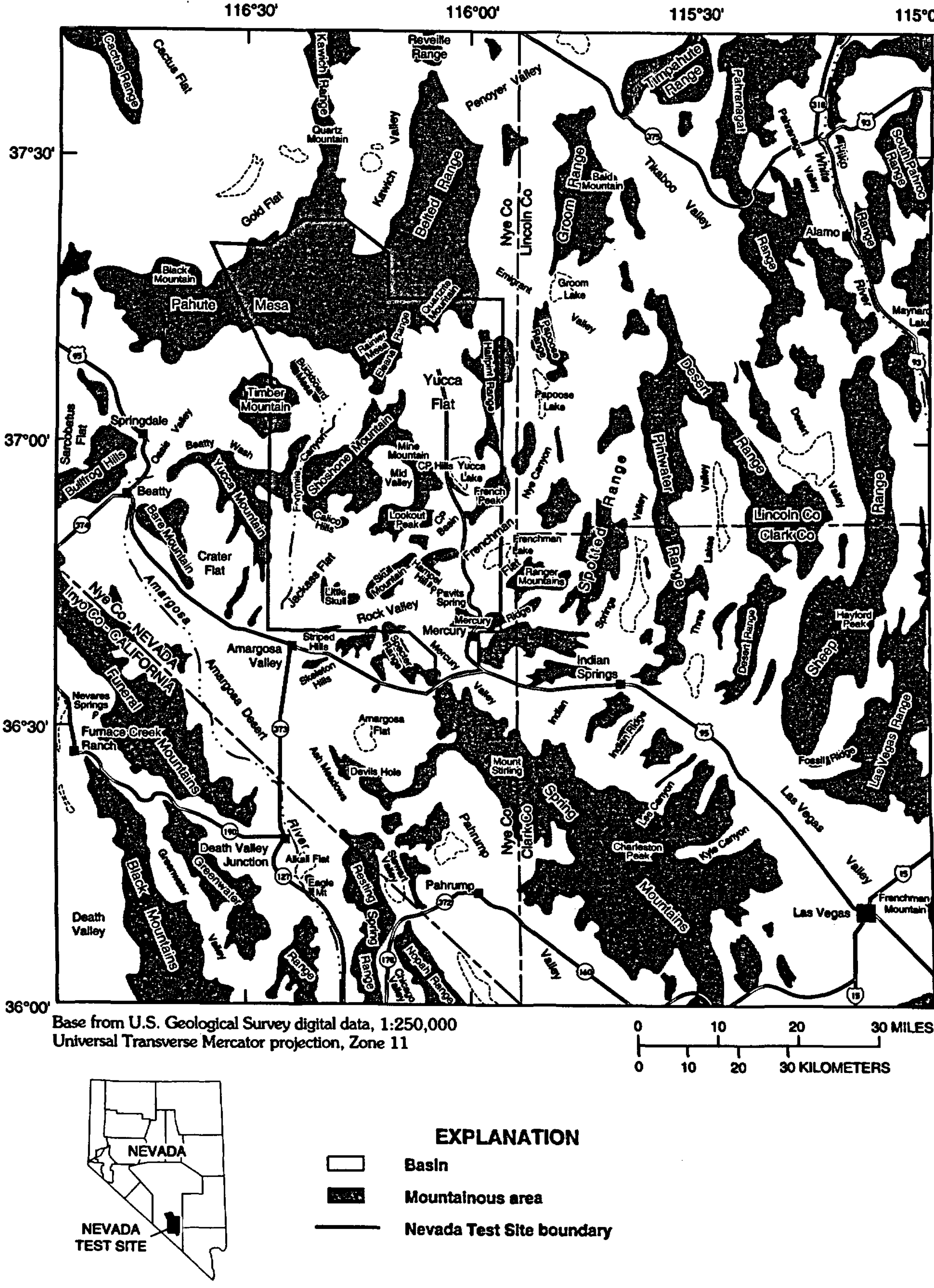
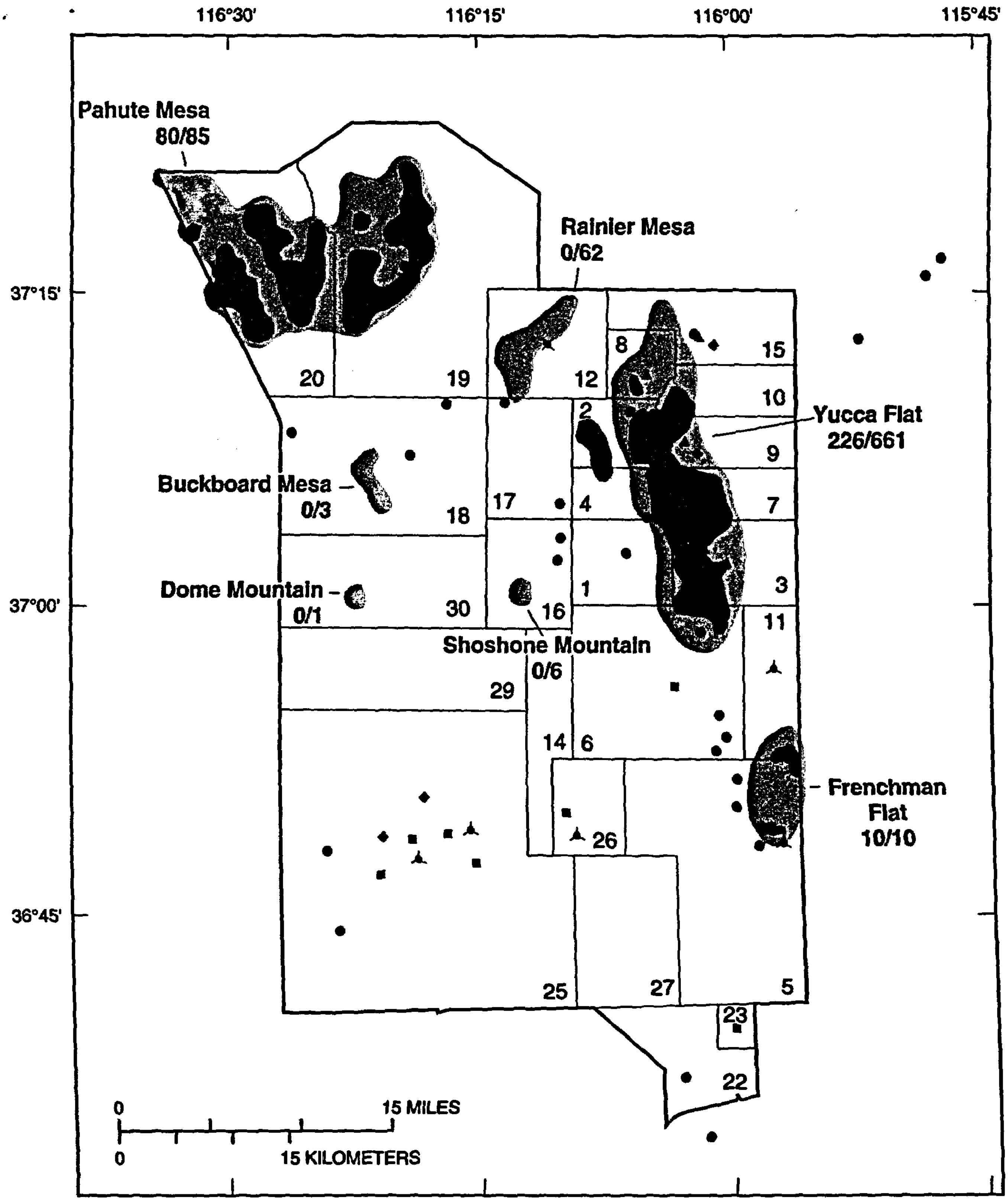


Figure 1. Location of Nevada Test Site and local physiographic and geographic features.



Base prepared by U.S. Geological Survey from
digital data, 1:100,000 1979-89
Universal Transverse Mercator projection
Zone 11

Figure 2. General areas of underground nuclear testing and other potential sources of subsurface contamination at Nevada Test Site.

EXPLANATION

0/3 — **Underground test area**–Darker shading delineates area where tests were detonated near or below water table. Number of tests near or below water table and total number of tests are indicated preceding and following slash, respectively. From Bryant and Fabryka-Martin (1991) and U.S. Department of Energy (1991, 1994); see table 4 for additional information

Nevada Test Site boundary

3 — **Area boundary within Test Site**–Area number is indicated

Other contaminant sources–From U.S. Department of Energy (1991)

- Tunnel tailings or drain pond
- Leachfield
- Sump or injection well
- Storage tank
- Waste site

U.S. Environmental Protection Agency sampling well–From U.S Environmental Protection Agency (1991)

Figure 2. Continued.

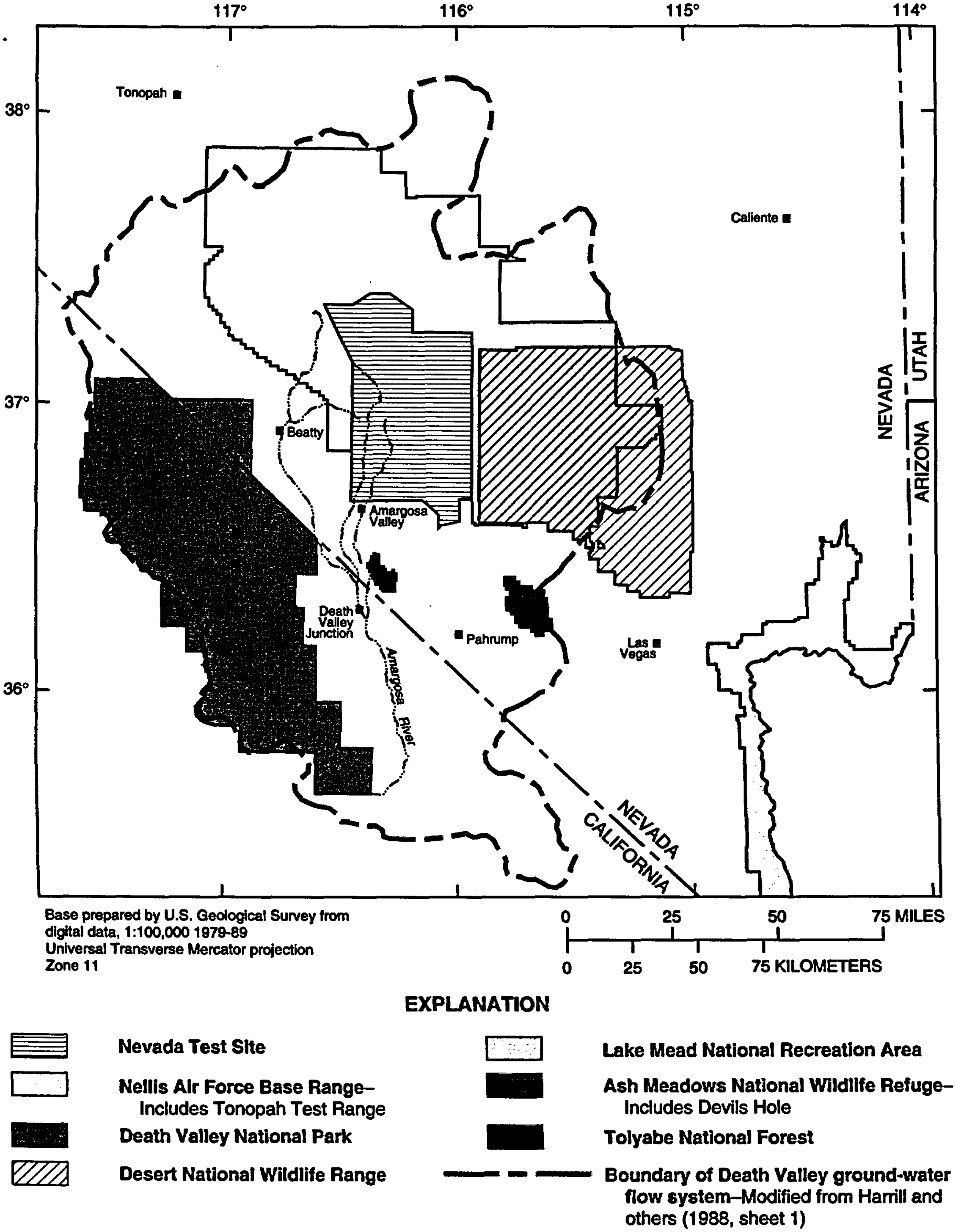


Figure 3. Location of Death Valley ground-water flow system in relation to local geographic features and areas of Federal land administration.

Base prepared by U.S. Geological Survey from digital data, 1:100,000 1979-89
Universal Transverse Mercator projection
Zone 11

0 10 20 MILES
0 10 20 KILOMETERS

Geology modified from Streitz and Stinson (1974), and Stewart and Carlson (1978)

EXPLANATION

(white box)	**Valley fill**	(pattern)	**Carbonate rock**	(pattern)	**Granitic rock**
(pattern)	**Volcanic rock**	(pattern)	**Clastic rock**		

— — — **Boundary of southwest Nevada volcanic field**–Modified from Carr and others (1986, fig. 1)

— — — **Subsurface boundary of regional carbonate-rock aquifer**–Approximate western limit of area where carbonate-rock aquifer is known to dominate ground-water flow system

——— **Nevada Test Site boundary**

Figure 4. Surface distribution of rocks in and near Nevada Test Site.

Table 1. Principal stratigraphic and associated hydrogeologic units of Nevada Test Site and vicinity

[Based on information from Blankennagel and Weir, 1973, table 1; Winograd and Thordarson, 1975, table 1; Byers and others, 1976; Cole and others, 1990; Sawyer and others, 1990; Sawyer and others, 1994; and R.G. Warren, Los Alamos National Laboratory, written commun., 1991]

Stratigraphic unit[1]		Principal lithology[2]	Hydrogeologic unit[3]	Known or inferred hydrologic significance[4]
Valley-fill deposits [Qa, QTa, Qp, Qe, Qc] Miocene to Quaternary		Gravel and sand (eolian sand and lakebed deposits)	Valley-fill aquifer	Generally unsaturated except in deepest structural basins at Yucca Flat, Frenchman Flat, Emigrant Valley, and Amargosa Desert. Saturated thickness highly variable and can exceed 1,000 ft locally; local source of recharge to regional carbonate-rock aquifer. Fine-grained lakebed deposits present in Ash Meadows area may inhibit regional flow and divert ground water to surface [AM, OV, AFFCR]
Basalt [Qb, QTb, Tb] Miocene to Quaternary		Basalt in thin flows, dikes, and cinder cones	n/c	Generally unsaturated; dikes and local flows may influence local ground-water movement [OV, AFFCR, AM]
Thirsty Canyon Group [Tt] 9.4 Ma		Variable welded peralkaline rhyolite ash-flow tuff (trachyte lava)	Welded-tuff aquifer	Generally unsaturated; may contain local perched water in Pahute Mesa and beneath Oasis Valley [OV, AFFCR]
Timber Mountain Group [Tm] 12.5-11.5 Ma	Ammonia Tanks Tuff	Variable welded ash-flow tuff (bedded tuff)	Welded-tuff aquifer	Generally unsaturated except in Oasis Valley and possibly Jackass Flats [OV, AFFCR?]
	Rhyolite of Tannenbaum Hill	Rhyolite lava	Lava-flow aquifer	Local aquifer in northwestern part of Timber Mountain caldera [AFFCR, OV]
	Rainier Mesa Tuff	Variably welded ash-flow tuff (nonwelded tuff; rhyolite lava)	Welded-tuff aquifer	Major aquifer in deeper parts of Yucca Flat, CP Basin, Frenchman Flat, and Jackass Flats, and in western Pahute Mesa and Oasis Valley [AM, AFFCR, OV]
	Pre-Rainier Mesa rhyolites	Rhyolite lava (nonwelded tuff)	Lava-flow aquifer	Local aquifers in Pahute Mesa and at Yucca Mountain [AFFCR]
Paintbrush Group [Tp] 12.8-12.7 Ma	Post-Tiva Canyon rhyolites	Rhyolite lava (nonwelded tuff)	Lava-flow aquifer	Generally unsaturated; may form local aquifers in fault blocks in western and central Pahute Mesa; contains perched water elsewhere [OV, AFFCR]
	Tiva Canyon Tuff	Variably welded ash-flow tuff (nonwelded tuff; locally zeolitized)	Welded-tuff aquifer (tuff confining unit)	Major aquifer in Pahute Mesa and Jackass Flats; confining unit where nonwelded in Yucca Flat [AFFCR, AM]
	Middle Paintbrush Group rhyolites (includes rhyolites of Echo Peak and Silent Canyon)	Rhyolite lava (welded ash-flow tuff; nonwelded tuff, locally zeolitized)	Lava-flow aquifer (welded-tuff aquifer; tuff confining unit)	Local aquifers in Pahute Mesa; minor confining unit at Yucca Mountain [AFFCR]
	Topopah Spring Tuff	Variably welded ash-flow tuff (nonwelded tuff, locally zeolitized)	Welded-tuff aquifer (tuff confining unit)	Major aquifer in western Pahute Mesa, Jackass Flats, southern Yucca Flat, CP Basin, and Frenchman Flat [OV, AFFCR, AM]
Calico Hills Formation [Ta] 12.9 Ma	Volcanics of Area 20	Rhyolite lava and nonwelded tuff, commonly zeolitized (welded tuff)	Lava-flow aquifer, tuff confining unit (welded-tuff aquifer)	Major aquifer in central and western Pahute Mesa; major confining unit in eastern Pahute Mesa, Yucca Mountain, Jackass Flats, and Yucca Flat [AFFCR, OV?]
	Rhyolite of Inlet	Rhyolite lava	Lava-flow aquifer	Major aquifer in eastern and central Pahute Mesa [AFFCR, OV?]

Table 1. Principal stratigraphic and associated hydrogeologic units of Nevada Test Site and vicinity—Continued

Stratigraphic unit[1]		Principal lithology[2]	Hydrogeologic unit[3]	Known or inferred hydrologic significance[4]
Wahmonie Formation [Tw] 13.0 Ma		Andesite and dacite volcanic breccia (lava; nonwelded tuff)	Tuff confining unit (lava-flow aquifer or confining unit?)	Confining unit west of Frenchman Flat and in Jackass Flats; contains perched water near Cane Springs and Pavits Spring; thin confining unit in Yucca Flat [AM, AFFCR]
Crater Flat Group [Tc] 13.25-13.1Ma	Prow Pass Tuff	Variably welded ash-flow tuff (nonwelded tuff, commonly zeolitized)	Welded-tuff aquifer (tuff confining unit)	Major aquifer at Yucca Mountain; confining unit where nonwelded in Yucca Flat and Rainier Mesa [AFFCR, AM]
	Middle units	Rhyolite lava (latite lava; nonwelded tuff)	Lava-flow aquifer	Local aquifers in Pahute Mesa; confining units where nonwelded and zeolitized [AFFCR,AM]
	Bullfrog Tuff	Variably welded ash-flow tuff (nonwelded tuff, commonly zeolitized)	Welded-tuff aquifer (tuff confining unit)	Major aquifer at Yucca Mountain; major confining unit in Pahute Mesa [AFFCR, AM]
	Tram Tuff	Variably welded ash-flow tuff	Welded-tuff aquifer	Major aquifer at Yucca Mountain [AFFCR, AM]
Belted Range Group [Tb] 13.85-13.6 Ma	Deadhorse Flat Formation	Rhyolite lava and variably welded ash-flow tuff (nonwelded tuff, commonly zeolitized)	Lava-flow aquifer; welded-tuff aquifer	Major aquifers in eastern Pahute Mesa [AFFCR, OV?]
	Grouse Canyon Tuff	Peralkaline welded ash-flow tuff (nonwelded tuff, commonly zeolitized)	Welded-tuff aquifer (tuff confining unit)	Local aquifer in Yucca Flat and Pahute Mesa [AFFCR, AM, OV]
Tunnel Formation [Tn] about 14 Ma		Nonwelded tuff, commonly zeolitized	Tuff confining unit	Major confining unit in Rainier Mesa and Yucca Flat; contains perched water at Rainier Mesa [AFFCR, AM]
Volcanics of Big Dome [Tu] about 15 Ma	Rhyolite of Quartet Dome	Peralkaline rhyolite lava	Lava-flow aquifer	Local aquifer in eastern Pahute Mesa [AFFCR]
	Tub Spring Tuff	Variably welded ash-flow tuff	Welded-tuff aquifer	Local aquifer in northern Yucca Flat and in parts of Pahute Mesa and Rainier Mesa [AFFCR, AM]
Older volcanics [To] 16-15 Ma	Tunnel bed 2 and Tunnel bed 1	Nonwelded tuff, commonly zeolitized	Tuff confining unit	Confining unit in Rainier Mesa and Yucca Flat; contains perched water at Rainier Mesa [AFFCR, AM]
	Red Rock Valley Tuff, Fraction Tuff, and pre-fraction tuffs	Variably welded ash-flow tuff; nonwelded tuff, commonly zeolitized	Tuff confining unit (welded-tuff aquifer)	Major confining unit where nonwelded in southern Yucca Flat and Frenchman Flat; local aquifers in northern Yucca Flat, southern Rainier Mesa, and parts of Pahute Mesa. Unit locally includes ash-flow tuffs of older mid-Tertiary volcanic centers [AFFCR, AM]
Pavits Spring Formation [Ts] Miocene		Tuffaceous sandstone; local conglomerate and siltstone (ash-fall tuff; lacustrine limestone)	n/c	Significance unknown; mapped as an informal unit east, south, and west of Frenchman Flat; partly coeval with some other volcanic units [AM]
Horse Spring Formation [Ts] mid-Tertiary		Conglomerate and tuffaceous sandstone (lacustrine limestone; ash-fall tuff)	n/c	Significance unknown; mapped as an informal unit south and west of Frenchman Flat along Rock Valley fault system [AM]

Table 1. Principal stratigraphic and associated hydrogeologic units of Nevada Test Site and vicinity—Continued

Stratigraphic unit[1]	Principal lithology[2]	Hydrogeologic unit[3]	Known or inferred hydrologic significance[4]
Paleocolluvium [Tx] Tertiary	Sedimentary breccia	n/c	Locally very porous; thickness variable along basal contact of Tertiary section; only known from Yucca Flat and Rainier Mesa areas; hydrologic significance uncertain but known to act as a local confining unit in Yucca Flat [AM, AFFCR]
Granite [Kg] Cretaceous	Porphyritic monzogranite	n/c	Relatively impermeable; forms local cylindrical stocks north of Rainier Mesa and Yucca Flat; locally yields water from fracture zones [AFFCR, AM]
Tippipah Limestone [PPt] Chiefly Pennsylvanian	Thin-bedded limestone (pebble conglomerate)	Upper carbonate-rock aquifer	Local aquifer in western Yucca Flat; limited lateral extent [AM]
Eleana Formation [MDe] and Chainman Shale [Mch] Chiefly Mississippian	Siliceous siltstone; chert sandstone; cobble conglomerate (shale; quartzite; bioclastic limestone)	Eleana confining unit	Major confining unit along boundary between AFFCR and AM subbasins in western Yucca Flat and northern Jackass Flats; saturated thickness variable and can exceed 5,000 ft at some locations; locally yields water from fracture zones in quartzite and limestone [AFFCR, AM]
Guilmette Formation [Dg] Devonian	Limestone, locally sandy and dolomitic		
Simonson Dolomite [Ds] Devonian	Dolomite, locally silty or cherty		Regional carbonate-rock aquifer; saturated thickness can exceed 15,000 ft; conveys most ground water in Yucca Flat-Frenchman Flat area and along Rock Valley fault system; principal aquifer throughout Ash Meadows subbasin; significant aquifer in southern part of Yucca Mountain and south into AFFCR subbasin [AM, AFFCR]
Sevy, Laketown, and Lone Mountain Dolomite; Roberts Mountain Formation; dolomite of Spotted Range [various symbols] Chiefly Silurian and Devonian	Dolomite, locally silty or cherty		
Ely Springs Dolomite [Oes] Ordovician	Dolomite, cherty dolomite		
Eureka Quartzite [Oe] Ordovician	Siliceous orthoquartzite	Lower carbonate-rock aquifer	
Pogonip Group [Op] Ordovician	Limestone and silty limestone (dolomite)		Due to displacement on low-angle faults, carbonate rocks of these stratigraphic units occur locally out of stratigraphic order above Eleana Formation or Chainman Shale; in such situations, structural blocks of these units do not form lower carbonate-rock aquifer, but rather act similar to upper carbonate-rock aquifer
Nopah Formation [€n] Cambrian	Limestone and dolomite, locally cherty and silty; Dunderberg Shale at base		
Bonanza King Formation [€bk] Cambrian	Dolomite and limestone (silty dolomite; chert)		
Carrara Formation [€c] Cambrian — [upper part]	Limestone and silty limestone		

Table 1. Principal stratigraphic and associated hydrogeologic units of Nevada Test Site and vicinity—Continued

Stratigraphic unit[1]		Principal lithology[2]	Hydrogeologic unit[3]	Known or inferred hydrologic significance[4]
Carrara Formation [€c] Cambrian	[lower part]	Shale and siltstone (limestone and quartzite)	Quartzite confining unit	Widespread confining unit that forms hydrologic basement throughout much of southern Nevada; saturated thickness can exceed 10,000 ft; forms major barrier to lateral ground-water flow in northeastern Yucca Flat, south of Oasis Valley near Beatty, and south of Ash Meadows; locally yields substantial water from fractured quartzite or fault zones in northern Yucca Flat [OV, AFFCR, AM]
Zabriskie Quartzite [€z] Cambrian		Siliceous orthoquartzite		
Wood Canyon Formation [€Zw] Cambrian and Eocambrian		Micaceous siltstone and orthoquartzite (dolomite; pebbly quartzite)		
Stirling Quartzite [Zs] Eocambrian		Siliceous orthoquartzite and micaceous siltstone (quartzite conglomerate)		
Johnnie Formation [Zj] Eocambrian		Siliceous orthoquartzite and micaceous siltstone (silty limestone)		
Noonday Dolomite [Zn?] Eocambrian		Dolomite	n/c	Known only from bottom of deep drillhole UE-15d in northern Yucca Flat; stratigraphic identity uncertain (Barnes, 1962)

[1] Map symbol shown in brackets. Approximate age given in millions of years ago (Ma) or indicated by geologic system.

[2] Rock type listed in order of decreasing prevalence; minor but significant rock types listed in parentheses.

[3] Hydrogeologic units in order of decreasing prevalence. Stratigraphic classification of Tertiary volcanic rocks is based on age and composition. Lithologic and hydrologic properties may be extremely variable from place to place. n/c, stratigraphic unit has not been characterized as a hydrogeologic unit, generally because its presence in the unsaturated zone is minor.

[4] Code in brackets at end of entry gives ground-water subbasin or subbasins in which stratigraphic units is prevalent. AFFCR, Alkali Flat-Furnace Creek Ranch; AM, Ash Meadows; and OV, Oasis Valley. Query indicates uncertainty regarding presence or significance of unit in subbasin.

Table 2. Nomenclature for hydrogeologic units of Nevada Test Site and vicinity

Regional hydrogeologic unit	Subregional hydrogeologic unit	Equivalent previous units (Winograd and Thordarson, 1975)
Valley-fill aquifer	Valley-fill aquifer[1]	Valley-fill aquifer
Volcanic-rock aquifer	Welded-tuff aquifer[1]	Welded-tuff aquifer Bedded-tuff aquifer
	Lava-flow aquifer[1]	Lava-flow aquifer
Volcanic confining unit	Tuff confining unit[1]	Tuff aquitard Lava-flow aquitard
N/R[2]	Granite[1]	Minor aquitard
N/R[2]	Upper carbonate-rock aquifer[1]	Upper carbonate-rock aquifer
Eleana confining unit	Eleana confining unit	Upper clastic aquitard
Carbonate-rock aquifer	Lower carbonate-rock aquifer	Lower carbonate-rock aquifer
Basement confining unit	Quartzite confining unit	Lower clastic aquitard

[1] Due to original lenticular or interlayed form of constituent rock bodies, or due to geometric modifications caused by faulting or folding, or both, these hydrogeologic units generally consist of more than one disconnected or partially connected aquifer or confining unit.

[2] N/R, no regional hydrogeologic unit is recognized because corresponding subregional units have limited areal extent and do not substantially effect regional ground-water flow.

Table 3. General characteristics of ground-water subbasins of Nevada Test Site and vicinity

[NTS, Nevada Test Site]

Ground-water subbasin	Surface area (square miles)	Relation to NTS underground test areas	Principal water-bearing rocks	Inflow[1]	Outflow[1]
Oasis Valley [OV]	550	Includes westernmost part of Pahute Mesa test area in northwestern NTS	Welded tuffs and lava flow; valley-fill alluvium locally important at Gold Flat and Oasis Valley	Precipitation recharge near Black Mountain; subsurface inflow from Cactus Flat	Springflow and evapotranspiration at Oasis Valley; subsurface outflow to AFFCR south of Beatty, Nev.
Alkali Flat-Furnace Creek Ranch [AFFCR]	2,800	Includes most of Pahute Mesa and all Buckboard Mesa and Dome Mountain test areas in western NTS; Rainier Mesa and Shoshone Mountain test areas are along boundary between AFFCR and AM	Welded tuffs and lava flows in test areas; limestone, dolomite, and valley-fill alluvium south of test areas and at discharge area	Precipitation recharge at Belted Range, Kawich Range, Quinn Canyon Range, Pahute Mesa, and Rainier Mesa and possibly at Timber Mountain and Fortymile Wash; subsurface inflow from Cactus Flat and from across discharge areas of OV and AM	Springflow at Death Valley and evapotranspiration from Alkali Flat and Death Valley
Ash Meadows [AM]	4,000	Includes all Yucca Flat and Frenchman Flat test areas in central, eastern, and southern NTS; Rainier Mesa and Shoshone Mountain test areas are along boundary between AM and AFFCR	Welded and nonwelded tuffs, limestone, dolomites and valley-fill alluvium in test areas; limestone, dolomite and valley-fill alluvium south and west of test areas and at discharge areas	Precipitation recharge at Belted Range, Reveille Range, Rainier Mesa, Timpahute Range, Pahranagat Range, Sheep Range, Spring Mountains, and possibly at Desert Range; subsurface inflow from Railroad Valley and Pahranagat Valley	Springflow and evapotranspiration at Ash Meadows spring line; subsurface outflow beneath Ash Meadows to AFFCR

[1] Based on information from Winograd and Thordarson (1975), Waddell and others (1984), and Harrill and others (1988).

Table 4. Distribution of underground tests relative to water table and estimated number of tests that have introduced test-generated contaminants into the ground-water flow system by major test area at the Nevada Test Site

[Working point is depth at which nuclear device is detonated; water table is estimated or measured altitude of regional water table prior to underground test; cavity radius (CR) is estimated or measured radius of cavity formed after underground test (typically determined by post-shot drilling as distance between working point and lower surface of the radioactive glass "puddle" formed in bottom of cavity). Source is U.S. Department of Energy (1994). Calculations based on measurements of cavity radius, and on working-point and static borehole water-level depths, as summarized in classified listing of test parameters (Lawrence Livermore National Laboratory, written commun., 1991).

	Number of underground tests							
	Location of working point relative to water table					Tests that introduced contaminants into ground-water flow system		
		Above						
NTS area (figure 2)	Below	Less than or equal to CR	Greater than one and less than or equal to two CR	Greater than two and less than or equal to five CR[1]	Greater than five CR	Certain or probable[2]	Maximum[3]	Total[4]
Yucca Flat								
1	0	0	0	0	3	0	0	3
2	19	10	6	21	81	35	56	137
3	9	5	12	43	183	26	69	252
4	16	3	2	5	8	21	26	34
6	0	0	0	1	4	0	1	5
7	30	8	8	6	10	46	52	62
8	0	1	0	1	8	1	2	10
9	1	2	1	5	90	4	9	99
10	1	2	2	6	45	5	11	56
15	0	0	0	0	3	0	0	3
Subtotal	76	31	31	88	435	138	226	661
Pahute Mesa								
19	14	15	3	2	2	32	34	36
20	20	22	3	1	3	45	46	49
Subtotal	34	37	6	3	5	77	80	85
Rainier Mesa								
12	0	0	0	0	62	0	0	62
Frenchman Flat								
5	1	2	1	1	0	4	5	5
11	0	1	1	3	0	2	5	5
Subtotal	1	3	2	4	0	6	10	10
Shoshone Mesa								
16	0	0	0	0	6	0	0	6
Buckboard Mesa								
18	0	0	0	0	3	0	0	3
Dome Mountain								
30	0	0	0	0	1	0	0	1
Total	111	71	39	95	512	221	316	828

[1] Zone includes region of widespread fracturing caused by detonation.

[2] Category defined as tests that certainly or probably have introduced test-generated contaminants directly into ground-water flow system; includes all tests detonated below water table and detonated above but within two cavity radii of water table.

[3] Category defined as the maximum number of tests (includes certain or probable category) likely to have introduced test-generated contaminants into ground-water flow system; includes all tests detonated below water table and detonated above but within five cavity radii of water table.

[4] Category includes all underground (and shallow cratering) tests. Number of tests is less than total number of detonations at Nevada Test Site because some tests include multiple detonations (U.S. Department of Energy, 1994).

Table 5. Water levels, underground tests, and associated test and hole parameters used to determine general position of test relative to the water table

[All depths referenced to land-surface datum. Altitude relative to sea level. Working point is depth at which nuclear device is detonated. Dashes indicate missing or non applicable parameter. Sources are U.S. Department of Energy (1994) and classified listing of test parameters (Lawrence Livermore National Laboratory, written commun., 1991, 1992)]

Hole name	Test name	Altitude (feet)	Depth of		Distance of test from water (feet)	Date of test	Yield of test (kilotons)
			Working point (feet)	Water (feet)[1]			
UE-18r	--	5,538	--	1,365	--	--	--
UE-18t	--	5,201	--	916	--	--	--
Water Well 8	--	5,695	--	1,076	--	--	--
U-19aa	Sheepshead	6,758	2,100	*2,326*	226	79-09-26	20-150
U-19ab	Towanda	6,928	2,182	2,024	-158	85-05-02	20-150
U-19ab 2/Inst.	--	6,930	--	2,015	--	--	--
U-19ac	Tierra	7,038	2,100	*2,284*	184	84-12-15	20-150
U-19ad	Chancellor	6,692	2,051	*2,123*	72	83-09-01	143
U-19ae	Nebbiolo	6,775	2,100	2,280	180	82-06-24	20-150
U-19af	Galveston	6,710	1,598	*2,280*	682	86-09-04	>20
U-19ai	Serpa	6,742	1,880	2,054	174	80-12-17	20-150
U-19aj	Harzer	6,891	2,090	*2,192*	102	81-06-06	20-150
U-19ak	Hosta	6,898	2,100	*2,192*	92	82-02-12	20-150
U-19am	--	6,710	--	*2,060*	--	--	--
U-19an	Labquark	6,978	2,021	*2,103*	82	86-09-30	20-150
U-19aq	Lockney	6,798	2,018	2,109	91	87-09-24	20-150
U-19ar	Cybar	6,706	2,057	2,119	62	86-07-17	119
U-19aS	Scotch	6,761	3,206	2,192	-1,014	67-05-23	155
U-19au	Alamo	6,535	2,038	2,077	39	88-07-07	<150
U-19av	--	6,512	--	2,022	--	--	--
U-19ax	Kearsarge	6,986	2,018	*2,297*	279	88-08-17	<150
U-19ay	Amarillo	6,713	2,100	2,129	29	89-06-27	20-150
U-19az	Houston	6,753	1,949	2,079	130	90-11-14	20-150
U-19b	Halfbeak	6,791	2,687	2,116	-571	66-06-30	365
U-19b 1	--	6,802	--	2,117	--	--	--
U-19ba	Bexar	7,037	2,064	2,152	88	91-04-04	20-150
U-19bg	Junction	6,691	2,041	*2,115*	74	92-03-06	20-150
U-19bg 1	--	6,694	--	2,119	--	--	--
U-19c	Rickey	7,032	2,241	2,320	79	68-06-15	20-200
UE-19c Water Well	--	7,033	--	2,336	--	--	--
U-19d	Chartreuse	6,861	2,185	*2,172*	-13	66-05-06	73
U-19d 2	--	6,861	--	2,177	--	--	--
U-19e	Muenster	6,920	4,764	2,222	-2,542	76-01-03	200-1,000
U-19e/Inst.	--	6,919	--	2,217	--	--	--
U-19f	Inlet	6,734	2,687	2,307	-380	75-11-20	200-1,000
U-19fS	--	6,735	--	2,306	--	--	--
U-19g	Estuary	6,734	2,848	*2,064*	-784	76-03-09	200-500
U-19gS	--	6,719	--	2,045	--	--	--
UE-19h	--	6,780	--	2,112	--	--	--
U-19i	Sled	6,836	2,389	*2,192*	-197	68-08-29	20-200
UE-19i	--	6,839	--	2,258	--	--	--
U-19L	Stinger	6,766	2,188	*2,100*	-88	68-03-22	20-200
U-19n	Scroll	6,754	735	*2,083*	1,348	68-04-23	<20
U-19p	Pool	6,899	2,884	*2,264*	-620	76-03-17	200-500
U-19q	Camembert	6,758	4,298	*2,192*	-2,106	75-06-26	200-1,000

Table 5. Water levels, underground tests, and associated test and hole parameters used to determine general position of test relative to the water table—Continued

Hole name	Test name	Altitude (feet)	Depth of Working point (feet)	Depth of Water (feet)[1]	Distance of test from water (feet)	Date of test	Yield of test (kilotons)
U-19t	Emmenthal	6,991	1,890	*2,231*	341	78-11-02	<20
U-19u	Mast	6,873	2,989	*2,185*	-804	75-06-19	200-1,000
U-19v	Almendro	6,876	3,488	*2,251*	-1,237	73-06-06	200-1,000
UE-19v PS 1D	--	6,842	--	2,297	--	--	--
UE-19w 1	--	--	--	*2,450*	--	--	--
U-19x	Backbeach	6,781	2,205	2,214	9	78-04-11	20-150
U-19yS	Panir	6,694	2,234	*2,116*	-118	78-08-31	20-150
U-19zS	Fondutta	6,888	2,077	*2,192*	115	78-04-11	20-150
U-19zS/Inst.	--	6,888	--	2,199	--	--	--
Pahute Mesa Ex. 1	--	6,558	--	2,099	--	--	--
Pahute Mesa Ex. 2	--	5,586	--	852	--	--	--
Pahute Mesa Ex. 3	--	5,823	--	1,457	--	--	--
U-20a	Buteo	6,520	2,284	*2,159*	-125	65-05-12	<20
U-20 Water Well	--	6,468	--	2,028	--	--	--
U-20a-1	Duryea	6,520	1,785	*2,172*	387	66-04-14	70
U-20a-2 Water Well	--	6,474	--	2,066	--	--	--
U-20aa	Colby	6,337	4,177	*1,874*	-2,303	76-03-14	500-1,000
U-20ab	Farm	6,581	2,261	2,116	-145	78-12-16	20-150
U-20ac	Colwick	6,473	2,077	*2,067*	-10	80-04-26	20-150
U-20ad	Pepato	6,366	2,234	*1,900*	-334	79-06-11	20-150
U-20ae	Tafi	6,189	2,231	*1,992*	-239	80-07-25	20-150
U-20af	Kash	6,360	2,116	*1,975*	-141	80-06-12	20-150
U-20ag	Molbo	6,234	2,093	*2,015*	-78	82-02-12	20-150
U-20ah	Gibne	6,445	1,870	2,001	131	82-04-25	20-150
U-20ai	Jefferson	6,503	1,998	2,052	54	86-04-22	20-150
U-20aj	Cabra	6,345	1,778	*1,874*	96	83-03-26	20-150
U-20ak	Salut	6,235	1,995	2,042	47	85-06-12	20-150
U-20aL	Egmont	6,124	1,791	*1,936*	145	84-12-09	20-150
U-20am	Kappeli	6,593	2,100	2,142	42	84-07-25	20-150
U-20an	Serena	6,462	1,959	1,991	32	85-07-25	20-150
U-20ao	Goldstone	6,279	1,801	1,957	156	85-12-28	20-150
U-20ap	Bodie	6,621	2,083	*2,139*	56	86-12-13	20-150
U-20aq	Darwin	6,155	1,801	*1,883*	82	86-06-25	20-150
U-20ar	Kernville	6,319	1,775	*1,841*	66	88-02-15	20-150
U-20ar 1/Inst.	--	6,319	--	1,841	--	--	--
U-20as	Belmont	6,227	1,985	2,013	28	86-10-16	20-150
U-20at	Delamar	6,240	1,785	*1,903*	118	87-04-18	20-150
U-20at 1/Inst.	--	6,241	--	2,027	--	--	--
U-20av	Hardin	6,464	2,051	2,075	24	87-04-30	20-150
UE-20av	--	6,458		2,128	--	--	--
U-20aw	Contact	6,585	1,785	2,086	301	89-06-22	20-150
U-20ax	--	6,535	--	2,173	--	--	--
U-20ay	Comstock	6,520	2,034	2,055	21	88-06-02	<150
U-20az	Barnwell	6,572	1,969	2,160	191	89-12-08	20-150
U-20b	Pipkin	6,534	2,047	*2,100*	53	69-10-08	200-1,000

Table 5. Water levels, underground tests, and associated test and hole parameters used to determine general position of test relative to the water table—Continued

Hole name	Test name	Altitude (feet)	Depth of: Working point (feet)	Depth of: Water (feet)[1]	Distance of test from water (feet)	Date of test	Yield of test (kilotons)
U-20bb	Tenabo	6,226	1,969	2,028	59	90-10-12	20-150
U-20bb 1	--	6,230	--	2,028	--	--	--
U-20bc	Hornitos	6,146	1,847	1,871	24	89-10-31	20-150
U-20bd	Bullion	6,486	2,225	2,038	-187	90-06-13	20-150
U-20be	Hoya	6,493	2,159	2,215	56	91-09-14	20-150
U-20bf	Montello	6,522	2,106	2,086	-20	91-04-16	20-150
U-20bg	--	6,567	--	2,129	--	--	--
U-20c	Benham	6,281	4,600	2,097	-2,503	68-12-19	1,150
UE-20c	--	6,283	--	2,126	--	--	--
U-20d	Knickerbocker	6,252	2,067	*2,075*	8	67-05-26	76
UE-20d	--	6,253	--	2,075	--	--	--
U-20e	Jorum	6,316	3,809	1,853	-1,956	69-09-16	<1,000
UE-20e 1	--	6,297	--	1,826	--	--	--
U-20f	Fontina	6,117	4,000	*1,952*	-2,048	76-02-12	200-1,000
UE-20f	--	6,116	--	1,954	--	--	--
U-20g	Greeley	6,470	3,990	2,017	-1,973	66-12-20	870
UE-20h	Rex	6,557	2,202	2,105	-97	66-02-24	19
U-20i	Boxcar	6,370	3,822	*1,903*	-1,919	68-04-26	1,300
U-20k	Palanquin	6,194	279	*1,993*	1,714	65-04-14	4.3
U-20L	Cabriolet	6,197	167	*1,997*	1,830	68-01-26	2.3
U-20m	Handley	5,903	3,967	1,270	-2,697	70-03-26	>1,000
U-20n	Cheshire	6,477	3,829	*2,051*	-1,778	76-02-14	200-500
UE-20n 1	--	6,461	--	2,134	--	--	--
U-20p	Stilton	5,559	2,402	*884*	-1,518	75-06-03	20-200
UE-20p	--	5,553	--	884	--	--	--
U-20t	Chateaugay	6,245	1,992	*2,074*	82	68-06-28	20-200
U-20u	Schooner	5,562	364	*899*	535	68-12-08	30
U-20v	Purse	6,088	1,962	*1,972*	10	69-05-07	20-200
U-20y	Tybo	6,257	2,510	2,067	-443	75-05-14	200-1,000
U-20z	Kasseri	6,509	4,151	*2,061*	-2,090	75-10-28	200-1,000

[1] Italicized values are estimated. Non-italicized values are measured. Estimates based on measurements in nearby wells and test holes or interpreted from water-level contours given in Blankennagel and Weir (1973, pl. 1).

Pahute Mesa and Rainier Mesa

The Pahute Mesa and Rainier Mesa underground test areas are in the northwestern part of NTS (figs. 1 and 2). These areas provided locations for 147 tests (U.S. Department of Energy, 1994), of which 85 were on Pahute Mesa and 62 on Rainier Mesa (tables 4 and 5). All underground tests within these areas were detonated in volcanic rock.

Pahute Mesa, an elevated plateau, ranges in altitude from about 5,500 ft along its western margin to more than 7,000 ft throughout its eastern extent. Testing has been confined to the eastern part of the mesa within NTS Areas 19 and 20 (pl. 4). The test area includes upgradient parts of the Oasis Valley and Alkali Flat-Furnace Creek Ranch ground-water subbasins (table 3, pl. 1). Most tests on Pahute Mesa were detonated near or below the water table (tables 4 and 5) in deep shafts drilled into volcanic rock. Of the 85 tests

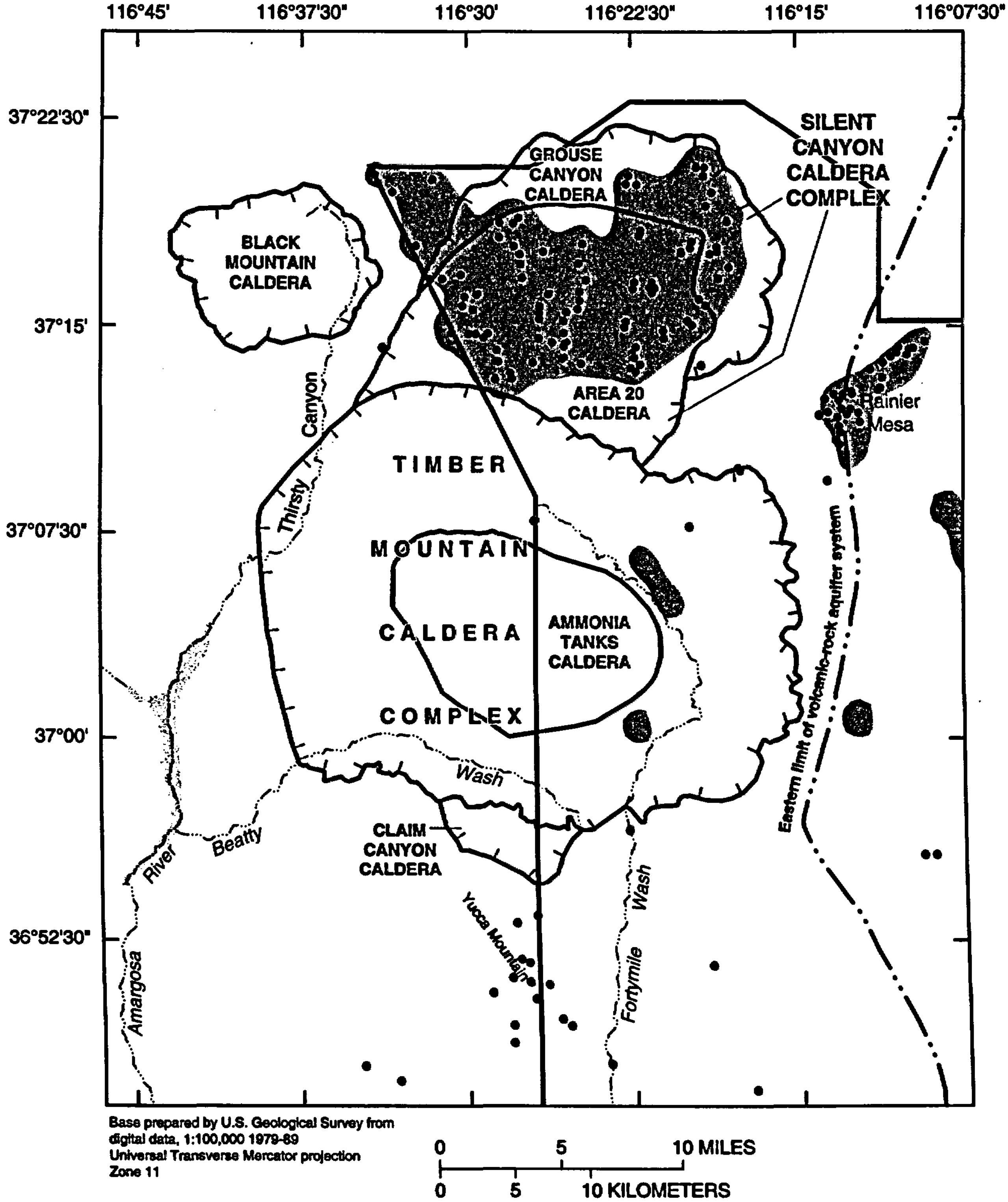


Figure 5. General features of volcanic-rock aquifer system in and adjacent to northwestern part of Nevada Test Site. Silent Canyon caldera complex and adjacent areas underlie Pahute Mesa.

EXPLANATION

Oasis Valley discharge area

Underground test area

Caldera or caldera complex boundary–Modified from Sawyer and others, 1994

Eastern limit of area where volcanic-rock aquifers dominate ground-water flow–Coincides with divide between Alkali Flat-Furnace Creek Ranch and Ash Meadows ground-water subbasins (see plate 1)

Boundary of Nevada Test Site

Well or test hole

Figure 5. Continued.

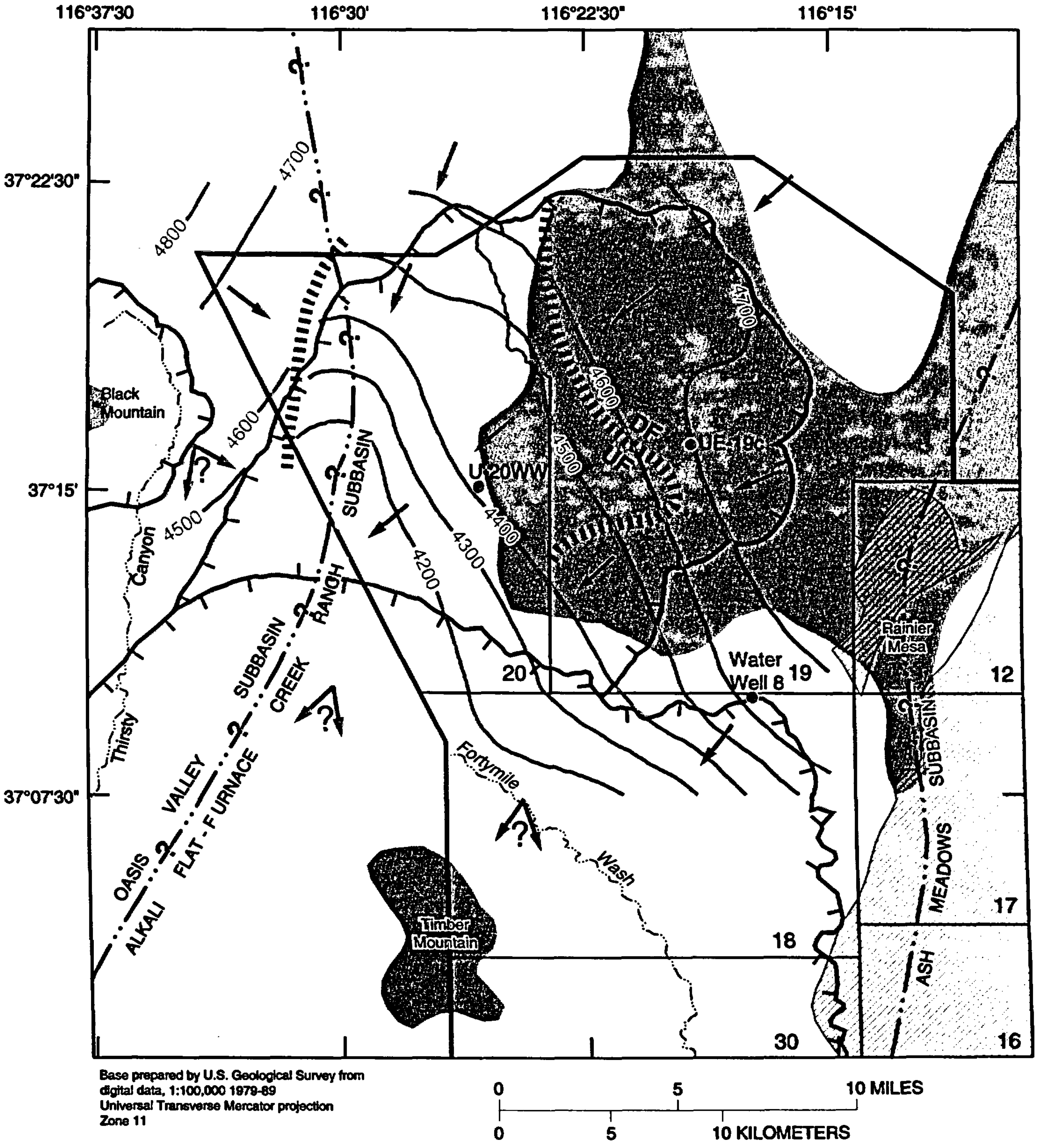


Figure 6. Major controls on ground-water flow in Pahute Mesa area.

EXPLANATION

Area of ground-water recharge–See plate 1 for additional information

Known areal extent of Eleana and basement (quartzite) confining units at altitude of water table–Modified from Winograd and Thordarson (1975, plate 1)

Caldera-complex boundary–Modified from Sawyer and others, 1994. See plate 3 for additional information

4400 **Water-level contour**–Shows altitude of water level. Interval 100 feet. Datum is sea level. Modified from Blankennagel and Weir (1973, plate 1)

Boundary of ground-water subbasin–Modified from Waddell and others (1984, plate 3) and Winograd and Thordarson (1975, plate 1)

Limited-flow barrier–Modified from Blankennagel and Weir (1973, plate 1)

DF UF **Boundary between area of upward flow (on west) and downward flow (on east)**–Modified from Blankennagel and Weir (1973, fig. 10)

General direction of ground-water flow–Queried where uncertain

Boundary of Nevada Test Site

18 **Area boundary within Nevada Test Site**–Area number is indicated

UE-19c **Water-supply well**–Label identifies well

Figure 6. Continued.

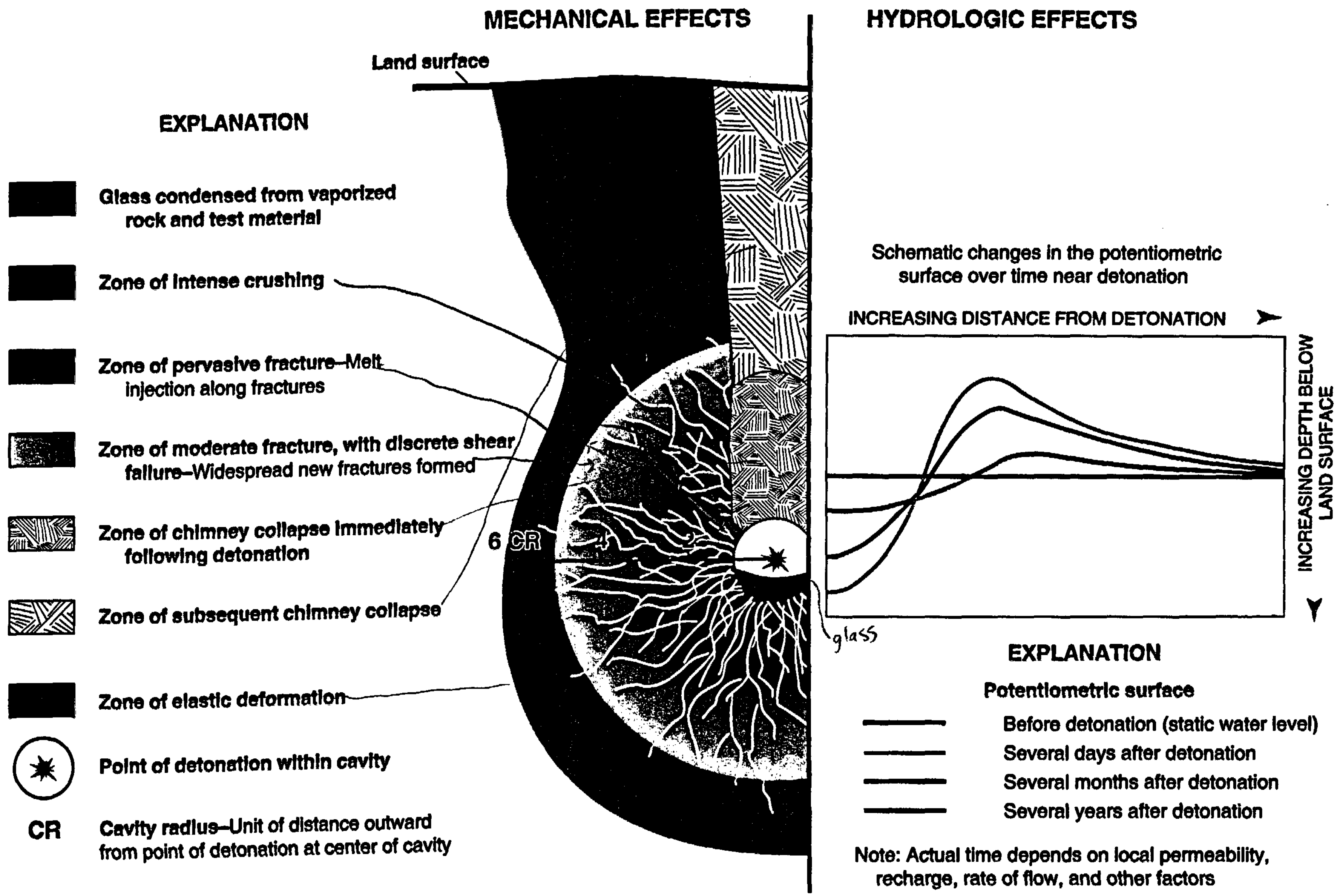


Figure 7. Diagrammatic section showing mechanical and hydrologic effects that may result from underground test detonated below water table.

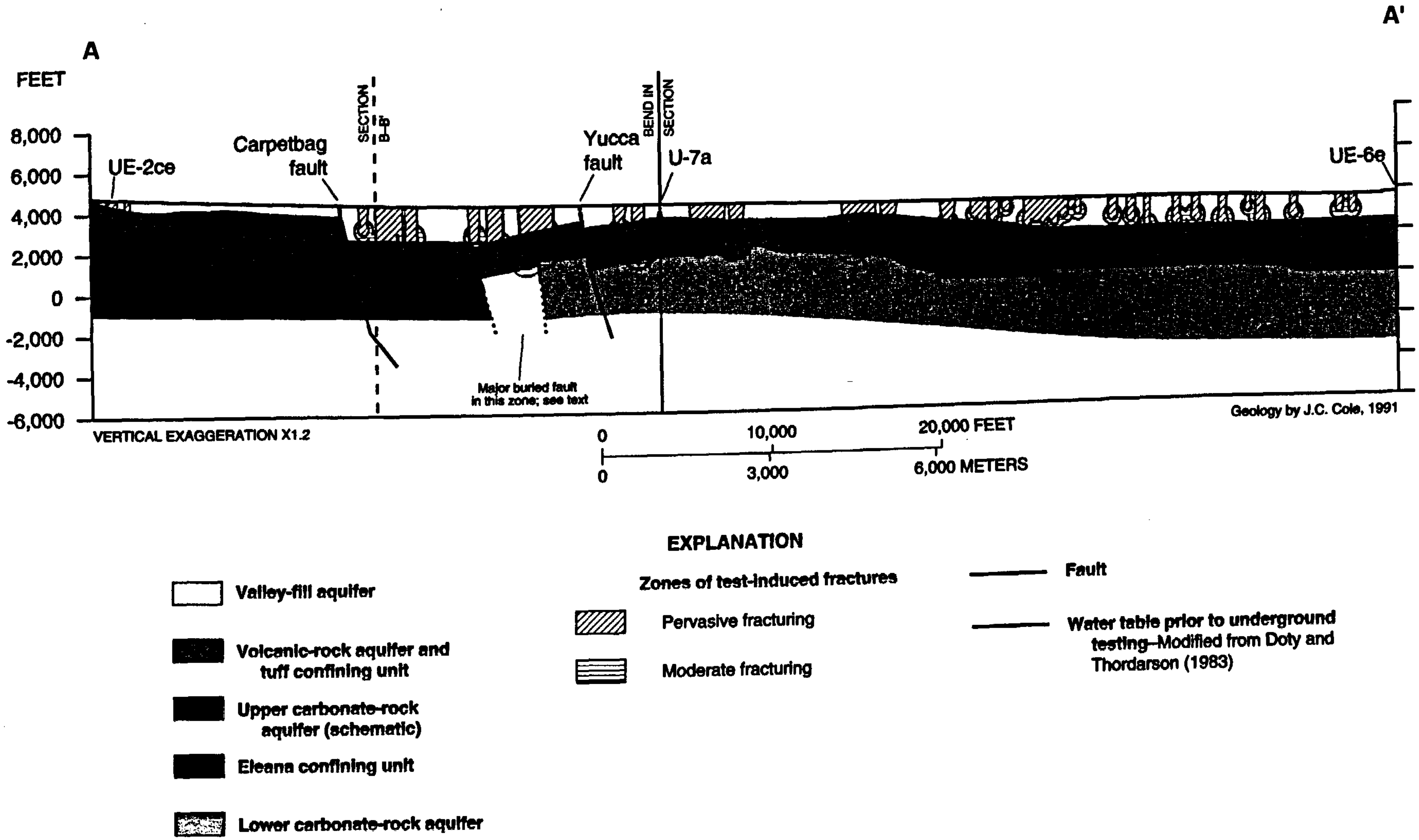


Figure 8. Generalized longitudinal hydrogeologic section across central Yucca Flat showing mechanical effects of underground testing. Underground test locations obtained from U.S. Department of Energy (1994). Cavity dimensions and fracture zones calculated using measurements of cavity radius and working-point depths as summarized in classified listing of test parameters (Lawrence Livermore National Laboratory, written commun., 1991). Location of sections is shown in figure 9.

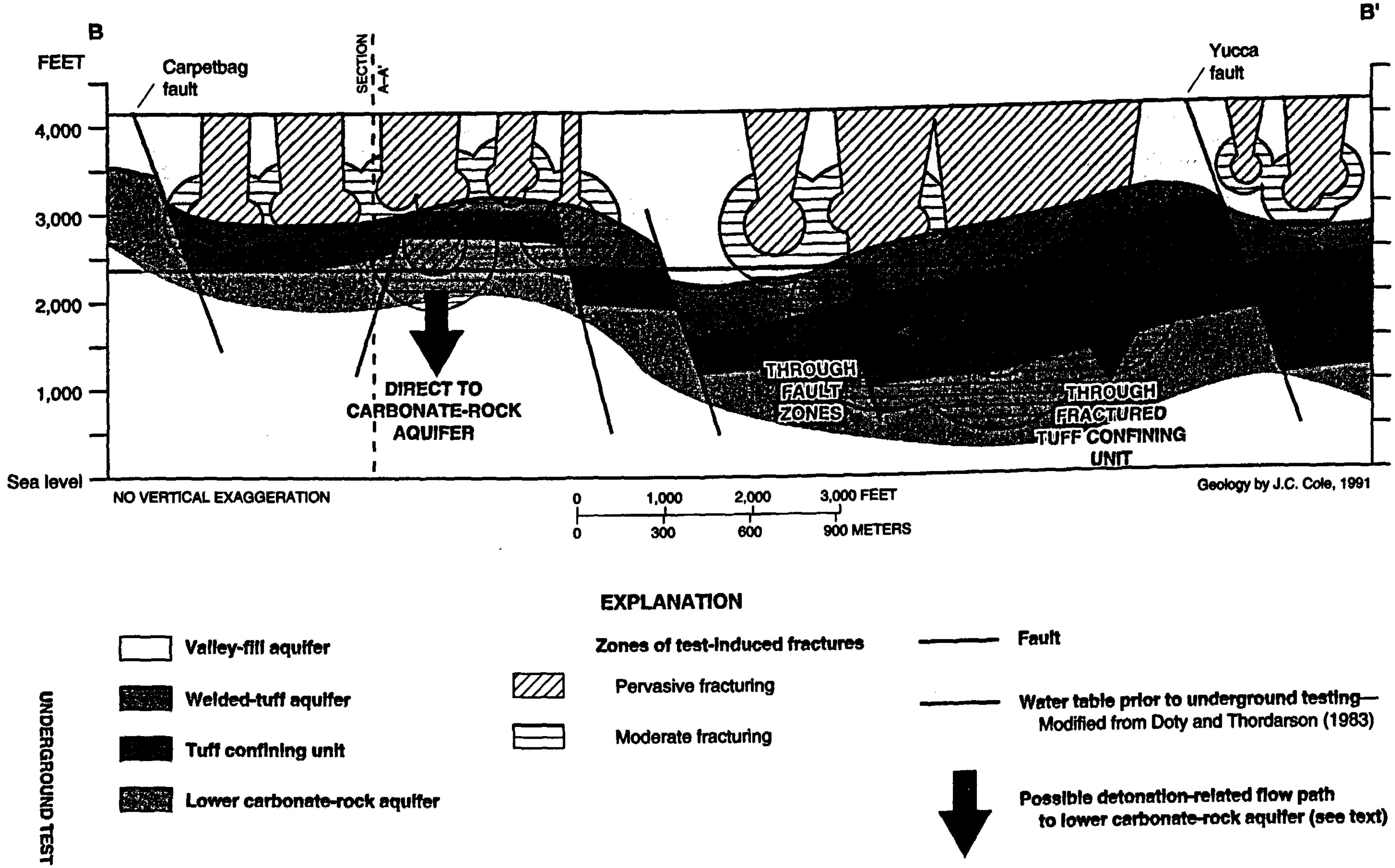


Figure 8. Continued.

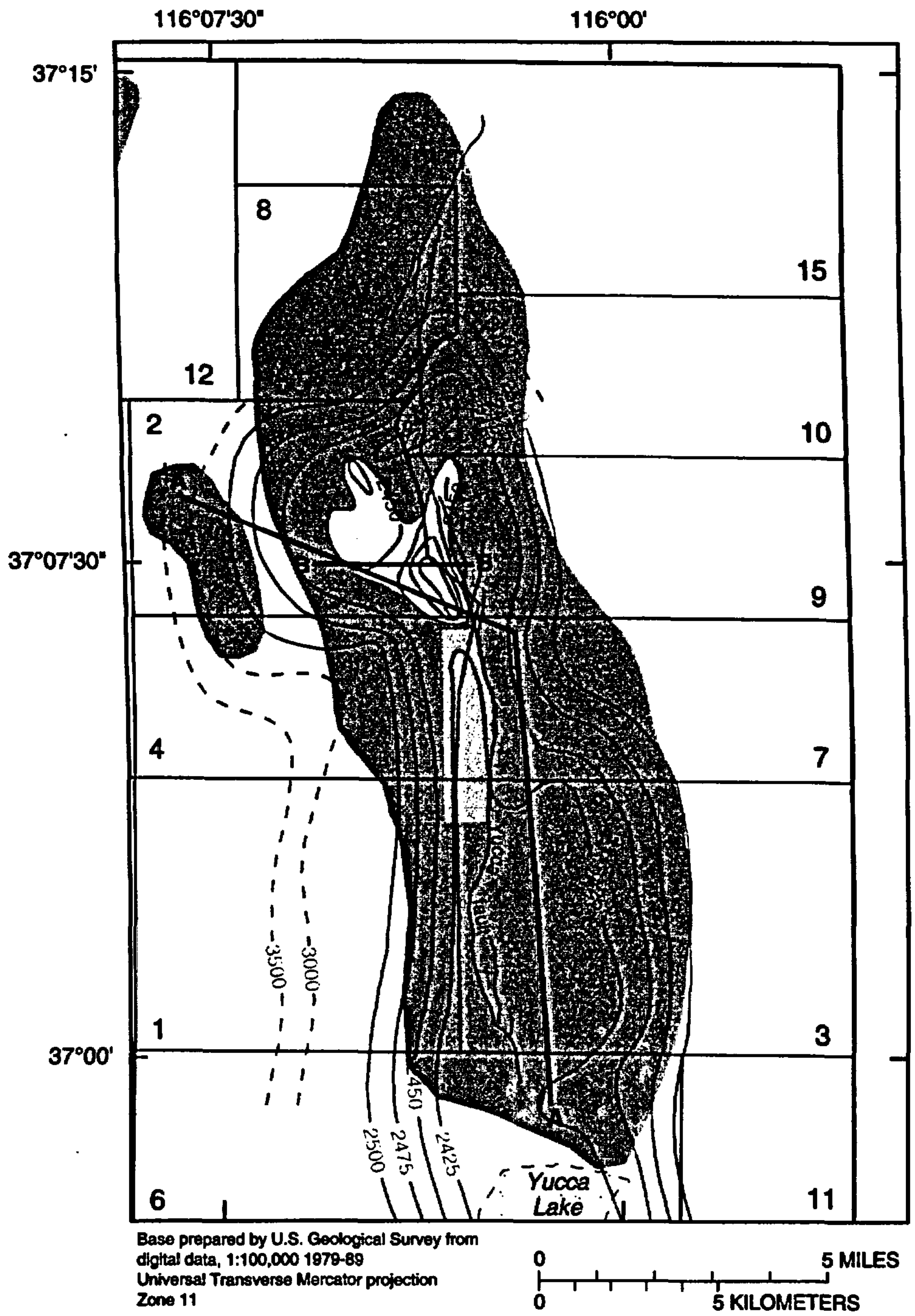


Figure 9. General areas within Yucca Flat where sustained, local hydrologic effects may have resulted from underground testing.

EXPLANATION

(dark shaded box)	**Approximate area used for underground testing**
(open box)	**Area of water-table mounding**–Approximate area where water table is mounded in measured wells. Modified from Hoover and Trudeau (1988, p. 366 and fig.1)
(stippled box)	**Area of increased hydraulic pressure**–Approximate area where water levels measured in tuff confining unit are higher than measured water table. Modified from Hawkins and others (1987)
(solid and dashed lines)	**Water-table contour**–Shows altitude of water table. Contour intervals 25 feet (solid line) and 500 feet (dashed line). Datum is sea level. Modified from Doty and Thordarson (1983)
B——B'	**Line of section**–Sections are shown in figure 8
(line)	**Nevada Test Site boundary**
8	**Area boundary within Test Site**–Area number is indicated

Figure 9. Continued.

determine their effects on contaminant transport. Chimneys that form above Rainier Mesa tests generally do not collapse to the ground surface, and contrary to conditions on Yucca Flat, few subsidence craters exist to create potential conduits for the downward infiltration of ponded surface runoff.

SUMMARY AND CONSIDERATIONS FOR ENVIRONMENTAL RESTORATION

Underground testing of nuclear weapons at the Nevada Test Site has introduced significant quantities of radioactive and chemical contaminants into the ground-water flow system of southern Nevada. These contaminants are distributed over a large area and a wide range of depths and in hydrogeologic environments that are variable and complex. Ground-water flow is the primary mechanism by which contaminants can be transported away from the underground test areas into a more accessible environment (areas of spring discharge and ground-water withdrawal) within and outside NTS boundaries. Therefore, any assessment of risk to human health or environmental quality resulting from exposures to test-generated contaminants must rely on quantitative knowledge of the ground-water flow system and the processes controlling contaminant transport.

This review and summary of existing information expands the regional and local hydrogeologic concepts established by previous investigators. NTS is centrally located in the regional Death Valley ground-water flow system. Ground water generally flows southward across southern Nevada to discharge areas primarily west and southwest of NTS. Most ground water originates from precipitation falling on the mountainous areas of central Nevada and to a lesser degree on higher mesas and mountain ranges along downgradient flow paths. Relative to NTS, ground water enters laterally across the northern and eastern boundaries of the site, and vertically beneath areas of higher elevation. Ground water leaves the NTS primarily across its southern and southwestern boundaries, ultimately reaching an intermediate discharge area or Death Valley, where it is released as springflow or is evaporated or transpired, unless otherwise removed by local pumping.

Ground water at NTS is thought to flow within one of three discrete ground-water subbasins. The western Oasis Valley subbasin, although not well studied, conveys ground water southward across the extreme northwest part of NTS through welded-tuff and lava-flow aquifers into Oasis Valley, where it is discharged by numerous springs and seeps and a few water supply wells. The central Alkali Flat-Furnace Creek Ranch subbasin, which includes most of Pahute Mesa test area, contains the rest of the western half of NTS. Ground water flows southward, first traversing complex, nested volcanic caldera structures that contain hydrologically diverse lavas, welded tuff, and bedded tuff, and later passes through alluvium and carbonate rock before discharging at Alkali Flat or the Furnace Creek Ranch area of Death Valley. The eastern Ash Meadows subbasin encompasses much of the eastern half of NTS, and includes the Yucca Flat and Frenchman Flat test areas. Ground water is conveyed primarily through the lower carbonate-rock aquifer, which is recharged locally from overlying alluvial and volcanic deposits that fill major valleys, and discharges primarily along a line of springs in Ash Meadows.

The boundaries between these subbasins are not well defined and are the subject of considerable scientific debate. Water budgets for individual subbasins have been derived from simple calculations based on regional estimates of recharge and discharge. Ground-water flow rates have been estimated on the basis of a few quantitative measurements, limited chemical and isotopic investigations, and a few model calculations, all which depend on regional assumptions about the flow processes. Porous (matrix) flow through quartzite, shale, and zeolitically altered tuff has been determined to be quite slow (less than 0.1 ft/d), whereas flow rates through fractured carbonate rock have been measured to be several orders of magnitude higher (hundreds of feet per day). Most flow is assumed to occur through fractures and fault zones, but few systematic studies have been completed to understand or quantify this process.

The geology of the Death Valley ground-water flow system, and in particular the NTS region, is complicated by the overlapping effects of major structural events. The Eocambrian and Paleozoic bedrock of the region, consisting of a thick lower quartzite unit, a middle limestone and dolomite unit, and an upper siltstone, conglomerate, and shale unit of Mississippian age, were folded and thrust toward the east and southeast during Mesozoic time and locally thrust westward as well. Subsequent extensional deformation on low angle faults and erosion produced a complex distribution of rock units during the Tertiary period. Middle Miocene time was heralded by major rhyolitic eruptions from the earliest calderas of the southwest Nevada volcanic field that buried the pre-existing topographic surface formed on the Paleozoic rocks. Volcanic eruptions continued over a period of about 8 million years from several nested calderas beneath the Pahute Mesa and Timber Mountain areas, and led to the accumulation of many thousands of feet of varied rhyolitic deposits covering a Paleozoic basement. During and following this period of extremely active volcanism, the NTS region has been intermittently extended by slip on low-angle normal faults. Deep alluvial basins formed in the areas of greatest extension and filled with eroded debris from surrounding fault blocks. The geology within major areas of testing is well known as an outgrowth of drilling and investigations related to the underground testing program, but is considerably less clear beneath and beyond specific areas of testing.

Expanding the current understanding of geology and hydrology in individual underground test areas requires a knowledge of processes and parameters at a more detailed scale than used to describe regional ground-water flow. This more local scale is particularly relevant in assessing the potential for contaminant migration because so many of the critical hydrogeologic factors are characterized by heterogeneities over distances of a few feet to a few miles. Ground-water flow is influenced by lithologic discontinuities (resulting from depositional facies, lithification, alteration, and others) and hydrologic parameters (local recharge, discharge, pumping, and aquifer geometry, among others) that can be quite diverse over a testing area or even at the scale of an individual drill hole. In addition, mechanical, chemical, and hydrologic effects of a nuclear detonation, which determine the initial distribution of contaminants and alter the geologic environment as well as local hydrologic conditions, also make this scale particularly relevant.

Most underground testing at NTS was done in two distinct geologic and hydrologic environments. The Yucca Flat and Frenchman Flat test areas lie within the Ash Meadows ground-water subbasin where most tests were detonated in alluvium and volcanic rock overlying the regional carbonate-rock aquifer. In the Pahute Mesa and Rainier Mesa areas, where the definition of effective aquifers are poorly understood and the downgradient pathways are uncertain, tests were detonated in thick, highly varied volcanic rocks. Tests detonated in tunnels at Rainier Mesa and at some of the smaller test areas were all essentially in unsaturated rock, and are secondary in terms of ground-water contamination and potential offsite migration, except possibly in areas of local recharge where test-generated contaminants could be transported into the ground-water flow system through the unsaturated zone by downward percolating water.

Yucca Flat has been the location for about 80 percent of the underground tests, although two-thirds were relatively small in yield and detonated above the water table. The remaining third were detonated near and below the water table primarily in bedded tuff east of the Carpetbag fault in the eastern part of the west-tilted Yucca Flat structural basin. The lower carbonate-rock aquifer lies below these tuff units and forms the primary conduit by which water can leave the basin. Ground water flowing within the lower carbonate-rock aquifer is constrained on the east by a regional southwest hydraulic gradient and on the west and north by the low permeability rocks. Thus, ground water flows southward into Frenchman Flat, ultimately reaching a downgradient discharge area, probably Ash Meadows. The lower carbonate-rock aquifer receives local recharge across the overlying tuff units, most of which have been altered to zeolites and therefore do not transmit water readily, except possibly along fault zones. Other than a few tests that were detonated within the lower carbonate-rock aquifer, available data are insufficient to asses the extent of test-generated contaminants migrating downward through the tuff units into the underlying lower carbonate-rock aquifer.

Pahute Mesa has been the location for 85 tests, 77 of which were detonated near or below the water table. The mesa provided sites for the deepest and largest yield tests and contains about two-thirds of the total nuclear yield generated by the testing program. The subsurface hydrologic environment at Pahute Mesa is complex because water moves primarily through fractures in discontinuous lava-flow and welded-tuff aquifers that are embedded in the tuff confining unit and are offset and broken by caldera forming and younger high-angle faults. Ground water generally flows across the test area under the influence of a south-southwest hydraulic gradient away from recharge areas in the eastern and northern parts of Pahute Mesa, and exits across the southern margins of the test area. All but a few tests in the extreme western area of testing were detonated within the Silent Canyon caldera complex. This region outside the caldera complex is characterized by higher water levels that form a local discontinuity in the hydraulic gradient that is approximately coincident with the boundary of the Oasis Valley subbasin and the buried structural margin of the Silent Canyon caldera complex. The specific cause, exact location, and the full areal extent of the hydrologic discontinuity is unknown because of a lack of drill-hole control outside the test area and because of younger, flat-lying volcanic deposits that obscure the geology that controls ground-water flow to downgradient discharge areas.

A review of existing literature indicates that the mechanical, thermal, and hydrologic effects of underground nuclear detonations are only known in broad general terms and have been studied only for a few small-yield explosions. The explosion produces a roughly spherical cavity of vaporized rock and test debris, and a surrounding zone of crushed and fractured rock that may contain injected contaminants out to a distance of about five cavity radii. Initially, ground water is expelled from the explosion zone causing a local annular rise in the water table around the explosion area. The rise eventually dissipates as ground water flows outward and inward to near equilibrium levels. Long-term hydrologic effects, such as sustained pressurized zones with confining units, have been noted, particularly in Yucca Flat. In the north-central part of the Yucca Flat basin, the water table has been elevated; farther south, hydraulic pressures within the tuff confining units are unusually high. Few systematic studies have been made of the extent of fracturing around cavity zones, the changes in rock permeability, the distribution of radionuclide and chemical contaminants, hydrologic effects of the collapsed chimney, or the thermal effects of underground detonations.

The preceding discussion summarizes what is known and inferred about the ground-water flow system at NTS and identify many elements that are little known and those properties that lack precise measurement. The objective of the USDOE Environmental Restoration Program is not to eliminate every hydrogeologic uncertainty, but rather to acquire sufficient knowledge from which to develop and implement efficient and cost-effective strategies for remediation (U.S. Department of Energy, 1990b, p. 10-17). Much of this knowledge would be acquired during the early characterization phases of the program. The following discussion highlights some of the hydrogeologic uncertainties discussed in the report and is intended to help prioritize investigations that would best characterize the ground-water flow system.

Important factors in developing a strategy to remediate contaminated ground water include knowledge of (1) the contaminant sources in terms of substances, quantities, distribution, and physical-chemical conditions; (2) the flow paths between contaminant sources and potential points of biological exposure; (3) the rate of ground-water flow; and (4) other processes controlling the fate and transport of contaminants along these flow paths. Contaminants at NTS have been introduced over large areas and at various depths, and the flow paths between contaminant sources and potential receptor populations span great distances. A strategy for remediating these contaminants, whether by removal, containment, treatment, or monitoring, would be enhanced by refining the current understanding of ground-water flow through this vast and hydrogeologically complex region. Uncertainties in the current understanding of the subsurface geology and hydrology are many, and many of the technical issues associated with resolving these uncertainties are complex.

Pioneering work throughout the 1960's and 1970's provides a substantial base from which to begin ground-water characterization. These early efforts, along with more recent investigations, have identified many of the regional controls on ground-water flow; including the general areas of recharge and discharge, the principal aquifers and confining units, and the major geologic structures. Although early conceptualizations of ground-water flow, based in part on these regional controls, led to the delineation of ground-water basins and subbasins and a general understanding of ground-water flow directions, many issues still remain unresolved at this broad scale. Those issues most pertinent to the assessment and remediation of NTS have to do with the nature and location of individual subbasin boundaries and the qualitative character of the estimates of flow rates and flow components. The resolution of these issues can be hastened by acquiring a more definitive understanding of the following: discharge at Oasis Valley, Ash Meadows, and Death Valley; recharge in the Pahute Mesa area and at other higher elevation localities; and lateral flow into and across subbasin boundaries. In addition, wells and test holes along with geophysical surveys and geologic mapping would provide geologic and hydrologic information to fill major data gaps, especially in the areas between underground testing and downgradient discharge.

Smaller-scale issues also need to be investigated because system controls are characterized by heterogeneities over distances of a few feet to a few miles. Examples of such issues include the distribution of contaminant sources; the mechanical and hydraulic effects of underground testing; the chemical reactions among the rock, water, and contaminant; and the rock properties that control ground-water flow. These types of spatial variation can result in preferential and locally unique flow paths, and are particularly relevant to assessing risk at NTS where contaminants can be highly toxic and long lived. Smaller scale controls and their effect on directions and rates of ground-water flow need to be understood if estimates of traveltime and concentrations at points of exposure are to be defended against public and regulatory scrutiny. Local-scale controls also are important in locating and constructing monitoring wells and in interpreting data from monitoring wells and other holes drilled in the test areas.

Investigators made some progress in identifying and defining smaller scale controls during the early days of the testing program. During succeeding years, the boundaries of test areas were expanded to accommodate increased activity. As the size and number of test areas grew to include more geologically and hydrologically diverse regions, efforts to collect hydrogeologic data and do supporting science did not keep pace. To fill these critical information gaps in a reasonable amount of time and at a practical cost, some drilling is needed to better identify and constrain principal flow paths away from underground test areas. Subsequent drilling then could be focused primarily on those areas where characterization of smaller scale controls and establishment of long-term monitoring are most critical.

About two-thirds of the test-generated radioactive contaminants have been released into the volcanic aquifers and confining units beneath Pahute Mesa (Bryant and Fabryka-Martin, 1991, table 2), but the present knowledge is insufficient to evaluate the quantity of ground-water flowing southwestward to Oasis Valley, southward beneath Timber Mountain, or southeastward beneath Fortymile Canyon. Oasis Valley, a major area of ground-water discharge, warrants particular attention because of its proximity to past tests at Pahute Mesa (only about 17 mi) and because the major hydrogeologic units and structural controls along flow paths from Pahute Mesa into Oasis Valley are uncertain. Is the limited-flow barrier (apparently coincident with the topographic wall of the Silent Canyon caldera complex in western Area 20) a real hydrologic feature? Is it caused by a specific geologic structure, and does it extend southward into the younger Timber Mountain caldera? What is the hydrologic significance of the Timber Mountain dome? Is it a recharge area, a barrier, or does it constitute a fractured-rock aquifer? What are the hydrologic effects of young, high-angle north-trending faults on ground-water flow? To what depths are flow paths likely to extend beneath and away from contaminated areas? How do fractures control flow rates, directions, and pathways? How are flow paths altered by the discontinuity of volcanic aquifers? What chemical and physical reactions result as a consequence of the heat and energy released by a nuclear detonation? How do these test-induced reactions alter the ground-water flow paths and the transport of test-generated contaminants?

Most tests at NTS have been detonated in valley-fill alluvium and volcanic rocks beneath Yucca Flat (table 4). Although current data indicate that ground water moves downward through these units into the underlying lower carbonate-rock aquifer, southward beneath Frenchman Flat, and then southwestward to a downgradient discharge area (probably Ash Meadows), little is known about the controlling processes. Of the limited number of drill holes open to carbonate rock, only a few penetrate more than a hundred feet into saturated section, and no quantitative studies have assessed the hydraulic connection between the lower carbonate-rock aquifer and overlying saturated units in Yucca and Frenchman Flats. Thus, studies are needed to ascertain where and how fast water moves from areas of testing into the underlying lower carbonate-rock aquifer. Does downward leakage take place primarily along faults, through dispersed fractures, or over the entire area where the carbonate-rock aquifer is confined by overlying units? What is the role of the Carpetbag-Yucca fault system in controlling flow into the carbonate-rock aquifer? How effective are the Eleana Formation and Chainman Shale as a confining unit? Do they form a continuous hydrologic divide between the Ash Meadows and Alkali-Flat Furnace Creek Ranch ground-water subbasins, and do they effectively block downward flow throughout their subsurface extent? Do carbonate rocks beneath the Eleana Formation convey moderate and large quantities of water and are they an active part of the lower carbonate-rock aquifer? If so, does ground water in these rocks flow into Yucca and Frenchman Flats or vice-versa? What is the role of fractures in controlling ground-water flow through carbonate rocks—do they create highly irregular and less predictable flow paths?

At Rainier Mesa and Shoshone Mountain, detonations have been relatively small in yield, and have taken place primarily in volcanic confining units above the water table. Nonetheless, a general understanding of the hydrogeology would permit a clearer assessment of the potential risk. Much less is known about ground-water conditions because few drill holes have reached the water table and even fewer have penetrated any significant thickness of saturated rock. Basic questions remain regarding depth to the water table, configuration of the potentiometric surface, and rocks that make up the flow system beneath these test areas. Specific questions concern the nature and location of the boundary between the Ash Meadows subbasin and the Alkali Flat-Furnace Creek Ranch subbasin in these areas; the hydrologic significance of dolomite beneath the volcanic section and the low-angle faults between dolomite and the Eleana Formation at Rainier Mesa; and the potential for local recharge to transport contaminants downward into the saturated-flow system.

Farther downgradient from the immediate areas of underground testing, ground water and its dissolved contaminants traverse complex and lesser studied geologic terranes. The subsurface geology of the Rock Valley fault system needs further study to establish flow paths between Frenchman Flat and downgradient discharge areas (Ash Meadows and possibly Alkali Flat and Death Valley). Such studies would address the possibility that low hydraulic gradients in this area reflect highly permeable rocks within the carbonate-rock aquifer and the likelihood of channeled flow, as was proposed by Winograd and Pearson (1976).

Several questions concerning the effects of nuclear tests on the movement of ground water and contaminant also seem worthy of investigation. How and for how long does a nuclear test affect water levels? What is the distribution of radioactive substances around the point of detonation, and what processes control the initial distribution of refractory and volatile substances? What is the post-shot distribution of fractures, and what is the permeability of fractured rock around the detonation point and in the chimney? What are the cumulative hydrologic, mechanical, thermal, and chemical effects that arise from multiple nuclear tests detonated in close proximity, and how might multiple events alter the distribution and accessibility of radionuclides to ground water? What are the thermal and mechanical effects near the point of nuclear detonation and how do they alter the ability of the rock to retain or transmit contaminants? To what extent does circulating hot ground water (resulting from the underground test) act to redistribute radionuclides in the subsurface?

The contaminant sources at NTS are large and distributed over considerable volumes of diverse and complex rock assemblages. Because any risk to human health or environmental quality depends on knowledge of how and where these contaminants migrate, the definition and quantification of ground-water flow away from the areas of testing are of importance. A cost-effective approach would be first to identify the major ground-water controls and to identify and explore the principal aquifers and confining units. Once constrained by adequate data, more complicated and expensive well designs could be used to determine heads within and between individual aquifers, quantify aquifer and confining-unit properties, and explore the interconnections of aquifers along the principal flow paths, specifically in those areas where detailed characterization is most critical. This staged approach also would expedite selection and help minimize the number of sites that would be necessary for long-term monitoring or that may be needed to support the selection and implementation of a remedial strategy.

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