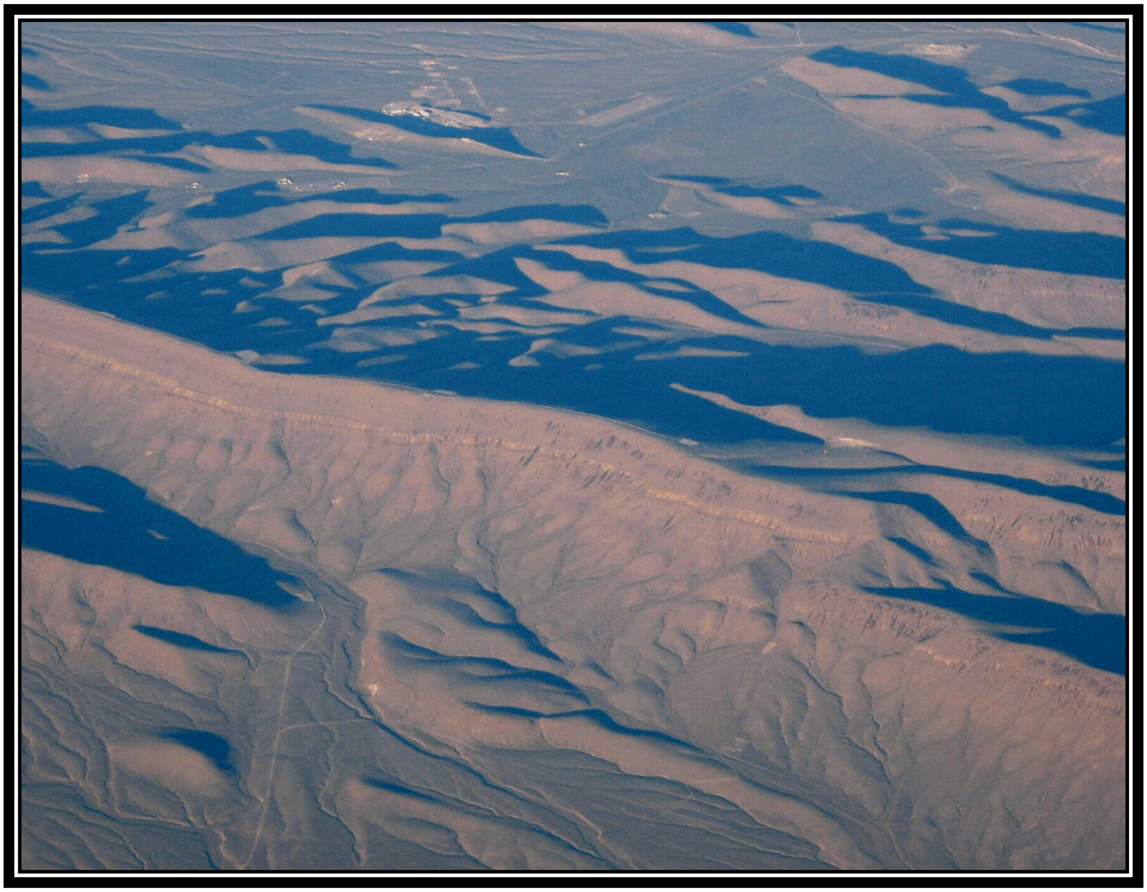
YUCCA MOUNTAIN REGION FIELD GUIDE



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Prepared by

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San Antonio, Texas

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Corrected Copy

Simplified Stratigraphic Column for Yucca Mountain

- Younger Alluvium
- Miocene Tuffs
  - Timber Mountain Group
  - Paintbrush Group
    - Tiva Canyon Tuff (Stop 2-2)
    - *Yucca Mountain Tuff*
    - *Pah Canyon Tuff*
    - Topopah Spring Tuff
      - Crystal-Rich Member
      - Crystal-Poor Member
        - Lithic Rich Zone
        - **Upper Lithophysal Zone**
        - **Middle Non-Lithophysal Zone** (Stop 2-1)
        - **Lower Lithophysal Zone**
        - **Lower Non-Lithophysal Zone**
        - Vitric Zone
  - Calico Hills Formation
  - Crater Flat Group
    - Prow Pass Tuff
    - Bullfrog Tuff (Stop 1-8)
    - Tram Tuff
  - Older Tuffs
- Older Alluvium
- Paleozoic Sedimentary Rocks
  - Regional Carbonate Aquifer (Stop 1-3)
  - Lower Clastic Aquitard (Stop 1-4)
- Older Precambrian Rocks (Stop 3-8)

Tuffs shown in italics and adjacent nonwelded tuffs in the overlying and underlying tuffs compose the PTn.

Zones shown in bold compose the Repository Host Horizon.

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ACKNOWLEDGMENTS AND DISCLAIMER

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–07–006. The activities reported here were performed on behalf of the USNRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. This report is an independent product of the CNWRA and does not necessarily reflect the view or regulatory position of the NRC. The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of a license application for a geologic repository at Yucca Mountain.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No original data were generated for this report. All CNWRA-generated data contained or referenced in this report meet quality assurance requirements described in the Geosciences and Engineering Division Quality Assurance Manual. Sources of other data should be consulted for determining the level of quality of those data.

ANALYSES AND CODES: None.

COVER PHOTOGRAPH: Cover photograph is a northeast view of Yucca Mountain, as seen from approximately 10,700 m [35,000 ft] on December 18, 2006, about 5:30 p.m. PST. Yucca Mountain is the highlighted ridge crossing the central part of the photograph. The surface facilities are visible on the east side of Exile Hill near the top of the photograph. Trench 14 (Stop 2-4) is on the west side of Exile Hill.

GENERAL INFORMATION

This field guide and trip are designed to provide U.S. Nuclear Regulatory Commission (NRC) and Center for Nuclear Waste Regulatory Analyses (CNWRA®) staffs with general background information on the geology, geophysics, hydrology, and cultural setting of the Yucca Mountain region and to familiarize them with the Nevada Test Site. The trip is designed to be covered in three days. Day 1 explores the geology along the US 95 corridor. Day 2 covers stops on the Nevada Test Site and in the Yucca Mountain Region and requires coordination and consultation with the U.S. Department of Energy. On Day 3, the hydrology and geology from south of Yucca Mountain to Death Valley and Pahrump, Nevada, are covered. To provide flexibility on future trips, the latitude and longitude of each stop are included and the route and stops as described in this guidebook are shown on Plate 1. The reference datum for the latitude and longitude provided in the road log and figures is the World Geographic System 1984 (NAD83).

Stops are indicated by two numbers (e.g., Stop 1-1). The first number refers to the day. The second number refers to a specific stop for that day. Stops and points of interest are also located by mileage from easy-to-find starting points. Mileage between stops is shown to the left of the forward slash, and cumulative mileage to each stop is to the right of the forward slash. To reduce cumulative mileage errors and permit flexibility on future trips, there are separate start points for the morning and afternoon of each day. All mileages were determined using Google Earth™ and spot checked on several trips.

Directions to points of interest described during the driving portion of the trip are referenced in the following manner. The forward direction of travel always corresponds to the 12:00 position on a clock. Features at 90° to the right are described as being at 3:00, while those at 9:00 would be at 90° to the left.

Conversions used in this guide are

1 foot	=	0.3048 meter
1 mile	=	1.6093 kilometer
1 meter	=	3.2808 feet
1 kilometer	=	0.6214 mile

The glossary follows the Day 3 section. Words included in the glossary are underlined and in bold at their first occurrence in the text. Where there are two bold words, the underlining indicates whether to look for one term (a continuous line) or two terms (a broken line).

INTRODUCTION TO THE GEOLOGY AND HYDROLOGY OF YUCCA MOUNTAIN REGION

This section contains background information on the **geology** and **hydrology** of the region at and around the potential **high-level waste** **repository** at Yucca Mountain, Nevada (Plate 1), allowing more focused and informative discussions at field trip stops.

Regional Stratigraphy

The oldest **rocks** in the region are Mesoproterozoic (Table 0-1) in age. These 1.7–1.3 billion-year-old rocks (U.S. Geological Survey, 2004) are exposed mainly in the southern Death Valley region (Stop 3-8). They consist of medium- to high-grade **metamorphic rocks** intruded by **plutonic** **igneous rocks** and represent the geologic **basement** of the region. Because of their low **permeability**, they also are part of the **hydrologic** basement, although when **fractured**, they can be highly permeable. Overlying the basement complex are Neoproterozoic (Table 0-1) and early Paleozoic (Cambrian) (Table 0-1) **sedimentary rock** (i.e., **sandstones**, **siltstones**, and **shales**) and their low-grade metamorphic equivalents [i.e., **quartzites** (Stop 1-4) and **schists**]. In addition, there are secondary amounts of **carbonate** rocks, including **dolomite (dolostone)**, **limestone** (Stop 1-3), and **marble**. Like the older rocks, the early Paleozoic and Neoproterozoic **clastic** rocks have low permeability. These rocks, combined with the Mesoproterozoic basement, are the base of the regional hydrologic flow, often referred to as the lower clastic **aquitard** (LCA) (Table 0-2) (Stop 1-4) (Winograd and Thordarson, 1975).

The Neoproterozoic and early Cambrian (Table 0-1) rocks formed from clastic **sediments** deposited in a shallow sea along a **passive continental margin**, somewhat analogous to the current eastern margin of North America. The actual margin was west of the geographic area covered in this guide. The source of the sediments was to the east in what is now eastern Nevada and Utah. In the middle Cambrian, the **sedimentation** in the region became predominantly carbonate (Stop 1-3). Today these carbonate sediments are represented by a thick sequence of limestones and dolomites. The carbonate sedimentation extended until the Permian Period (Table 0-1)—an interval of about 272 million years. The Paleozoic Era (Table 0-1) sediments accumulated in a slowly subsiding shallow **marine** environment that extended from east of Las Vegas, Nevada, to west of Death Valley, California. Occasional thin **formations** of clastic rocks occur within the carbonate sequence (Table 0-2). An exception is a thick accumulation of Devonian to Mississippian (Table 0-1) clastic sedimentary rocks (i.e., the Eleana Formation, Table 0-2) that extends from northern Yucca Flat (Stop 2-7) southwest to beneath the Calico Hills (Stop 2-2). The source area of these rocks was north and northwest of the region; they are absent to the south of Yucca Mountain. The Regional Paleozoic **Stratigraphy** is discussed at Stop 1-1.

The Eleana Formation rocks are often referred to as the upper clastic aquitard (Table 0-2) on the Nevada Test Site, with the relatively thinner section of carbonate rocks above them referred to as the upper carbonate **aquifer**. To the south and east, beyond the limit of the Eleana Formation, the total carbonate rock package is referred to as the Regional Carbonate Aquifer (Table 0-2).

Sedimentary Mesozoic (Table 0-1) rocks are absent in the area covered by this field guide. They do occur in the southern Spring Mountains west of Las Vegas, where they are predominantly **continental** clastic rocks. However, in the region covered on this field trip, the Mesozoic Era is represented by the 101-million-year-old Climax **stock** (Stop 2-6) and some nearby smaller **granitic** **intrusions** at and near the north end of Yucca Flat.

Table 0-1. Geological time

Eons	Eras	Periods Epochs
Phanerozoic (542 mya*–present)	**Cenozoic** (65 mya–present)	Quaternary (2.0 mya–today) Holocene (10,000 yrs–today) Pleistocene (2.0 mya–10,000 yrs)† Tertiary (65–2.0 mya) Pliocene (5.3–1.8 mya) Miocene (23.8–5.3 mya) Oligocene (33.7–23.8 mya) Eocene (54.8–33.7 mya) Paleocene (65–54.8 mya)
	Mesozoic (251–65 mya)	Cretaceous (144–65 mya) Jurassic (206–144 mya) Triassic (248–206 mya)
	Paleozoic (542–251 mya)	Permian (290–248 mya) Pennsylvanian (323–290 mya) Mississippian (354–323 mya) Devonian (417–354 mya) Silurian (443–417 mya) Ordovician (490–443 mya) Cambrian (543–490 mya)
Precambrian (4,500–542 mya)	**Proterozoic** (2,500–542 mya)	Neoproterozoic (900–543 mya) Mesoproterozoic (1,600–900 mya) Paleoproterozoic (2,500–1,600 mya)
	Archaean (3,800–2,500 mya)	
	Hadean (4,500–3,800 mya) (NOTE: Age of Earth estimated to be 4,500 mya)	

*mya = million years ago

†Geologists consider the Pleistocene Epoch to extend from 1.8 mya to 10,000 years ago. For regulatory purposes, the U.S. Nuclear Regulatory Commission considers the Pleistocene Epoch to start at 2 mya.

Table 0-2. Generalized stratigraphic column for Yucca Mountain region

Rocks Exposed in Southwestern Nevada*

	Age†	**Unit**	**Approx. Thickness (m)**	**Lithology**	**Informal Hydrologic Designation**
	Cenozoic to **Holocene** Clastic rocks	Alluvium and colluvium	Variable	Predominantly sand and gravel	Unconfined or Valley Fill aquifers
	Miocene	Tuffs and lavas of the Southwestern Nevada Volcanic field (See Table 0-3)	Variable	Ash flow, ash fall, bedded and reworked tuffs and lavas, basaltic cinder cones	Contains both aquifer and aquitards
	Cretaceous	Climax stock	---	Granodiorite and quartz monzonite	Intrusive aquitard‡
Paleozoic	Permian and Pennsylvanian	Tippipah Limestone/ Bird Spring Formation	1,100	Limestone	Upper Carbonate Aquifer‡
	Mississippian and Devonian	Eleana Formation	2,320	Argillite Quartzite	Upper Clastic Aquitard‡
		(Monte Cristo Limestone)	---	Limestone	Regional Carbonate Aquifer or Lower Carbonate Aquifer (when Eleana Formation is present)
	Devonian	Devils Gate Limestone	420	Limestone	
		Nevada Formation (Sultan Limestone)	465	Dolomite	
			---	Limestone	
	Devonian and Silurian	Dolomite of Spotted Range	430	Dolomite	
	Ordovician	Ely Springs Dolomite	93	Dolomite	
		Eureka Quartzite	104	Quartzite	
		Pogonip Group:			
		Antelope Valley Limestone	466	Limestone	
		Ninemile Formation	102	Siltstone	
		Goodwin Limestone	290	Limestone	
	Cambrian	Nopah Formation	565	Limestone, dolomite	
		Dunderberg Shale Member	49	Shale	
		Bonanza King Formation	1,400	Limestone, dolomite	
		Carrara Formation	710	Limestone/shale and siltstone	
		Zabriskie Quartzite	67	Quartzite	Lower Clastic Aquitard
		Wood Canyon Formation	695	Quartzite, siltstone	
Precambrian	Neoproterozoic	Stirling Quartzite	915	Quartzite	
		Johnnie Formation (base not exposed)	915	Quartzite, limestone, dolomite	
	TOTAL THICKNESS		11,000+		

* Orkild, P.P. "Geology of the Nevada Test Site." Proceedings of the First Symposium on Containment of Underground Nuclear Explosions, Monterey, California, August 26–28, 1981. B.C. Hudson, E.M. Jones, C.E. Keller, and C.W. Smith, compilers. Report LA–9211–C. Los Alamos, New Mexico: Los Alamos National Laboratory. pp. 323–338. 1981.

†See Table 0-1

‡Not present at Yucca Mountain, Nevada.

The oldest Tertiary rocks (Table 0-1) are **conglomerates** and sandstones interbedded with **lacustrine** limestones. Stratigraphically (see **stratigraphic**), they rest **unconformably** on the older Paleozoic rocks and below the Miocene (Table 0-1) **volcanic** rocks. These Tertiary sedimentary rocks are Eocene (Gutenkunst, et al., 2005) and younger and indicate **deposition** in a continental **basin** or basins (Stops 2-9 and 3-1). These rocks extend east-to-west from Frenchman Flat (Stop 2-9) to the Grapevine Mountains (Plate 1) in northern Death Valley and as far south as the Death Valley Junction, California, area (Stop 3-1). North of Frenchman Flat in and around Yucca Flat, these rocks are absent. There the stratigraphic interval is represented by a thin {<61-m [<200-ft]} layer or **bed** of **colluvium** composed of weathered (see **weathering**) Paleozoic rocks with an increasing admixture of volcanic **ash** in the upper part of the colluvium. The northern basin boundary was probably in northern Frenchman Flat, where a **gravity-inferred depth-to-basement map** shows a steep gradient shallowing to the north (Phelps and Graham, 2002).

About 15.25 million years ago (mya) (Sawyer, et al., 1994) (Table 0-3), the first of a series of large-size **volcanoes** erupted in the Yucca Mountain region. The eruption and deposition of **silicic** **tuffs** from volcanoes located from a few kilometers to about 50 km [31 mi] north of Yucca Mountain lasted from 15.25 to <9.4 mya (Sawyer, et al., 1994). Also during and following this period of large volcanic eruptions, smaller-size volcanoes sporadically erupted **basalt** in the region surrounding Yucca Mountain.

Continental clastic sedimentation continued during and after the period of extensive volcanism. These clastic rocks formed predominantly by growth of **alluvial fans** (Stop 1-1) from the mouths of canyons emerging from upland areas and **sheet wash** (Stop 2-1) off the slopes of the surrounding ranges, as well as small amounts of ash from distant volcanic eruptions. The thickness of the basin fill ranges from 0 m [0 ft] at basin margins to >600 m [>2,000 ft] in the deeper parts of some basins. Alluvial fans (Stop 3-8) are still forming through the Yucca Mountain region.

Regional Structure and Tectonics

The regional structural geology and **tectonic** setting is the result of numerous periods (Table 0-4) and styles of **deformation**. Ignoring the deformation prior to 900 mya and starting with deformation occurring in the Neoproterozoic or early Cambrian, the earlier **Rodinia** continent was rifted (see **rift**) apart (Table 0-4). The rifted margin was west of the Yucca Mountain Region. To the west of the rift margin was **oceanic crust** and to the east **continental crust**. On the continental crust, a passive continental margin, similar to the present-day east coast of North America, developed. As noted previously, carbonate sediments accumulated on a slowly subsiding **continental margin** from the Cambrian through the Permian periods. This shallow marine basin is now represented in the Yucca Mountain region by the carbonate rocks described previously. The first deformation that was influential in the Yucca Mountain region is recognized to the north and northwest of the region as the Devonian Antler **Orogeny** (Table 0-4). Although the Antler Orogeny deformation occurred well to the north and northwest, it is represented in the Yucca Mountain region by the Devonian-Mississippian Eleana Formation (Table 0-2; Stop 2-7), which formed from the sediments that were shed south and southeast of the Antler Mountains in what is now north central Nevada.

Table 0-3. Volcanic stratigraphy of the southern Nevada volcanic field			
Principal Cenozoic Volcanic and Sedimentary Units*†			
Unit	**Inferred Volcanic Center**	**General Composition**	**Approx. Age (mya‡)**
Alluvium	N/A	Mixed	0–6
Younger Basalts	Numerous	Basalt (hawaiite)	0.3–7
Thirsty Canyon Tuff	Black Mountain Caldera	Trachytic soda rhyolite	7–9
Rhyolite of Shoshone Mountain	Shoshone Mountain	High-silica rhyolite	9
Basalt of Skull Mountain, Basalt of EMAD	Jackass Flat (?)	Quartz-bearing basaltic andesite	10
Timber Mountain Group Intracaldera ash flow tuffs Ammonia Tanks Member Rainier Mesa Member	Timber Mountain Caldera	Rhyolite to quartz latite	12.5–11.45
Paintbrush Group Intracaldera ash flow tuffs Tiva Canyon Member Yucca Mountain Member Pah Canyon Member Topopah Spring Member	Claim Canyon Caldera	Rhyolite to quartz latite	12.7–12.8
Calico Hills Tuff	Claim Canyon Caldera	Tuffs and lava (often zeolitized)	12.9
Wahmonie and Salyer Formations	Wahmonie-Salyer Center	Dacitic tuffs and lavas	13
Crater Flat Group (coeval with Tuffs of Area 20) Prow Pass Member Bullfrog Member Tram Member	Uncertain	Rhyolite	13.25
Stockade Wash Tuff (Coeval with Crater Flat Tuff)	Area 20 Caldera	Rhyolite	14
Belted Range Tuff Grouse Canyon Member Tub Spring Member	Grouse Canyon Caldera	Rhyolite	13.5–13.7
Tuff of Yucca Flat	Uncertain	Rhyolite	15.1
Redrock Valley Tuff	Uncertain	Rhyolite	15.25
Rocks of Pavit Spring (underlies Crater Flat Tuff)	N/A	Continental sedimentary rocks, lacustrine limestone, and tuffaceous sediments	14–?
Horse Spring Formation	N/A	Mostly sediments	30
*Orkild, P.P. "Geology of the Nevada Test Site." Proceedings of the First Symposium on Containment of Underground Nuclear Explosions, Monterey, California, August 26–28, 1981. B.C. Hudson, E.M. Jones, C.E. Keller, and C.W. Smith, compilers. Report LA–9211–C. Los Alamos, New Mexico: Los Alamos National Laboratory. pp. 323–338. 1981. †Sawyer, D.A., R.J. Fleck, M.A. Lanphere, R.G. Warren, D.E. Broxton, and M.R. Hudson. "Episodic Caldera Volcanism In the Miocene Southwestern Nevada Volcanic Field: Revised Stratigraphic Framework, 40Ar/39Ar Geochronology, and Implications for Magmatism and Extension." *Geological Society of America Bulletin*. Vol. 106. pp. 1,304–1,318. 1994. ‡ mya = million years ago			

Table 0-4. Major periods of deformation in the western United States

Name	Style of Deformation	Duration	Location Relative to Yucca Mountain Region
Eastern California **Shear**	Transtensional (Shear)	<5 mya*	West
Basin and Range Extension	Extensional (Rifting)	<17 mya	At and to North and East
Laramide Orogeny	Compressional	70–40 mya	Mostly to East
Sevier Orogeny	Compressional	140–50 mya	In Yucca Mountain Region
Nevadan Orogeny	Compressional	180–146 mya	Mostly to West
Sonoma Orogeny	Compressional	270–240 mya	Northwest
Antler Orogeny	Compressional	375–300 mya	To North and Northwest
Rodinia Breakup	Extensional (Rifting)	~750–850 mya	West

*mya = million years ago

The Permian–Triassic Sonoma and Jurassic Nevadan orogenies (Table 0-4) occurred west of the Yucca Mountain region and had little effect on the region. **Compressional deformation** (see deformation) during the Sevier Orogeny (140 to 50 mya) resulted in the development of **folds** (Stop 1-5) and **thrust faults** (see **fault**) (Stop 1-1, 3-12) in the Paleozoic marine rocks across southern and central Nevada.

Following the Sevier Orogeny, the Laramide Orogeny occurred to the east and had little effect on the Yucca Mountain area. Starting about 35 mya, the Yucca Mountain Region began to undergo extensional deformation. The initial **extensional** deformation (see deformation) is indicated by the deposition of early Tertiary (Table 0-1) continental sediments, sandstones, and conglomerates (Stops 1-6, 2-9, and 3-1) and lacustrine limestones in basins developed on continental North America. An example of such continental rocks occurs along the south edge of Frenchman Flat (Murray, et al., 2002, 2003) north of Mercury, Nevada.

The north-northeast-trending **Basin and Range** extension **faulting**, whichinitiated about 17 mya (Stewart, 1978) (Stop 1-2), coincided with this period of extensive volcanism in the region (Table 0-3) (Stop 1-8).

To the west of Yucca Mountain and perhaps (Wernicke, et al., 2004) influencing the tectonic setting of Yucca Mountain is an area of **transtensional** deformation (see deformation) (Stop 3-8) represented by the eastern California **Shear Zone**. This deformation was initiated about 5 mya in the central Death Valley area.

Regional Volcanology

Nevada has been the site of volcanism since approximately 42 mya (McKee and Moring, 1996). Volcanism started in northeastern Nevada and progressed southwestward, reaching the southwest Nevada volcanic field (i.e., Yucca Mountain region) about 16 mya (Sawyer, et al., 1994). In the Yucca Mountain Region, there are two types of volcanic rocks. Each type provides important considerations for the potential repository at Yucca Mountain. The output from large silicic volcanoes, also known as **calderas**, provides the host rock for the potential repository (Stops 2-1 through 2-3). The smaller basalt volcanoes, often referred to as **cinder cones** (Stops 1-7, 1-10, and 3-9), are a potentially important consideration in evaluating the long-term safety of the potential repository.

The Miocene volcanic rocks underlying Yucca Mountain were formed by the eruption of several large calderas. The Claim Canyon and Timber Mountain calderas (Table 0-3) were north and northwest of Yucca Mountain (Figure 0-1; Stop 2-2). The **effusive** products of these volcanoes range from 68 to 77 percent SiO_2 (silicon dioxide). One of the characteristics of **magma** with high SiO_2 is its high viscosity. As a result, gases that exsolved from the magma cannot rapidly escape, creating an increasing internal gas pressure resulting in violent explosions (eruptions) as the magma nears the surface and the **lithostatic pressure** decreases. Although the size of the fragmented magma particles can vary, ash-sized particles are predominant away from the immediate environs of the caldera. The ash is erupted into the atmosphere in a dense column that may reach >15,240 m [>50,000 ft] in height. When the ash column collapses or when the volcano explodes horizontally, a mixture of hot ash and gas flows along the Earth's surface at speeds as great as 724 km per hr [450 mi per hr] (Tilling, et al., 1990) and travels more than 16 km [10 mi] outward from the volcano. These ash particles can still be molten. When they solidify, **ash flow** tuffs (Stops 1-8 and 3-11) result.

In the southwestern Nevada volcanic field, the tuffs have high SiO_2 and can be thought of as the volcanic equivalent of **granite**. The two most common volcanic rocks are **rhyolite** and **quartz latite**. Often in outcrop, crystal-poor rhyolitic tuffs grade upward into quartz latite tuffs that contain up to 20-percent quartz crystals. This upward change reflects the inverse compositional layering in the magma chamber, where the rhyolitic portion of the magma overlies latite composition magma, which contains quartz crystals. When the volcano erupts, the rhyolitic magma is the earliest eruptive product followed by the crystal-bearing magma that is deposited on top of the rhyolite.

In addition to the chemical layering, distinctive zones develop as the ash flow is deposited and cools. Many variations can occur, depending on initial ash temperature, trapped gas content in the ash, underlying **topography**, the occurrence of multiple ash flows, and cooling history. A single ash flow sheet (one eruption) often consists of multiple zones as a result of these conditions and processes. A generalized description of the zonal development follows (see Glossary—tuff). The first ash to land on the ground cools quickly, with the individual ash particles remaining as distinct fragments, forming a nonwelded ash flow (Stop 1-8). Such **units** are characterized by high porosity [up to 70 percent (Ross and Smith, 1961)] and low bulk density and cohesiveness. As the deposit thickens with the addition of more ash, the underlying hot ash acts as an insulator and the accumulating ash increases the pressure so that the individual ash fragments begin to fuse or weld together. However, the tuffs in this zone still retain some intergranular porosity (partially **welded tuff**) (Stops 1-8 and 3-11). Transitions between zones are often difficult to define. With deposition of additional ash, the fragments completely weld together, further reducing the porosity and increasing the density and strength of the material in this zone (densely welded tuff, Stops 1-8, 2-1, and 3-11). With very thick deposits, all the porosity is squeezed out, resulting in a solid glassy rock [**vitrophyre** (**obsidian**) (Stop 3-11)]. Vitrophyres can be thin, thick, or absent. Maximum welding generally occurs at about a third of the way above the base (Ross and Smith, 1961). Subsequently, as lesser amounts of ash are deposited, the cooling occurs in an upward direction toward the

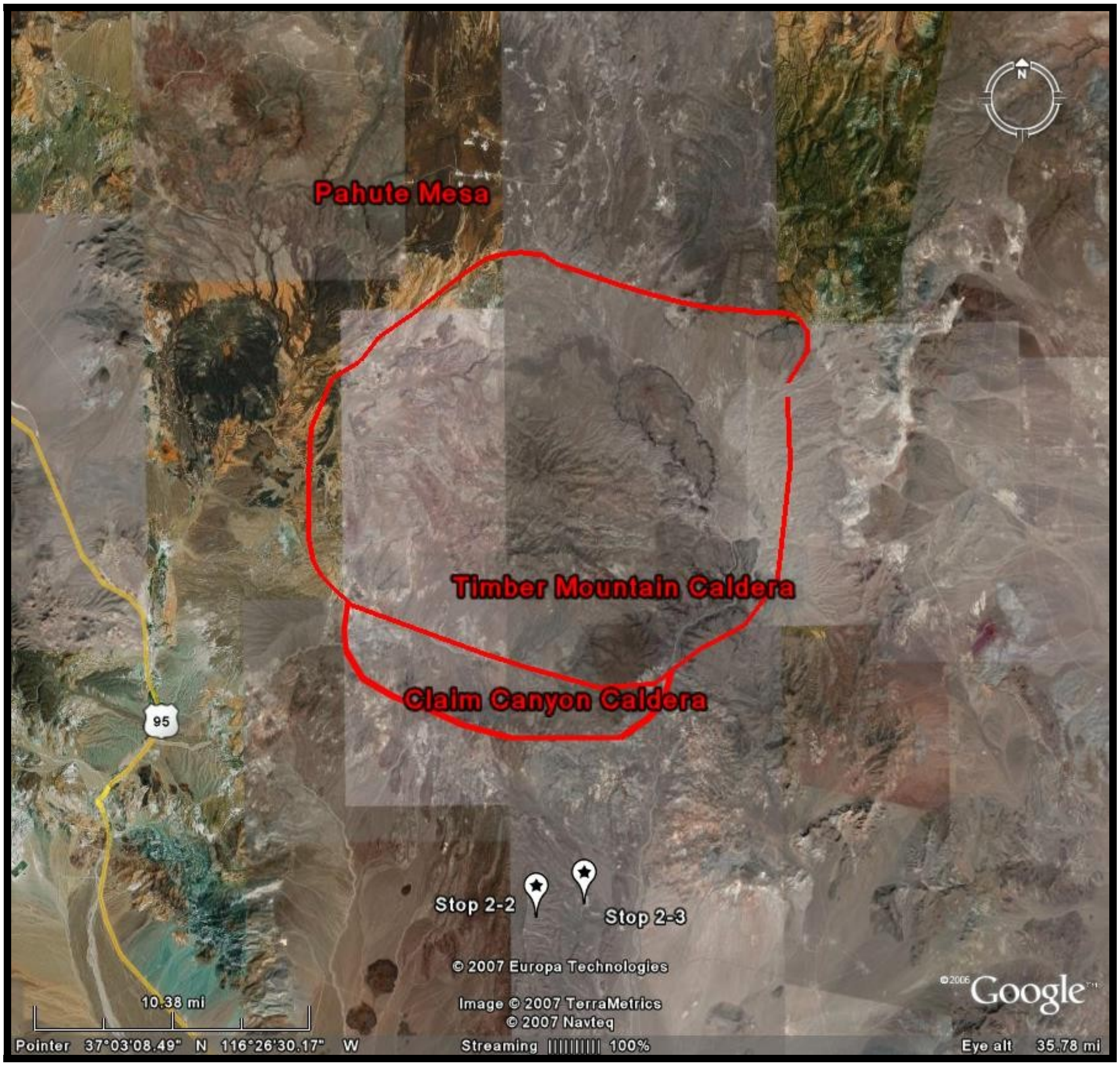

Figure 0-1. Locations of the Timber Mountain caldera complex and the Claim Canyon caldera segment. Except for this small segment, the earlier Claim Canyon caldera was obliterated by the later Rainier Mesa and ammonia tanks volcanoes included within the Timber Mountain caldera complex. Several older buried calderas occur beneath Pahute Mesa to the north. Stops 2-2 and 2-3 are at Yucca Mountain.

atmosphere, the material becomes less dense, and porosity increases. The topmost zone will again consist of nonwelded ash fragments (**nonwelded tuff**). This upper zone is usually quickly eroded away and is rarely preserved. A wide variety of contemporary and subsequent processes can modify this idealized zonation. Exsolving gases and trapped air can cause bubbles (lithophysae, Stops 2-1 and 3-11) to develop in the hot plastic ash, forming a **lithophysal** tuff. In many ash flow tuffs, the cooling is slow enough so that tiny crystals of **minerals** (**quartz**, **feldspar**) nucleate in the glass, resulting in **devitrified** tuffs (Stop 2-1). The rocks of the potential **repository host horizon** are devitrified partially welded lithophysal (Tprl) and non-lithophysal (Tprn) tuffs. In addition, wind can carry the ash away from the erupting volcano, resulting in **ash fall** tuffs (Stop 1-8). Ash fall tuffs can occur hundreds to thousands of miles from the erupting volcano. Rain, **groundwater**, or primordial steam can cause alteration (development of **zeolites** and **clay** minerals, Stop 3-3) of the tuffs shortly after their deposition. Subsequent to deposition, nonwelded ash can be easily eroded and redeposited in stream beds, lakes, and ponds forming reworked or **bedded tuffs** (Stop 1-8). When fragments of the wall rock around the volcanic **vent** are incorporated into an ash flow, a **lithic tuff** results. Because of the magma's high viscosity, the **lavas** do not flow far before they begin to solidify and stop moving; therefore, they are commonly found within and adjacent to the calderas.

The Claim Canyon and Timber Mountain calderas (Figure 0-1) are north and northwest of Yucca Mountain (Stop 2-2). The volcanoes deposited successive layers of hot ash to form the rocks at Yucca Mountain. The magma volume of the Timber Mountain and Paintbrush tuffs is estimated to have been >2,200 km^3 [>528 mi^3] each (Sawyer, et al., 1994).

Eruptions of small basaltic volcanoes occurred contemporaneous with and subsequent to development of the large silicic volcanoes. These volcanoes erupted basalt ash and lavas, initially from linear vents, but with time concentrated into a single location, such as the Lathrop Wells cinder cone (Stop 1-7). These volcanoes consist of lava and ash at the volcano with the ash forming the cinder cone. Volcanic ash from the Lathrop Wells cinder cone has been found in **fissures** related to **faults** in the Yucca Mountain area, linking **seismicity** and volcanism (Whitney, et al., 2004).

Regional Hydrology

Surface Water

This trip focuses on two different watersheds. From Las Vegas, Nevada, to a few miles east of Mercury, Nevada (Day 1, Mile 54.3), **surface water** (see water) drains to the southeast into the Colorado River at Lake Mead and ultimately into the Gulf of California. West of the divide and in the region around Yucca Mountain, surface water drains toward Death Valley, California. On the east side of the crest of Yucca Mountain (Stop 2-2), surface water flows east and southeast into Fortymile Wash, then south toward the Amargosa River. On the west side of the crest, surface water drains south through Crater Flat, out through the southern hills, just east of Stop 1-9, and into the Amargosa River. Rarely, but when there is sufficient runoff in the region, surface water from Yucca Mountain flows to Badwater, California, in Death Valley (Stop 3-8). In most years, surface runoff infiltrates into the subsurface or evaporates into the atmosphere long before it reaches Death Valley.

During earlier periods (>7,000 years ago) when the climate was wetter, active **springs** (Stops 1-1, 1-9, 3-4, and 3-5) and surface runoff fed river systems in southwestern Nevada that were probably filled with running water year round. As the climate became drier, the river systems dried up and now only flow following very large rainstorms.

Groundwater

Groundwater, the water below the surface of the Earth that completely fills (i.e., saturates) all the voids and openings in a rock, is an important resource in southern Nevada and is a much-studied possible release path for radionuclides from the proposed repository. The top of the saturated zone is the **water table** (see water). In an aquifer confined between two aquitards, the level to which water will rise in a cased (sealed) well drilled into the aquifer depends upon the hydraulic head in the aquifer and is called the potentiometric surface. Regionally, southern Nevada groundwater flows from topographically higher areas (see Figure 1-1) with more rainfall in central Nevada to lower and dryer areas in southern Nevada. The groundwater flow is predominantly through the Paleozoic carbonate rocks and to a more limited extent through the alluvium valley fill in the basins between the mountain ranges. In the carbonate rock **bedding** planes, **fractures**, joints, and fault zones, often widened by solution of the rock, provide a multitude of individual interconnected pathways that collectively result in the Regional Carbonate Aquifer. Flow in such openings is termed fracture flow. In the alluvial-filled basins, water flows by moving through the small openings (i.e., pores) between the rock and mineral fragments in the alluvium. This is termed porous flow.

Within the aquifers, local variations in sediment composition at the time of deposition or subsequent alteration of the deposited units can result in local aquitards within the aquifer systems. This is more prevalent in the smaller Alluvium and Volcanic Aquifer systems than the Regional Carbonate Aquifer. For example, alteration of the oldest units in the Volcanic Aquitard result in a basal aquitard (Luckey, et al., 1996) that separates the Volcanic and Regional Carbonate Aquifers, preventing water in the tuffs mixing with water in the regional aquifer. Within the Alluvial Aquifer, **caliche** layers can act as barriers to movement of water.

The groundwater environment covered on this trip is controlled by the regions of four hydrologic systems: (i) the Regional Carbonate Aquifer; (ii) the Volcanic Aquifer; (iii) the Alluvial Aquifer; and (iv) the Lower Clastic Aquitard or basement aquitard, which is beneath these aquifers (Figure 0-2, Table 0-2, right-hand column). The aquifers listed previously do contain local zones of low **transmissivity** (i.e., aquitards). Figure 0-2 schematically shows the relationships of these systems to each other in the Yucca Mountain region. In the bottom part of Figure 0-2, the system is composed of the oldest rocks (i.e., the Lower Clastic Aquitard, indicated by LCA), overlain by the Regional Carbonate Aquifer System (RCA). Rocks of the regional Carbonate Aquifer are older and therefore beneath the Volcanic and Alluvial Aquifers (Figure 0-2). Rocks of the Alluvial Aquifer were deposited before, during, and after deposition of the volcanic rocks that make up the Volcanic Aquifer (Figure 0-2). Figure 0-2 also shows normal faulting juxtaposed the regional Carbonate and Alluvial Aquifers. Deposition of the volcanic rocks over the carbonate rocks is illustrated along the right side of the figure. Unless impeded by local aquitards or impermeable fault zones, the groundwater can flow from one aquifer system to another depending on the **hydraulic gradient**.

The third system is the Volcanic Hydrologic System, which occurs beneath the southwestern Nevada volcanic field (i.e., Yucca Mountain region). Stippling in Figure 0-2 indicates aquitards within the volcanic hydrologic system, such as altered bedded units or altered ash flow tuffs. The fourth hydrologic system shown in the figure is the Alluvial Basin-Fill Aquifer. Limited or local zones (clay beds or well cemented caliche layers) may retard or divert the water movement in alluvium.

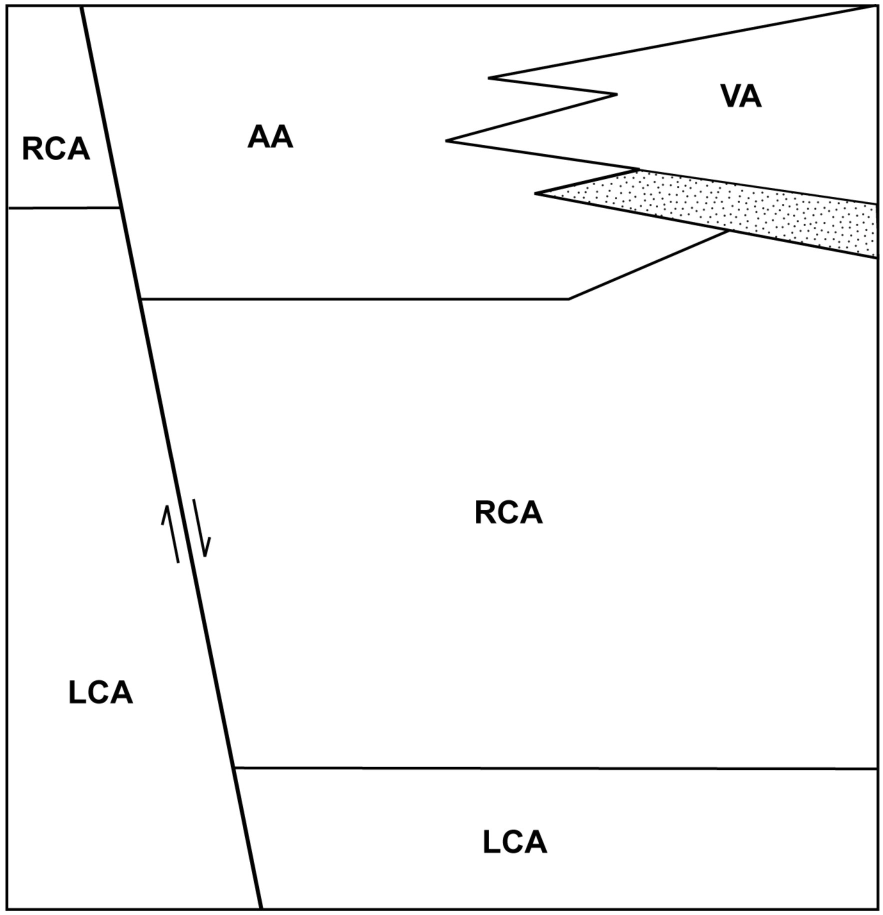

Figure 0-2. Schematic representation of the relationship between the aquifer and aquitard systems in the Yucca Mountain region. AA–Alluvial Aquifer, VA–Volcanic Aquifer, RCA–Regional Carbonate Aquifer, and LCA–Lower Clastic Aquitard. Stippled area in the VA represents a basal aquitard within that aquifer system. Arrows show relative movement on normal fault.

The Regional Carbonate Aquifer underlies an estimated 45,000 km^2 [17,375 mi^2] (Belcher, et al., 2002) in Nevada and California. As noted previously, this aquifer system is composed of an estimated 8,000 m [20,000 ft] of Paleozoic carbonate rocks (Table 0-2), with a few thin units having low permeability. Areas of the Lower Clastic Aquitard locally interrupt the aquifer (e.g., the north end of the Spring Mountains and the southern end of the Grapevine Mountains) or may divert flow, but do not greatly impede the regional hydrologic flow. In northern Yucca Flat, the Eleana Formation (Stop 2-7) forms the Upper Clastic Aquitard and divides the Regional Carbonate Aquifer into upper and lower (Figure 0-2) subunits. Again, this is a local feature that has little effect on regional flow.

Although the Sevier deformation and Basin and Range faulting (Table 0-4) offset the Paleozoic carbonate formations (i.e., the Regional Carbonate Aquifer), the deformation did not compartmentalize the aquifer into smaller subbasins, which would lower the overall transmissivity of the Regional Carbonate Aquifer. This lack of compartmentalization resulted from three factors: (i) the large regional distribution of the carbonate rocks; (ii) the thick carbonate sequence, which ranges up to 8,000 m [20,000 ft] (Belcher, et al., 2002); and

(iii) the presence of only a few thin aquitard units within the Paleozoic carbonate sequence. Had the carbonate sequence been more restricted, been thinner, and/or contained more and thicker aquitards, transmissivity might have decreased as a result of the Sevier orogeny and subsequent deformation. In fact, because there is no significant compartmentalization, deformation of the aquifer probably enhanced the transmissivity as a result of the faulting and fracturing and subsequent solution of the carbonates rocks along bedding, faults, and fractures (Stop 1-3). In addition, because the aquifer extends to the north into areas of higher elevation with abundant rainfall, this aquifer has good **recharge** compared to aquifers in less favorable recharge areas.

Generally, groundwater in the Regional Carbonate Aquifer is transmitted at depths of more than 500 m [1,640 ft] in the north and becomes shallower to the south (Grauch, et al., 1999). Surface discharge from this aquifer occurs at Ash Meadows (near Stop 3-2) and in Death Valley (Stop 3-7).

The Volcanic Aquifer occurs within the Southwestern Nevada Volcanic Field. This hydrologic system occurs to the west, northwest, and above the Regional Carbonate Aquifer. The Southwestern Nevada Volcanic Field covers an area of >10,000 km^2 [>3,861 mi^2], is up to 4 km [2.5 mi] thick in the center of the field, and thins outward to 0 m [0 ft] (Ferguson, et al., 1994).

Generally, the regional groundwater flow direction within the Volcanic Aquifer in the Yucca Mountain region is southward and southeastward with the water table occurring at depths as great as 752 m [2,467 ft] at U.S. Geological Survey well H-3, 0.92 km [0.57 mi] south of Stop 2-2.

The volcanic hydrologic system consists of both aquifer and aquitard units. The aquifers are commonly either fractured welded tuffs or lava flows. Porous flow occurs in some of the unaltered bedded tuffs. The aquitards are generally composed of altered bedded and nonwelded tuffs. In the Yucca Mountain area, Luckey, et al. (1996) place the Topopah Spring tuff in the Upper Volcanic Aquifer. A confining unit (i.e., an aquitard), composed of Crater Flat Formation and the basal nonwelded unit of the Topopah Spring, separates the Topopah Spring tuff from the underlying Crater Flat Group that forms the Lower Volcanic Aquifer. The lower confining unit is composed of all the older tuffs (pre-Crater Flat Group) and separates the Volcanic Aquifer from the Regional Carbonate Aquifer. The hydrologic units in the Volcanic Aquifer are thinner and less continuous as compared to the Regional Carbonate Aquifer, resulting in (i) hydrologic properties that vary more vertically and laterally and (ii) aquifers that are typically less transmissive (Grauch, et al., 1999). In addition, the inherent hydrologic characteristics of the volcanic rocks have been modified by Basin and Range normal faulting. These faults, many of which are favorably oriented for flow in the modern *in-situ* stress field, present potential preferential hydrologic flow paths within the Volcanic Aquifer System (Ferrill, et al., 1999).

The **alluvium** hydrologic system contains both aquifer and aquitard units. Alluvium and colluvium fill all the intermountain basins to varying depths and constitute a large area. However, alluvium aquifers occur only when alluvial basins extend below the water table. Uncemented sands, gravels, and cobble beds are common in the aquifers, while clays and tightly caliche-cemented sand and gravel beds act as aquitards. The most significant alluvial aquifer along the flow path away from the Yucca Mountain region is the alluvial aquifer south of the volcanic aquifer in the Amargosa Desert. North of Stop 1-6, groundwater from the Yucca Mountain area flows from the volcanic aquifer into the Amargosa Desert alluvial aquifer, a source of domestic and agricultural water.

Nuclear Activities in Southern Nevada

Southern Nevada has a long history of nuclear activities; the most notable were nuclear tests at the Nevada Test Site from 1951 until 1992. Tests were conducted both in the atmosphere and underground. **Atmospheric testing** stopped in 1962. Between 1951 and 1992, there were a total of 924 nuclear tests at Nevada Test Site, of which 824 were underground (DOE, 2000).

Several sites for nuclear waste disposal also exist in southern Nevada. Since the 1960s, two sites on the Nevada Test Site (Stops 2-8 and 2-9) have stored waste generated on the site and waste from the dismantlement and cleanup of the U.S. Department of Energy (DOE) and U.S. Department of Defense weapons production complex. USEcology operates a commercial site for nuclear waste storage 17.7 km [11 mi] southeast of Beatty, Nevada (Stop 1-12). The U.S. Ecology Beatty Facility was the first commercially operated low-level **radioactive** waste disposal site in the United States and was licensed by the **U.S. Atomic Energy Commission** in 1962. Disposal of nuclear waste at this site was suspended in 1992 by the State of Nevada, which had taken jurisdiction.

DAY 1

0.0/0.0[1] US Highway 95 at West Cheyenne Avenue, Las Vegas, Nevada (36° 13' 05.34" N; 115° 14' 48.71" W; Elevation 2,313 ft).

As we head northwest out of Las Vegas, we begin to traverse the middle section of the Kyle Canyon alluvial fan. Alluvial fans are one of the most common landforms in arid areas and extend outward into valleys from the point where streams exit mountains. They are composed of fine (clay and sand) to coarse (boulders) sediments deposited by torrential ephemeral streams that cross back and forth over the preexisting fan surface. The head of this alluvial fan is in the Spring Mountains (11:00) and is built from **detritus** from the Kyle Canyon and Harris Spring Washes. Alluvial fans are commonly divided into three sections: (i) a **fanhead** or **proximal** section, (ii) a middle section, and (iii) a **distal** section. From its apex in the Spring Mountains, the fan extends approximately 22.5 km [14 mi] to its distal end in the Las Vegas Valley at 3:00. In general, the size of the fragments or **clasts** in fans decreases from the fanhead to the distal end, as do the associated physical and hydrologic properties (Wagoner and McKague, 1986). The surfaces of alluvial fans often reveal a complex history of **erosion** and deposition and changes in the paths of the streams crossing the fan. As we cross the middle section of this fan, notice the active and abandoned **channels** and the **interfluves** of higher, older alluvium into which the younger streams channels are incised. Watch for channels at 3:00 and 9:00 between mileages 10.5 and 11.5.

Studies of alluvial fans often reveal tectonic and climatological histories that go back hundreds of thousands of years. Changes in clast composition indicate changes in source area. This will be further discussed at Stop 2-7. However, the observable sediments in this fan are composed of more than 90 percent carbonate rocks (Bell, et al., 1999), indicating a stable homogeneous source area in the Spring Mountains. Deeper portions of active **washes** and information derived from boreholes extend the knowledge of fan development back in time. When they are exposed, buried **paleosol** **horizons** and caliche layers indicate periods of tectonic stability. Buried stream channels indicate periods of erosion and deposition thousands of years ago. The geologic history of a fan, and therefore an understanding of the conditions under which it is formed, is developed from studies of the fan surface and subsurface features revealed in the walls of washes cut deeply into the older alluvial deposits. Sowers (1986) recognized four geomorphic surfaces developed on the Kyle Canyon fan. The age of the oldest, surface 1, is >750,000 y BP (years before present). The ages of surfaces 2, 3, and 4 are approximately 120,000 y BP, 5,000–35,000 y BP, and 5,000 to present, respectively. This suggests the uplift of the Spring Mountains was episodic (Sowers, 1986).

While observing a large fan like the Kyle Canyon fan, it is difficult to appreciate the fan's total extent and features. To fully appreciate the extent and features of a fan, look across the valley (2:00 to 3:00) at the fans originating in the Las Vegas and Sheep Ranges as we travel to Stop 1-1.

[1]See General Information on Page xiii for explanation of driving information.

6.3/6.3	Exit from US Highway 95 to North Durango Drive.

Floyd Lamb State Park is about a mile to the northeast. Because of home construction over the last 5 years, the park is no longer visible from US Highway 95. However, as we proceed northwest along US Highway 95, the treetops in the park are visible above the roof lines between 1:00 and 3:00. Tule Spring is one of several springs located in the park. Las Vegas Wash extends southeast from the Tule Springs area and has been a source of water for the last 12,000 years (Las Vegas Wash Coordination Committee, 2008). During the Pleistocene Epoch (2 million to 10,000 years ago) (Table 0-1), the head waters of Las Vegas Creek, which now rarely flows down the valley, began near the Nye–Clark County line. The creek passed through the Corn Creek Spring area (Stop 1-1) and then near the Tule Spring area. From the Tule Spring area, the creek flowed through the present-day Las Vegas Wash wetlands (seen out the right-side windows of most flights into Las Vegas from the east) and out of the valley to what are now Lake Mead and the Colorado River. During past wetter periods, streams from other springs joined the creek along its course. Marshes existed at a number of springs, and ephemeral lakes were periodically present at Corn Creek and Tule Springs. During the Pleistocene Epoch, the Las Vegas Valley was drastically different than it is today. The climate was cooler and much wetter. The Las Vegas Valley was green with completely different communities of plants and animals. Fossils of Pleistocene animals living in the valley included mammoths, camels, jaguars, huge grizzly-bear-sized ground sloths, early horses, American lions, and bisons (Nevada Legislative Counsel Bureau Research Library, 2003).

About 7,600 years ago, the climate became drier and eventually rainfall decreased to the point that the upper reaches of Las Vegas Creek ceased flowing. The full length of the stream became ephemeral, reaching the Colorado River only in the wetter times. In the valley today, both Las Vegas Creek and Duck Creek, a southern tributary of Las Vegas Creek, flow at least some distance all year. The three wastewater reclamation facilities are now a major source of water in the Las Vegas Wash (Las Vegas Wash Coordinating Committee, 2008).

2.5/8.8	US Highway 95 and Nevada State Highway 157.

The Kyle Canyon Road to the left follows the major wash of the fan into the Spring Mountains. Deep **incised exposures** along the road reveal many internal features of the fan.

As we proceed northwest along US Highway 95, we travel along the Las Vegas Valley. The Las Vegas (3:00) and Sheep (1:00) Ranges (Plate 1) are along the northeast side of the valley. At 5:00 is Frenchman Mountain. At 9:00 is the La Madera Range, and from 10:00 to 11:00 are the higher Spring Mountains. Mt. Charleston {3,633 m [11,918 ft]} is the highest point in southern Nevada (Plate 1). Gass Peak in the Las Vegas Range is 2,116 m [6,943 ft] and Hayford Peak in the Sheep Range is 3,024 m [9,912 ft]. The nearest peak over 3,048 m [10,000 ft] to the west of Mt. Charleston is Telescope Peak {3,365 m [11,041 ft]}, approximately 129 km [80 mi] away on the west side of Death Valley (Stop 3-8). As seen in Figure 1-1, the Spring Mountains are surrounded by a broad region of lower elevation. This is a result of the regional tectonics as will be described at Stop 1-2.

3.5/12.3	Junction of road to the 1,560 ha [3,850 acres] of Las Vegas Paiute Tribal Land.

3.9/16.2	Josua trees at 3:00.

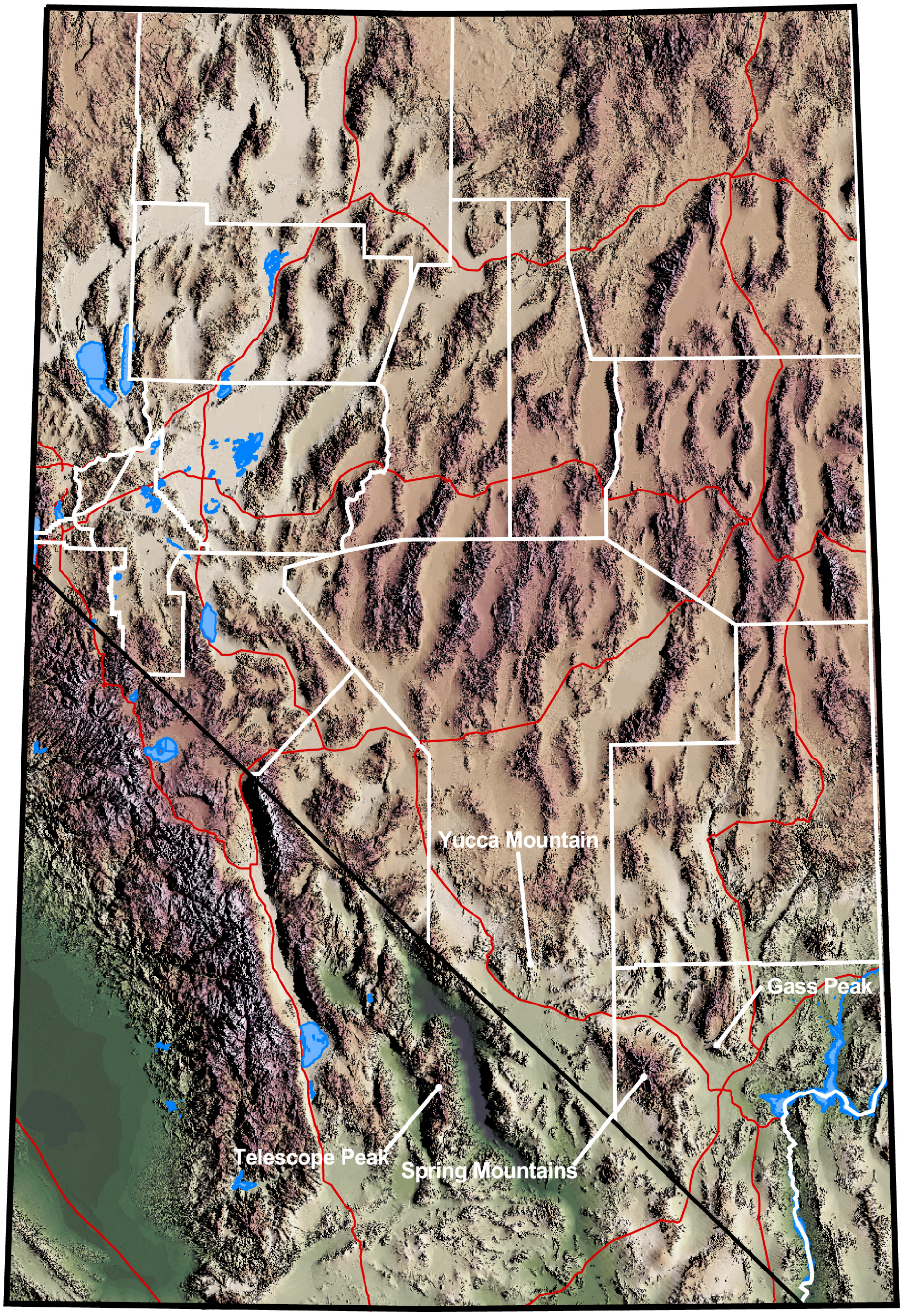

Figure 1-1. **Digital elevation map** showing regional topography. Mauve through brown colors indicate higher elevations. Beige through green colors indicate lower elevations. County boundaries are shown in white. Road system is shown in red.

While crossing the Kyle Canyon alluvial and Lee Canyon fans, notice the Joshua trees (*Yucca brevifolia*), which are a member of the Lily family. Joshua trees are restricted to elevations between 600 and 1,830 m [2,000 and 6,000 ft]. In this region, they are commonly found on the sloping surfaces of alluvial fans, where they occur both individually and in groves. Generally, they seem to be restricted to the upper and middle portions of fans. This may relate to the drainage characteristics of the fan surfaces. Notice that in the low area between the Kyle Canyon and Lee Canyon fans, Joshua trees are not present near the road. For additional information and a guide to some of the common plants in southern Nevada, see Appendix A.

1.8/18.0 Turn right onto Corn Creek Road.

This road leads to the Desert National Wildlife Refuge via the Corn Creek Field Station. Corn Creek was a stagecoach stop in the 19th and early 20th centuries. Stagecoaches went from Las Vegas to Beatty, Rhyolite, Goldfield, and Tonopah (U.S. Fish and Wildlife Service, 2008).

0.2/18.2 Stop 1-1: Corn Creek Spring and Lake Deposits (36° 25' 31.08" N; 115° 25' 09.11" W) Elevation 0.9 km [3,000 ft]

Turn cars around and park.

Geology

The regional Paleozoic (543–248 mya) geology is evident in this stop (Figure 1-2). A generalized stratigraphy is shown in Table 0-2. During the Paleozoic period, the Las Vegas area was located between a stable continental region to the east and a shallow marine basin here and to the west (Figures 1-3 and 1-4). As a result, the stratigraphy of the **craton** (east of Las Vegas) is characterized by relatively thin sedimentary formations (individual units are tens to hundreds of meters thick) that are predominantly composed of flat-lying clastic rocks (i.e., sandstones and shales) as shown in Figure 1-5. These rocks indicate deposition in a shallow near-shore environment or on land. By contrast, sequences of similarly aged rocks are thicker here and to the west beyond Yucca Mountain and are composed predominantly of carbonate (limestones and dolomites) rocks that reflect their shallow marine origin. Stratigraphic units west of this area are often hundreds to thousands of meters thick (Figure 1-3 and Table 0-2). Throughout much of southern Nevada, these carbonate rocks are the host for the Regional Carbonate Aquifer (Table 0-2) that controls the regional hydrologic flow. In the area west of this stop, the Paleozoic carbonate sequence of rocks overlies older sedimentary clastic rocks (sandstones, shales, and quartzites) that, along with still older Precambrian metamorphic rocks, make up the Lower Clastic Aquitard. The Lower Clastic Aquitard and the Regional Carbonate Aquifer are the dominant hydrogeologic features in southern Nevada. The youngest material at this stop is the alluvium forming the Lee Canyon fan that we are standing on.

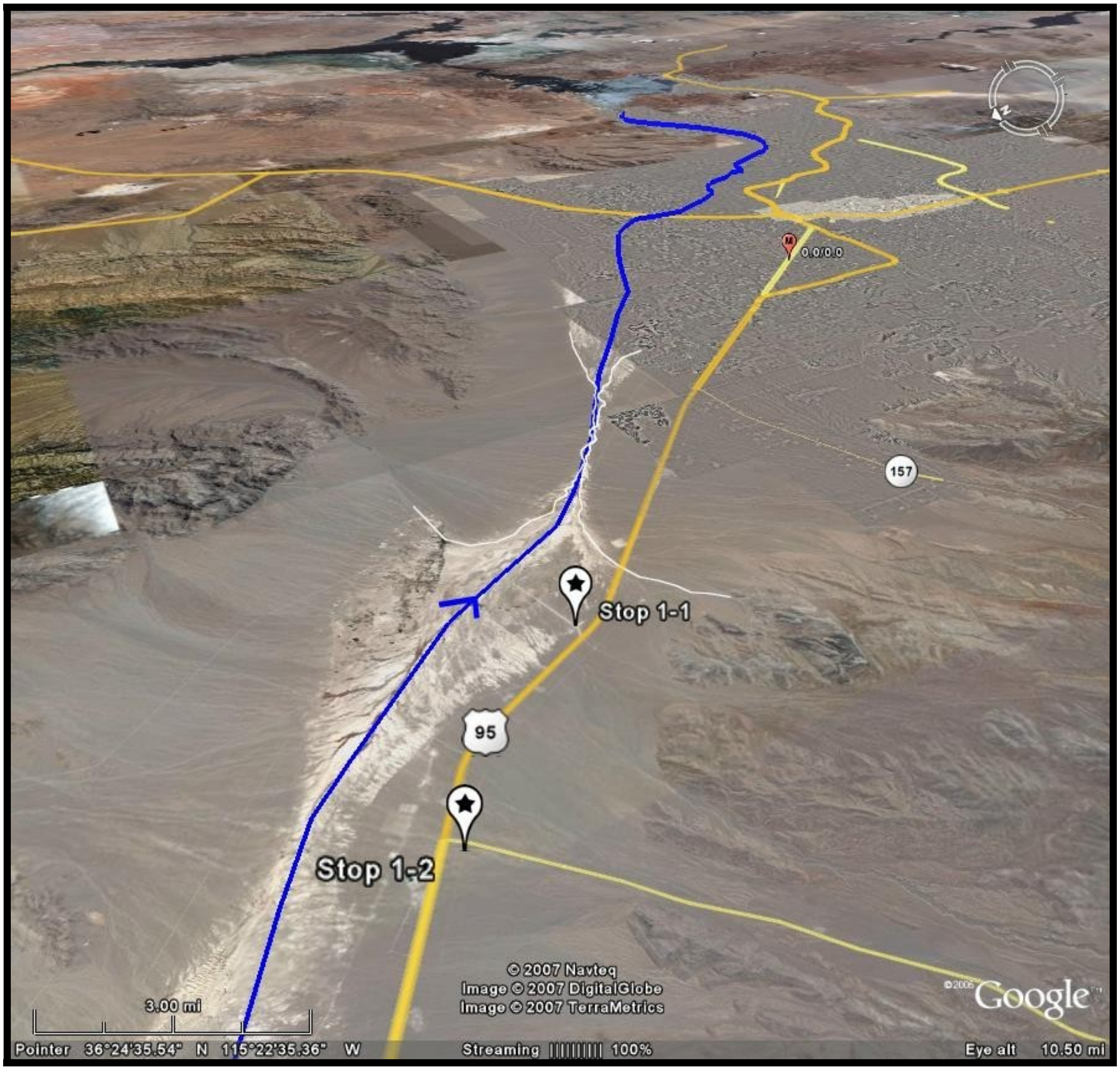

Figure 1-2. Looking southeast showing Stops 1-1 and 1-2. White lines indicate distal ends of Kyle Canyon (right) and Las Vegas–Sheep Range (left) alluvial fans. Blue line indicates approximate path of Corn Creek–Las Vegas Wash drainage toward Lake Mead. Red balloon with "M" is starting point of trip.

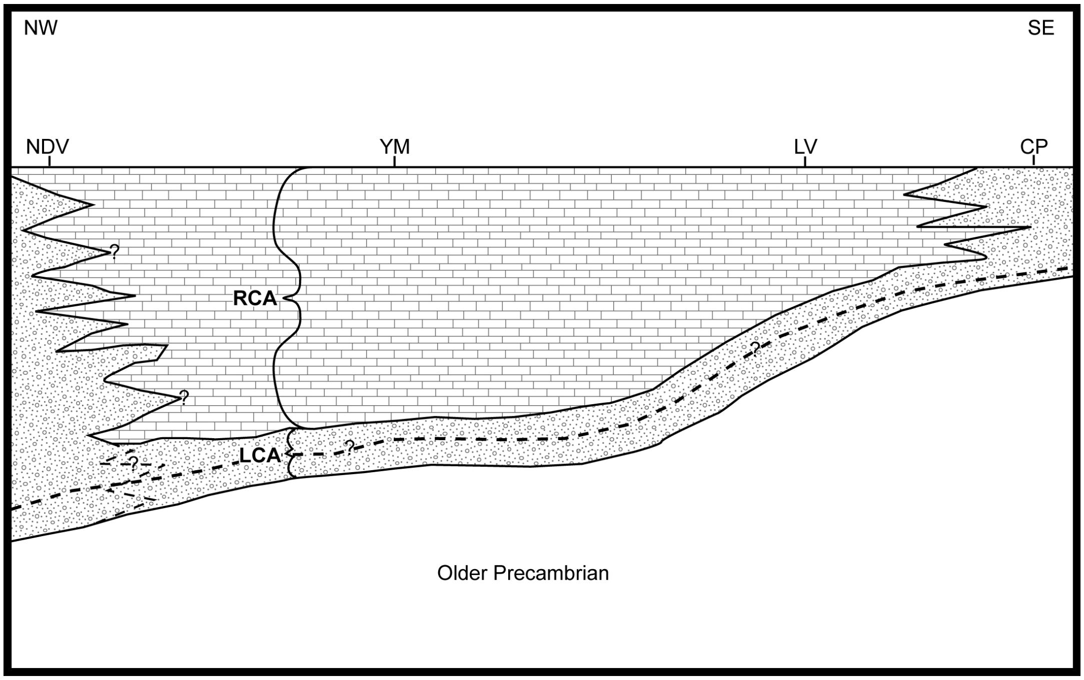

Figure 1-3. Schematic cross section through undeformed Paleozoic rocks in southern Nevada. Cross section shows increasing thickness of Regional Carbonate Aquifer to northwest of Las Vegas, Nevada. CP–Colorado Plateau, LV–Las Vegas, YM–Yucca Mountain, NDV–Northern Death Valley.

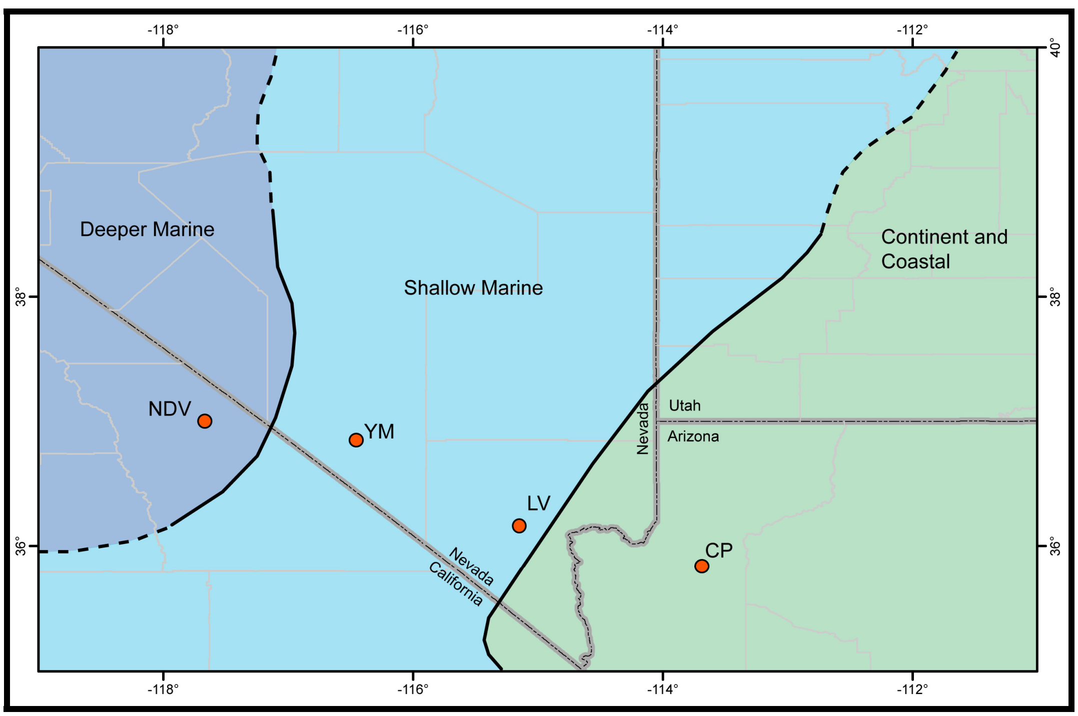

Figure 1-4. Map showing approximate distribution of middle Paleozoic marine and continental environments. CP–Colorado Plateau, LV–Las Vegas, YM–Yucca Mountain, NDV–Northern Death Valley.

Figure 1-5. Photograph of the Grand Canyon showing the flat-lying, thin-bedded rocks characteristic of the Colorado Plateau. Although some carbonate rocks such as limestones and dolomites occur in the Grand Canyon, most are clastic rocks deposited in shallow waters at or near shore. This figure shows Colorado River incised into the rocks of the Colorado Plateau.

Surficial Geology

This stop is on the Kyle Canyon alluvial fan. Alluvial fans are composed of alluvium and develop when streams issuing from narrow canyons no longer have the energy required to transport the sands, gravels, and boulders they are moving downstream with each storm.

Looking down the valley toward Las Vegas, notice that the Kyle Canyon fan is larger than the alluvial fans originating in the Las Vegas and Sheep Ranges across the valley (Figure 1-2). This is a consequence of the higher elevation of the Spring Mountains, which provides both more precipitation and a higher source area, resulting in increased erosional energy. As the Kyle Canyon fan developed, it forced the drainage in the valley to the northeast, narrowing the valley drainage between the fans on opposite sides of the valley. This narrowing is illustrated on Plate 1 by the two black lines that enhance the 2,800- and 3,000-ft contour lines. Notice how the 2,800-ft contour narrows between the fans, while the 3,000-ft contour enlarges in the area upstream from the fans. This narrowing resulted from higher energy streams carrying more and larger clasts down the fans and further into the valley in wetter periods. Such streams, originating in the mountains on both sides, may have caused temporary damming or flow restriction in the valley, causing a temporary lake in the Corn Creek Flats area and extending to the northwest as much as 32 km [20 mi].

Hydrology

Groundwater Hydrology

The simplest conceptual model for the regional hydrology for much of southern Nevada consists of a Lower Clastic Aquitard overlain by a Regional Carbonate Aquifer (Figure 0-2) (Table 0-2, right-hand column). The carbonate rocks seen in the mountains on either side of the Las Vegas Valley are representative of the rocks in the Regional Carbonate Aquifer. In some areas, the Regional Carbonate Aquifer is confined between Upper and Lower Clastic Aquitards (Stop 2-7), while in other areas it is unconfined (Stop 3-2). In most basins, the Regional Carbonate Aquifer underlies alluvial or volcanic material (Figure 0-2). In alluvium-filled basins, such as in the Amargosa Desert south of Yucca Mountain (Stop 3-1), an unconfined aquifer is present where the alluvial basin extends below the water table. Similar unconfined aquifers are the source of much of the drinking and irrigation water in the western United States.

The southeastern boundary of the Regional Carbonate Aquifer system is projected to be in the general area of this stop. Thus, while surface water moves toward the Colorado River system to the southeast, groundwater below this stop will move west and southwest around or under the Spring Mountains toward Death Valley (Plate 1, green arrows). The surface water divide is about 42 km [26.1 mi] northwest at cumulative mileage point 1-52.4. (Day 1 at first half mileage 52.4—see description).

Surface Hydrology

The Las Vegas Valley spring system is used to identify a series of springs and spring deposits that include, from northwest to southeast, deposits at Cactus Springs, Indian Springs, Corn Creek Flat, and Tule Springs. **Paleospring** deposits also occur within the Las Vegas Valley. The fine-grained, light-colored beds, with the badlands topography that is common along US Highway 95 northwest of here, are remnants of a Pleistocene lake(s) (approximately 25,000–7,600 yr BP) deposits (Quade, et al., 1995) that were in part fed by these paleosprings. Quade, et al. (1995) describe several types of springs that occur in southern Nevada.

(1) ***Springs with little or no associated geologic deposit***. These small springs, often with intermittent flow, are located in mountains. These springs tend to display low to moderate temperatures with low **total dissolved solids** and undersaturation with respect to calcite. Such springs may occur in noncarbonate rocks or have short flow paths through carbonate rocks. These types of springs include Captain Jack Spring, White Oak Spring, and Topopah Spring and Cane Spring (Day 2, second half mileage 7.1/11.1) on the Nevada Test Site. Often the source is a **perched aquifer**.

(2) ***Springs associated with travertine***. The water feeding these springs flows partly or completely through the Regional Carbonate Aquifer. Compared to other springs, these waters have higher total dissolved solids, temperatures, and chemical saturation indices with respect to mineral solubility. The higher mineral content of these waters sometimes results in extensive deposits of travertine. Examples include Big Spring and Point of Rock Spring in Ash Meadows and Nevares Spring in Death Valley. Paleodeposits from this type of spring are found at Devils Hole (Stop 3-2) and in Furnace Creek Wash (Stops 3-4 and 3-5). Stop 1-9 is at a similar paleospring deposit, but with a silica-rich, rather than carbonate-rich, deposit marking its location.

(3) ***Springs associated with extensive fine-grain deposits***. Sediments associated with these springs are the most common type of paleospring deposits in the southern Great Basin (Quade, et al., 1995). These spring systems occur most commonly in valley bottoms where the regional or local alluvial water table intersects the land surface and may be further subdivided, based on whether the discharge occurs with no diversion or localization by faults (free-face systems) or as a result of a fault (Corn Creek Spring). These spring deposits are more complex than the other types, and their characteristics are influenced by the associated vegetation. A spring or a line of these springs generally occurs where the coarser proximal alluvium gives way to the finer grained, more impermeable distal part of an alluvial fan. Surrounding and downstream from the spring, the vegetation traps the finer sediment moving down the fan. The coarser material is trapped upslope of the spring by phreatophyte plants. Quade, et al. (1995) explain this process in greater detail. Many springs along the Las Vegas Valley are of this type.

The source of the water issuing from the paleosprings in this area was predominantly from the southwest (Spring Mountains). Across the valley, the source of the flow was the Sheep Range area. Flow from the southwest was discharged at a free-face, while the Corn Creek fault may have forced and continues to force flow from the northeast (Sheep Range) to the surface.

After formationof the lake and spring deposits, a thin veneer of coarser alluvial material covered them. They were subsequently exposed during the last 7,600 years by a period of renewed erosion (Figure 1-6).

Return to US Highway 95.

4.4/22.8/26.5 Turn left onto Lee Canyon Road.

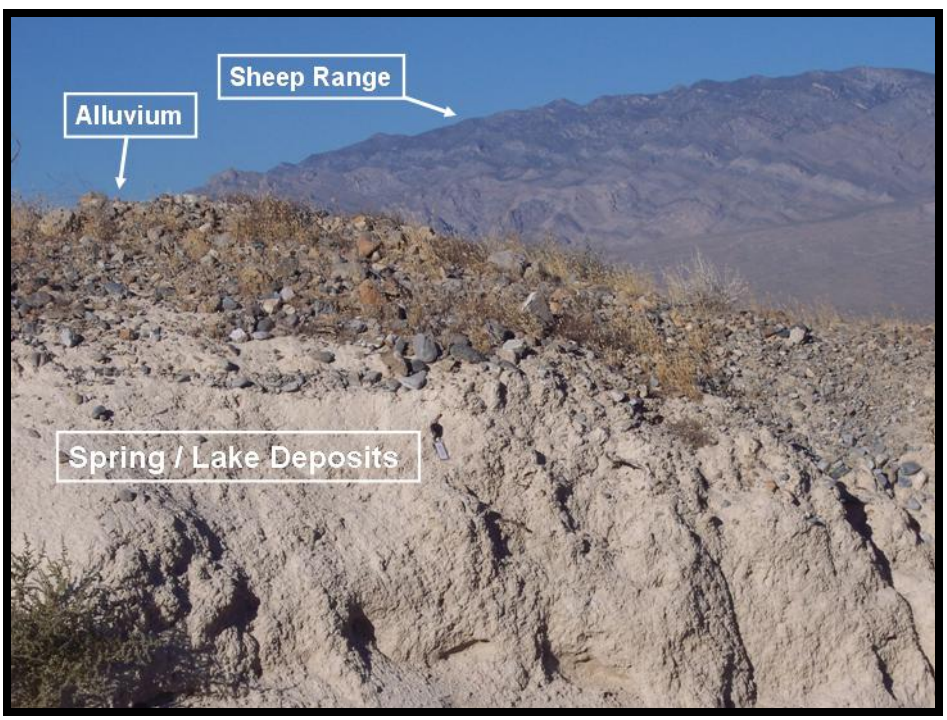

Figure 1-6. Recent (<10,000 years old) alluvial gravels deposited over older (14,000–7,500 years old) spring/lake deposits

0.1/22.9 Stop 1-2: Lee Canyon Road (36° 28' 33.48" N; 115° 28' 09 71" W) Elevation 1,016 m [3,336 ft]

Park in pull-off area to the right.

Geography and Physiography

We are now at the northeast end of the Spring Mountains. The Sheep Range is across the valley and to the east (2:00–3:00). The Desert Range is to the north-northeast, and the Pintwater Range is to the north-northwest. Three Spring Valley is located between the latter two ranges. The flat white area in the valley is a **playa**. Playas are dry lake bottoms that are extremely flat and generally fairly large in size (a half mile or more in diameter). They occupy the lowest part of basins and can be areas of groundwater discharge (Stop 3-8). Most of the year or for several years, there is no water in them, but during periods of intense or extended rain, they may flood, filling with several feet of runoff water. The lakes return to their dry state as the water evaporates or drains through the fractures in the playa as at Yucca Flat Playa (Day 2, second half; mile 25.8).

Tectonics

As described previously, southern Nevada and eastern California have undergone numerous periods and styles of deformation and have a long complex tectonic history (Table 0-4). Three styles of deformation have taken place in southern Nevada [e.g., compressional, **extensional**, and transtensional (see deformation)]. The earlier deformations of the post-Neoproterozoic rocks were characterized by compression and are now represented by folds (Stop 1-5) and thrust faults (Figure 1-7) (Stops 1-2 and 3-12). This style of deformation occurred before approximately 140–50 mya. The younger styles of faulting are characterized by extension or shearing of the crust. Extensional deformation is characterized by **normal faults** (see fault) (Stops 1-10 and 1-13). The classic area for extensional deformation is the Basin and Range Province north and northeast of this stop.

Transtensional (shear) deformation is characterized by horizontal deformation along vertical faults; the San Andreas Fault is a classic example. Active transtensional deformation occurs from Death Valley to the Sierra Nevada Mountains and is characterized by long, northwest-trending right-lateral **strike-slip faults** (see Glossary—fault) like the Furnace Creek Wash Fault (Plate 1).

The pre-Cenozoic (>65 mya) compressional faulting in this area is represented by a series of low-angle thrust faults and **overturned folds** (see fold) that are present in the mountains and ranges on both sides of the Las Vegas Valley and elsewhere throughout Nevada. East of this stop, the Pennsylvanian and Permian rocks in the Las Vegas Range are separated from the overlying but older Cambrian and Ordovician rocks in the south end of the Sheep Range by the north-**dipping** Gass Peak thrust fault (Figure 1-8). The fault is mapped as occurring in the valley between the ranges to the south of Fossil Ridge. Thrust faults are present in the Spring Mountains to the west. In the Spring Mountains, the Wheeler Pass fault, along the Lee Canyon road, separates a similar sequence of rocks (i.e., Pennsylvanian and Permian) from the overlying and older Cambrian and Ordovician rocks (Wernicke, et al., 1989, 1988).

The Wheeler Peak thrust is considered to be the extension of the Gass Peak thrust that has been offset by strike-slip motion along the Las Vegas shear zone. The Las Vegas shear zone has been relatively inactive over the last 17 million years (Longwell, 1960).

A period of regional extensional faulting before the Basin and Range faulting probably started in the late Oligocene Epoch (34–24 mya) (Gutenkunst, et al., 2005) (Tables 0-1 and 0-4). One characteristic of normal faulting is thinning of the crust as the rocks extend (stretch). It has been estimated that there may be as much as 250 km [155 mi] of west-northwest extensional deformation at the latitude of Las Vegas, Nevada (Wernicke, et al., 1989, 1984). The Spring Mountains represent a relatively unfaulted high-standing structural block, unaffected by later deformation. The mountains to the east (3:00) and northeast (1:00–2:00) are extensively faulted and represent an extended (stretched) area of the crust that is topographically lower than the Spring Mountains (Figure 1-1).

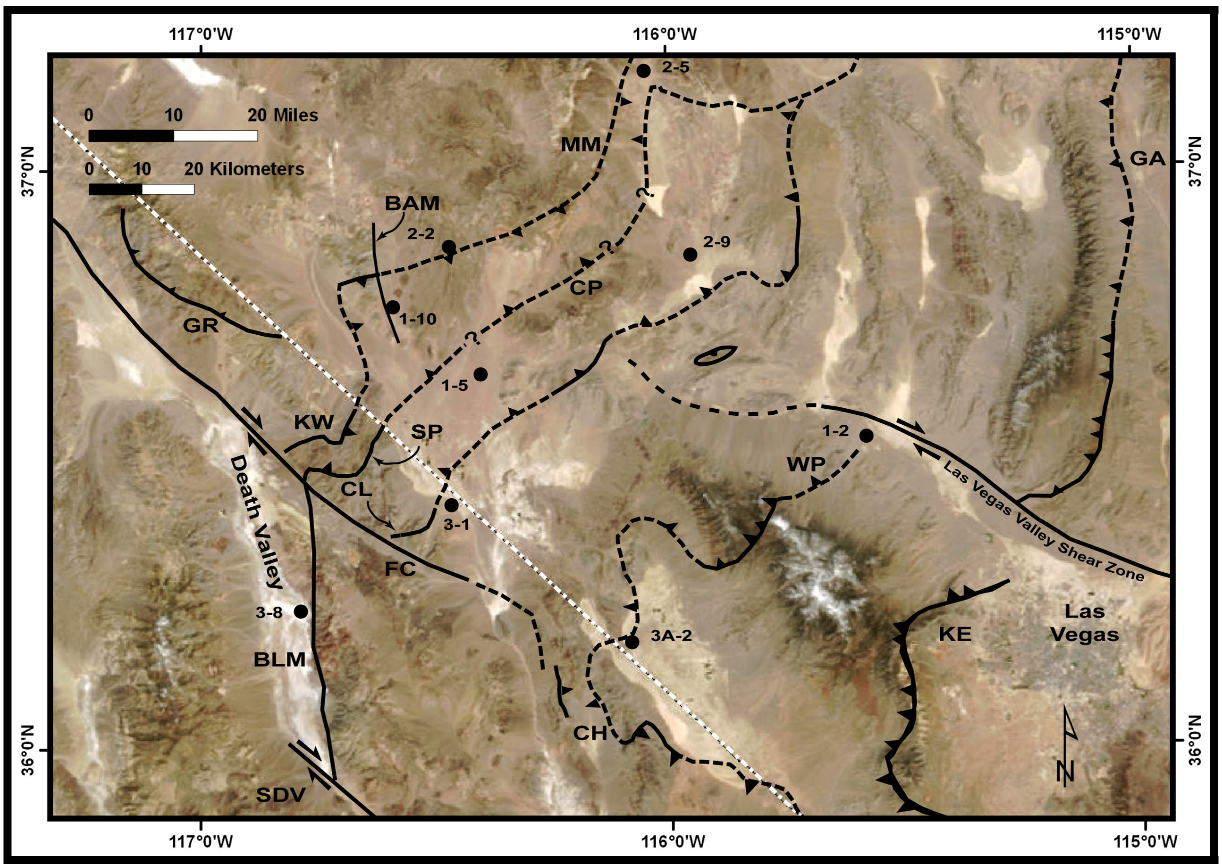

Figure 1-7. Map showing regional thrust systems and other selected faults. The thrusts on this figure were formed during the Sevier Orogeny. Thrust faults: BR–Belted Range, CH–Chicago Pass, CL–Cleary, CP–CP, GA–Gass Peak, GR–Grapevine, KE–Keystone, KW–Kean Wonder, MM–Mine Mountain, SP–Schwaub Peak, and WP–Wheeler Peak. Normal faults: BAM–Bare Mountain and BLM–Black Mountain. Strike-slip faults: FC–Furnace Creek and SDV–Southern Death Valley. Trip Stops: 1-2–Lee Canyon, 1-5–Amargosa City, 1-10–Crater Flat, 2-2–crest of Yucca Mountain, 2-5–Sedan Crater, 2-9–Area 5 Waste Management Site, 3-1–Inyo Country BLM#1, 3-8–Badwater California, and 3A-2–Chicago Pass Thrust.

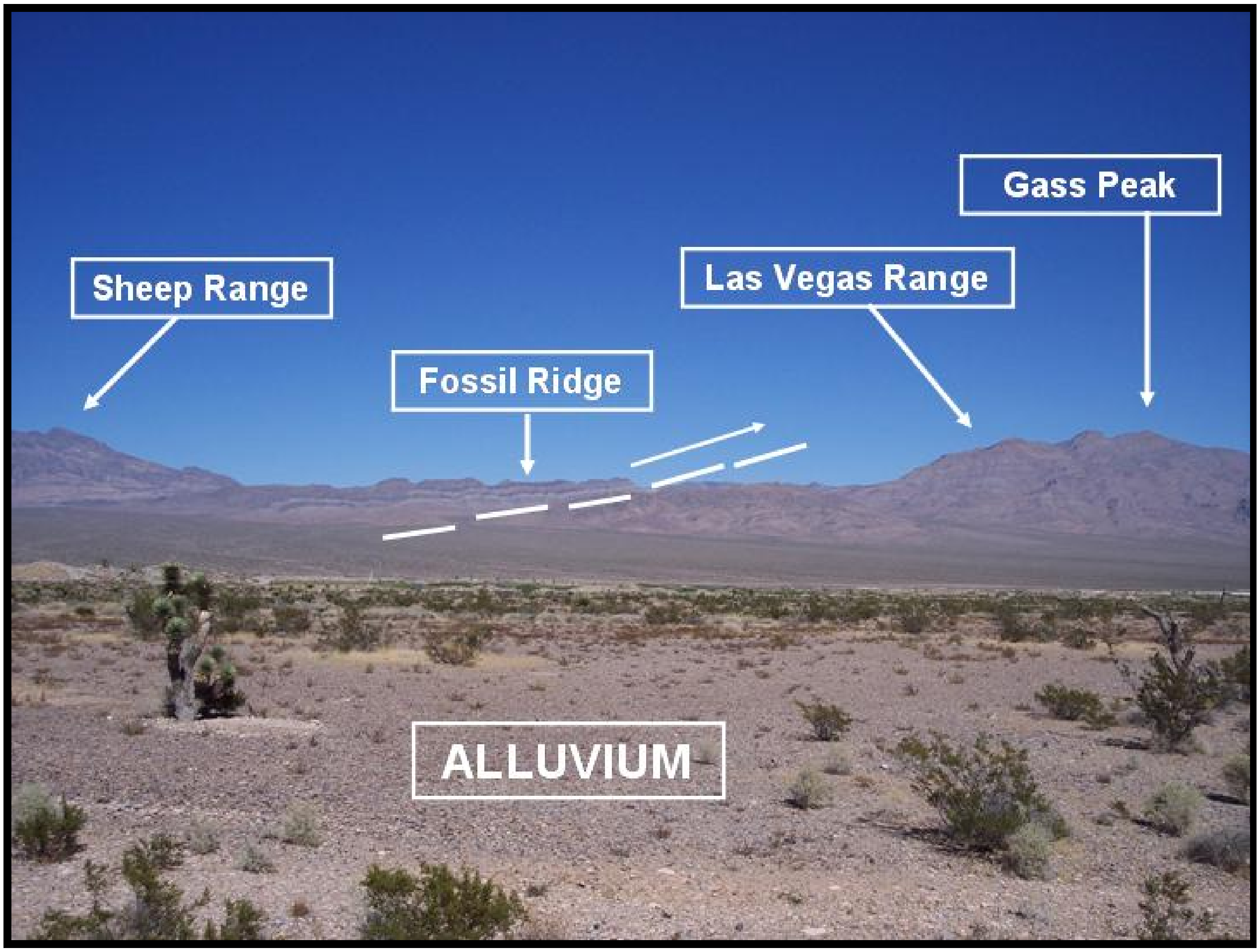

Figure 1-8. Gass Peak thrust separates the upper plate of Cambrian rocks in Fossil Ridge from the lower plate of Pennsylvanian and Permian rocks in the Las Vegas Range. Low angle dashed line is representative of Gass Peak thrust fault. Vegetation is mainly creosote bushes and Joshua trees. View is to the east.

Las Vegas Shear Zone

Las Vegas Valley is coincident with the Las Vegas shear zone, a major northwest-trending transtensional feature. The shear zone separates the relatively unextended Spring Mountains block on the southwest from the extended terrain across the shear zone to the northeast. The extended terrain includes, from southeast to northwest, the Las Vegas, Sheep, Desert, and Spotted Ranges (Plate 1). Thirty kilometers [19 mi] to the north, the mountain ranges (Plate 1) trend north-south; however, nearer the shear zone, they are bent clockwise up to 90° (Plate 1). Evidence for right-lateral **displacement** along the Las Vegas shear zone (Plate 1) (Figure 1-6) is demonstrated by offset across the Las Vegas Valley of Gass Peak thrusts, at the base of the Las Vegas Range (Stop 1-1), and the Wheeler Pass thrust up Lee Canyon to the northwest of this stop. The correlation of sedimentary **facies** and stratigraphic thickness on opposite sides of the valley offers corroborative evidence of lateral movement. The clockwise rotation of Mesozoic geologic structures and mountain ranges (Plate 1 and Figure 1-7) also supports movement along a right-lateral strike-slip along the Las Vegas shear zone. Age of movement on the Las Vegas shear zone is uncertain, but it appears to predate 17 mya (Longwell, 1960).

Across the valley to the northeast, the Sheep Range rocks are a thick stratigraphic section of typical southern Nevada shallow marine carbonate rocks of Ordovician, Silurian, and Devonian age. The two prominent black bands at 3:00 are the lower member of the Ordovician Ely Springs Dolomite (Table 0-2) repeated by faulting. The light-colored Eureka Quartzite is beneath the upper of the two black bands. Beneath the Eureka Quartzite is the brownish-gray carbonate unit of the lower Pogonip Group, which in turn is underlain by the Nopah Formation, the uppermost part of which has prominent black and white stripes. Above the black lower member of the Ely Springs is a unit of light-gray dolomite representing the upper member of the Ely Springs and lower part of the Silurian section. The thin black band is a dark dolomite unit within the Silurian section (McKague, et al., 1989).

Wernicke, et al. (1989) proposed that movement along the Sheep Range **detachment** (normal) fault on the east side of the Sheep Range has resulted in eastward rotation of the Sheep Range. Along the west side of the Sheep Range is an area of complexly deformed Paleozoic rocks also formed by Miocene extensional deformation (Guth, 1990) (Figure 1-9).

5.5/28.5 State Correctional Facility at 9:00.

7.7/36.2 Village of Indian Springs.

HISTORY: From the 1870s until the advent of rail and auto transportation in about 1905, animal power moved all goods and people in southern Nevada. There is no question that the routes were dictated by the locations of springs in this area.

Teams of 6, 12, 16, and 20 horses or mules pulled freight moved in wagons. To haul freight from Las Vegas to Bullfrog {near Beatty, about 193 km [120 mi] northwest} took a week. The first night's stop was at Tule Springs. The second night's stop was here at Indian Springs. A dry camp was required the third night. The fourth night was at Ash Meadows, near Devils Hole (Stop 3-2). The last two or three nights required dry camping. The freighter made $600 for a round trip.

Stagecoaches were the fastest way for people to move around. The nonstop trip from Las Vegas to Bullfrog required about a 60-hour trip. The route was probably the same to Indian Springs. From here the route is unclear or there may have been more than one route. The stage route may have followed the freight route to Ash Meadows and on to Beatty, or it may have taken a more northerly route around the Spotted Range, across Frenchman Flat (Stop 2-9) to Cane Springs on the Nevada Test Site. From there it may have gone across Jackass Flat and the southern end of Yucca Mountain (location of Stagecoach Road Fault), passed north of the Lathrop Wells cinder cone (Stop 1-7), across southern Crater Flat and out into the Amargosa Valley at Steve's Pass. Either way, the trip by today's standards must have been long, dirty, tiring, and unpleasant.

0.6/36.9 Creech Air Force Base at 3:00.

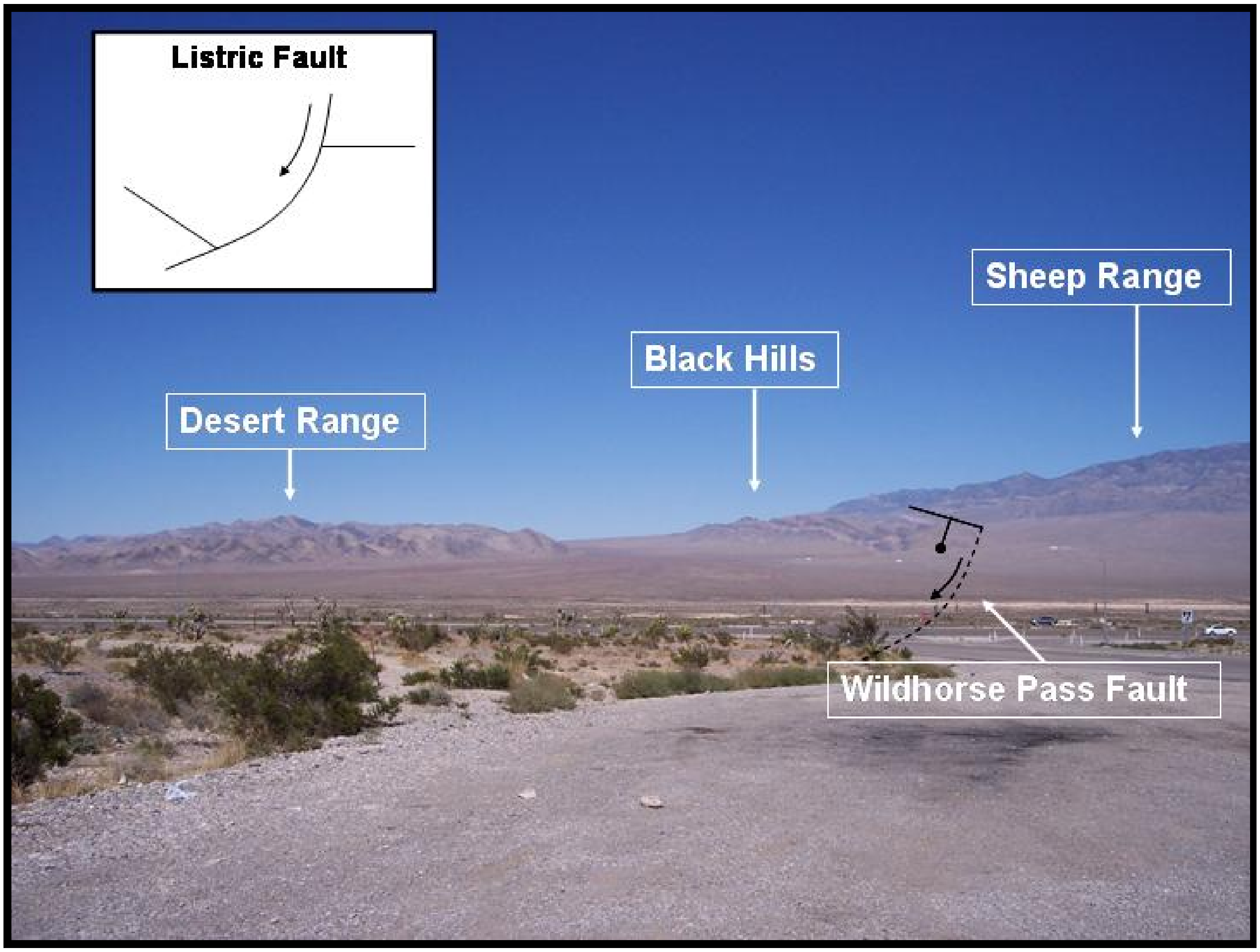

Figure 1-9. Extended terrain view to north. Movement along **listric** (normal) **faults** (see fault) that have increasingly shallower dips with depth cause the mountain ranges to rotate. Rocks in Black Hills dip 45° to the east into the Wildhorse Pass fault. (See Location, Plate 1.)

HISTORY: The Air Force renamed the former Indian Springs Air Force Auxiliary Airfield in honor of General W.L. "Bill" Creech in June 2005. The airfield, originally built by the Army in the early 1940s to support the Second World War effort, was named for the nearby community of Indian Springs, Nevada, in 1964. The base is currently (2005) home to the Unmanned Aerial Vehicle Battle Lab and the 11th Reconnaissance Squadron (Predators).

2.6/39.5 Village of Cactus Spring.

After leaving Cactus Spring, notice the spring and lake deposits on both sides of the road. These deposits extend to the west (12:00) for another 13 km [8 mi].

7.3/46.7 Indian Springs Valley Surface Hydrology.

At 9:00 there is another small area of paleospring and marsh deposits (Quade, et al., 1995). This is the highest {1,100 m [3,330 ft]} of the spring-marsh deposits in the Las Vegas Valley spring/lake system. During wet periods, this area was the head of an ephemeral stream system that extended to Tule Springs and beyond to the Colorado River. As we have seen, these deposits can be traced back to Las Vegas at an altitude of 800 m [2,625 ft]. This suggests southeast tilting of about 3.6 m/km [19 ft/mi] after the lake beds were deposited. (Also see Stop 1-5, Geodesy.)

2.4/49.1 Nye/Clark County line.

1.3/50.4 Spotted Range Geology (36° 35' 11.40" N; 115° 55' 02.53" W)

There is a view of Paleozoic units in the Spotted Range between 2:00 and 4:00. Rocks seen to the north in the Spotted Range are typical of thick marine **strata** from this part of southern Nevada (Table 0-2). Similar but older rocks will be seen at Stop 1-3. Visible units include limestone of the Ordovician Pogonip Group, Eureka Quartzite, and Ely Springs Dolomite; Silurian and Lower Devonian dolomite; Lower and Middle Devonian dolomite and quartzite; and Upper Devonian limestone (includes some dolomite and quartzite). Uppermost Devonian and Lower and Upper Mississippian rocks cannot be seen from here, but are present in an overturned syncline on the far side of the ridge on the skyline. Strata generally dip 30° to 40° north-westward and form the southeast limb of the Spotted Range syncline. The rocks are displaced by a prominent system of northeast-trending faults. The white Eureka quartzite visible just above valley fill at 1:30 is overlain by black dolomite of the lower member of the Ely Springs. The ridge on the skyline between 12:30 and 2:30 is South Ridge and is capped by Devils Gate limestone (McKague, et al., 1989).

In the center of Figure 1-10, a photo taken near here, a well-developed alluvial fan is issuing from between two low dark ridges of Pogonip Group carbonates. The Devils Gate limestone is on the skyline. The characteristic craggy and ledgy topography and the typical grey to black colors of carbonate rocks in this part of Nevada are obvious and usually make identification of carbonate rocks easy (Figures 1-10 and 1-11).

2.0/52.4 Surface water divide (36° 35' 48.30" N; 115° 57' 09.57" W).

West of this point, the surface water flows toward Death Valley, while east of here, surface water flows toward the Colorado River (see Plate 1). The groundwater divide between the Colorado River system and the Death Valley–Ash Meadows system is near Stop1-1. Also see discussion at Stop 1-6.

To the south (9:00) is the north end of Spring Mountains. The smooth, rounded topography is characteristic of areas underlain by rocks of the Lower Clastic Aquitard. Compare this with the ledgy, craggy topography of areas underlain by carbonate rocks previously described at Day 1, mileage 1.3/51.2. These differences in topography allow the separation of the Regional Carbonate Aquifer from the Lower Clastic Aquitard in many areas (Figure 1-11).

0.4/52.8 American Cement Company quarry.

The road to the right leads to the American Cement Company quarry in the Eureka Quartzite (sandstone).

Figure 1-10. Spotted Range from US Highway 95. In middle distance is the coalescing alluvial fans. Creosote bushes dominate the foreground. View to north.

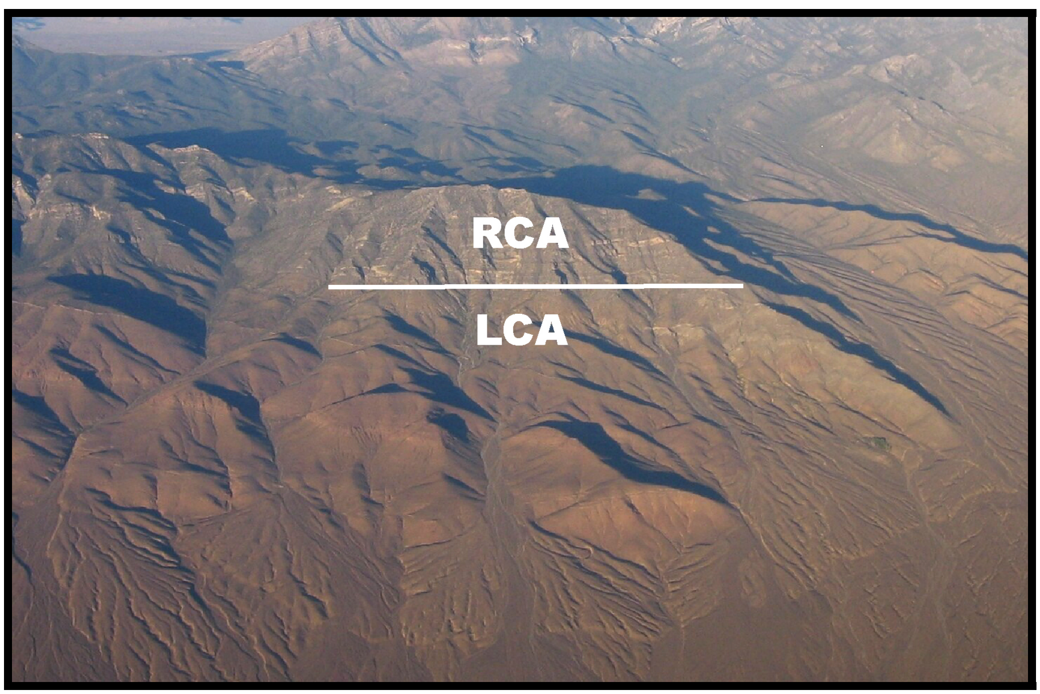

Figure 1-11. West side of Spring Mountains looking east. Notice the more subdued rounded topography over the reddish-brown rocks of the Lower Clastic Aquitard (LCA) in the middle of the picture. The rocks of the Regional Carbonate Aquifer (RCA) are the banded rocks above the LCA. Note the coalescing alluvial fans with incised washes (lower section). Photo taken December 18, 2006, about 5:45 p.m.

In 2002, "Silica LLC began mining quartzite from the Sugar mining claims, which are about 5 km [3.1 mi] southeast of Mercury in Nye County. A Plan of Operations submitted to the Bureau of Land Management in 2001 called for annual production of as much as 66,225 metric tons [73,000 tons]. The material mined, the Ordovician Eureka Quartzite, was described as strongly brecciated and fractured and amenable to mining without blasting." (U.S. Geological Survey, 2003).

0.75/53.5 Mercury Valley.

Geography

Ahead, Mercury Valley (see Figure 1-12) is from 12:00 to 4:00, Little Skull Mountain is at 2:00, and Skull Mountain at 2:30; both mountains are capped by 12 mya basalt. Timber Mountain and Paintbrush, as well as older tuffs, underlie the basalt on the mountains. At 12:00 to 1:00 is the Specter Range underlain by rocks of the Regional Carbonate Aquifer. At 8:00 is Mount Sterling, which is composed of Stirling Quartzite (part of the Lower Clastic Aquitard).

In Mercury Valley, the former Camp Desert Rock was located east (right) of the Desert Rock Air Strip (Figure 1-12). It was used from 1951 to 1958 to house members of the military during early atmospheric nuclear testing. Members from all services participated in the tests in Frenchman Flat.

1.3/54.8 Mercury, Nevada, exit.

HISTORY: The American Nuclear Testing Program, except for the Trinity Test in 1945, was initially conducted at the Pacific Proving Grounds (DOE, 2000). The Nevada Test Site, originally called the Nevada Proving Grounds, was established in January 1951 to test nuclear explosives on the continental United States. Its main goals were to expedite the testing program and reduce costs. Testing in Nevada continued until September 23, 1992 (DOE, 2000).

2.5/57.3 Army Well No. 1 at 3:00.

This well was drilled to 382 m [1,253 ft] and is used as a water supply well for Mercury, Nevada. The depth to the water table is 321 m [1,052 ft].