Utah Seismic Safety Commission
Nevada Earthquake Safety Council
Joint Meeting
Field Trip

Friday, May 11, 2007, 8:00 a.m. – 12:00 noon
St. George, Utah

Springdale landslide in Springdale, Utah, which moved in response to the 1992 M 5.8 St. George earthquake.

UTAH GEOLOGICAL SURVEY

UTAH DNR
GEOLOGICAL SURVEY

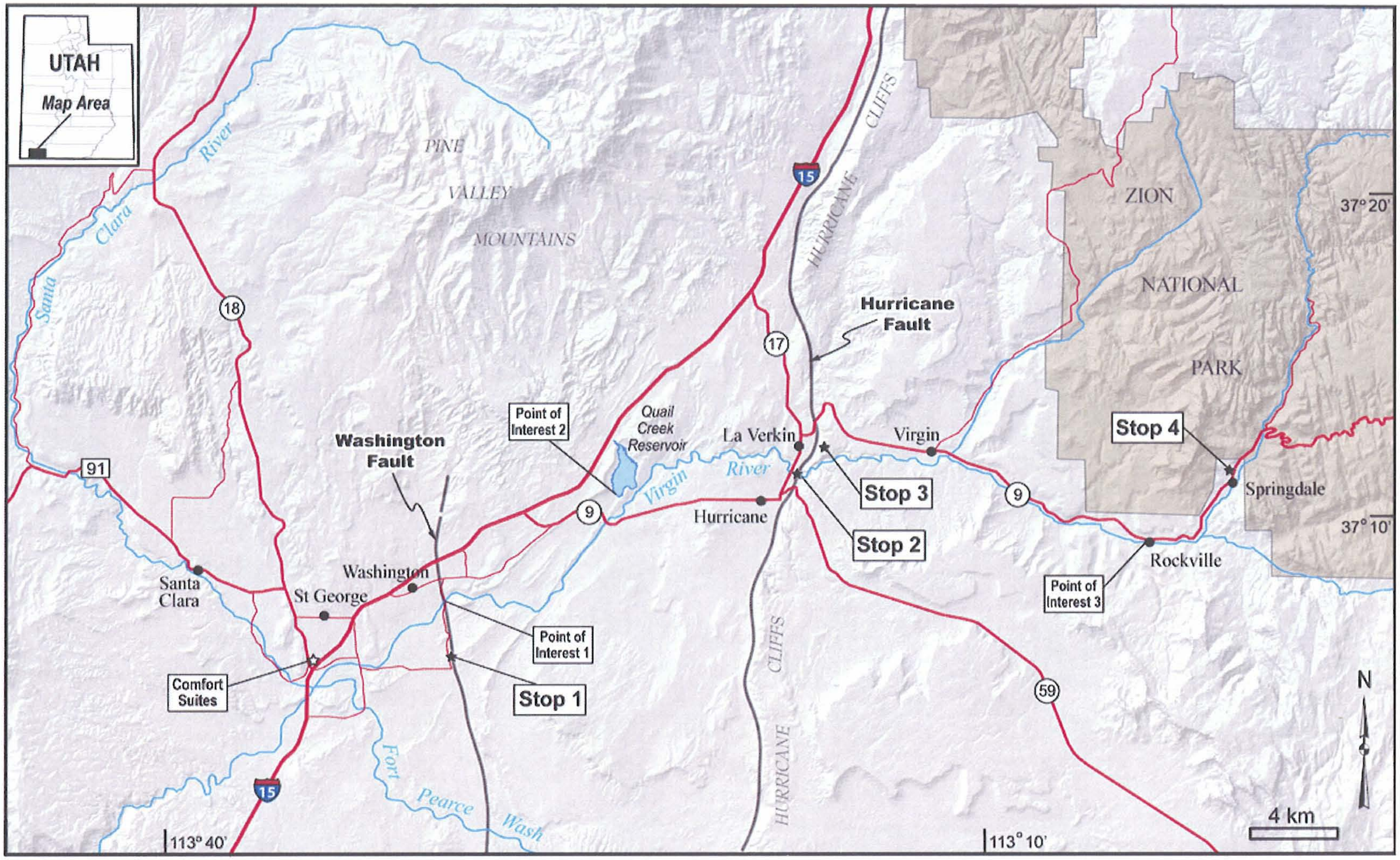

Figure 1. Field-trip stops and points of interest.

INTRODUCTION

Southwestern Utah's mild climate and beautiful scenery combine to make it one of the nation's fastest growing regions. In terms of percent growth, the 2000 census showed that from 1990 to 2000 the population of Washington County increased 86 percent (Loomis, 2001). Subsequently, the county's population grew from 90,354 residents in 2000 to an estimated 126,000 residents in 2007, for a growth rate of almost 40 percent (Canham, 2007). Officials estimate that Washington County will have a population of 400,000 by 2035. Adjacent areas of Arizona and Nevada are experiencing similar rapid growth, and nearby Zion National Park receives more than 2.5 million visitors annually. As a result of this rapid growth, land well suited for development has become increasingly scarce, and urbanization has moved into less favorable areas where geologic hazards, including earthquake hazards, are frequently encountered.

This field trip begins in St. George, Utah, and ends in Springdale, Utah, near the entrance to Zion National Park (figure 1). Over the course of the trip, we will traverse part of the approximately 100-mile–wide transition zone between the Basin and Range and Colorado Plateau physiographic provinces before entering the Colorado Plateau proper. We will travel through a stratigraphic section that extends from the Permian to the Holocene, and will examine the active Washington and Hurricane faults, view a major earthquake-induced landslide, and note in passing other geologic hazards related to flooding, the catastrophic failure of a dam and reservoir, and a damaging rock-fall event.

This trip was prepared for the USSC/NESC Joint Meeting in St. George, Utah by the Utah Geological Survey (UGS). The trip leaders are Bill Lund and Tyler Knudsen with the UGS Geologic Hazards Program. Bob Biek and Janice Hayden with the UGS Geologic Mapping Program also contributed extensively to this field-trip road log.

Assemble at the Comfort Suites, 1239 South Main, St. George, Utah, at 7:30 a.m.; the field trip will depart at 8:00 a.m. sharp.

ROAD LOG

Inc. Mileage	*Cum. Mileage*	**Milepost**	***Description***
0.0	0.0		Comfort Suites, 1239 South Main, St. George, Utah
0.1	0.1		**Stoplight, turn left onto Bluff Street.** Before turning, at 12:00 note the hummocky landslide topography covered by basalt talus along the flank of West Black Ridge. West Black Ridge is capped by two mafic lava flows (Higgins and Willis, 1995; figure 2). The higher flow is $^{40}Ar/^{39}Ar$ dated at 2.34 million years old (Ma) and the lower flow is $^{40}Ar/^{39}Ar$ dated at 1.23 Ma (UGS unpublished data). Both lava flows originally traveled down paleostream channels of tributaries to the Virgin River, and have now been left stranded high above St. George by subsequent fluvial erosion. This is an excellent example of inverted topography. The red sedimentary rocks that crop out in the hillside beneath the lower flow consist of the Triassic Chinle Formation at the south end of the ridge and the Jurassic Moenave and Kayenta Formations (figure 2) at the north end of the ridge. The formations dip gently northeastward beneath the mostly talus-covered hillside. The Petrified Forest Member of the Chinle Formation chiefly consists of bentonitic clay, and is frequently associated with landslides and foundation problems in the St. George area.
0.1	0.2		**Stoplight, south onramp to Interstate 15 (I-15), continue straight and cross above I-15.**
0.2	0.4		**Stoplight, north onramp to I-15, turn left toward Salt Lake City.**
0.8	1.2	MP-7	Historic St. George LDS Temple at 9:00.
2.0	3.2	MP-9	Middleton Black Ridge at 12:00. Road cut (figure 3) exposes the Middleton basalt flow, which occupies a now-inverted valley in the Jurassic Kayenta Formation (Willis and Higgins, 1995). The Middleton flow is about 200 feet above the Virgin River. Best and others

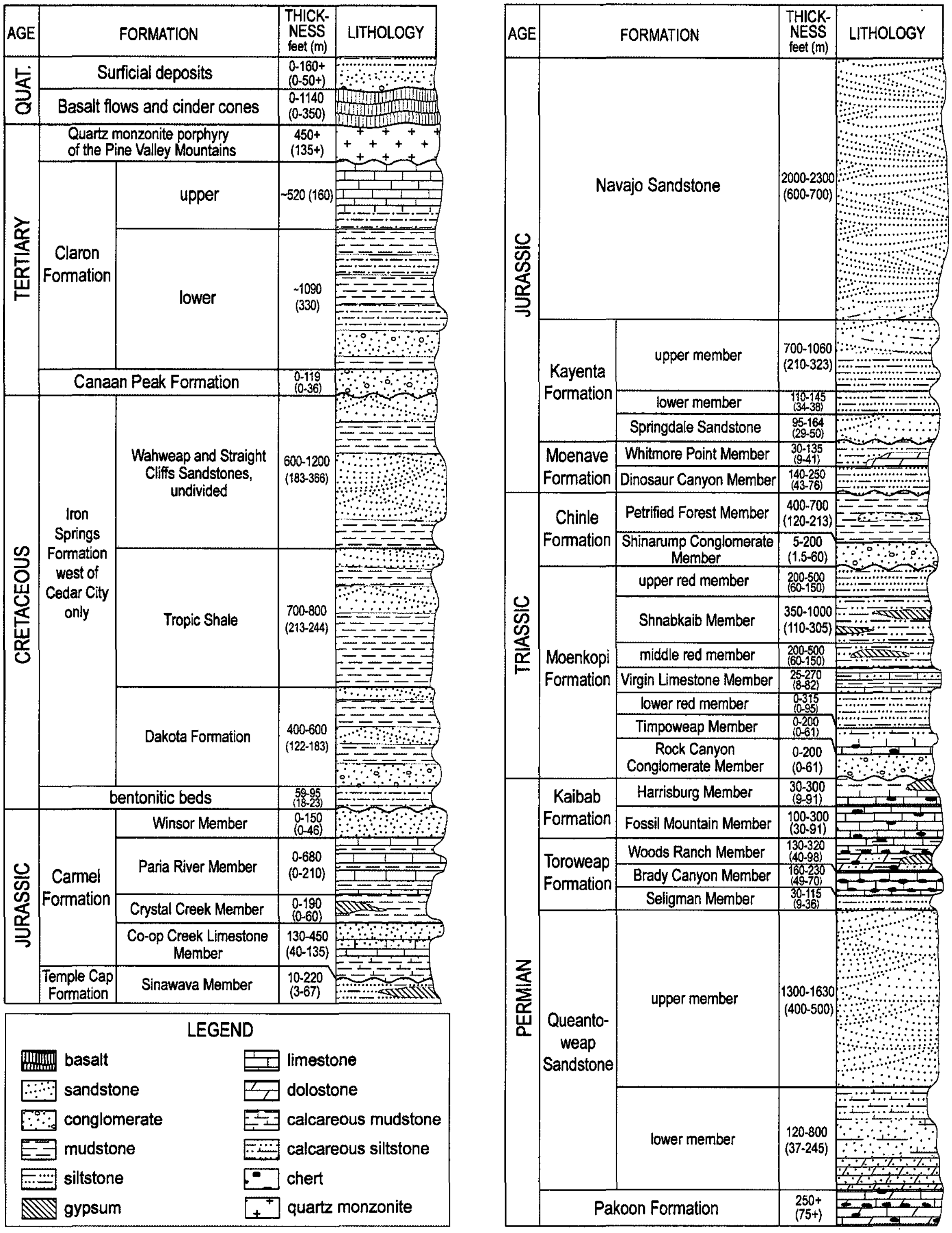

Figure 2. Stratigraphic section showing the name, age, thickness, and rock type of the geologic units that crop out in the field-trip area (modified from Hintze, 1988).

Figure 3. Road cut on the southbound side of I-15 through Middleton Black Ridge. Early Jurassic Kayenta Formation is capped by Quaternary fluvial deposits (light brown outcrops), which are in turn overlain by a Pleistocene (1.5 Ma) basalt flow (black) that originally flowed down the channel of a tributary of the Virgin River (photo courtesy J. D. Harris, Dixie State College).

(1980) obtained a K-Ar age of 1.5 ± 0.1 Ma for this flow.

1.0 4.2 MP-10 Kayenta Formation crops out at 11:00.

1.0 5.2 MP-11 View left of Shinob Kibe Butte at 9:00 and of Washington Dome at 11:00. Shinob Kibe Butte is the namesake and type section of the Shnabkaib Member of the Moenkopi Formation (bacon-slab appearing unit characterized by alternating layers of red siltstone/sandstone and white gypsum; figure 2).

The name Shnabkaib may be a misspelling of the Piute *Shinob* (Great Spirit) and *Kaib* (mountain), loosely translated as *Mountain of the Lord* (Gregory, 1950). Washington Dome is the middle of three structural domes along the length of the 40-mile-long, northeast-trending Virgin anticline, each of which exposes the Lower Permian Harrisburg Member of the Kaibab Formation (figure 2). The Virgin anticline likely formed in the Late Cretaceous (about 85 to 72 million years ago Hurlow and Biek, 2003) above a blind thrust fault in Cambrian Bright Angel Shale (Davis, 1999), and effectively marks the eastern limit of significant Sevier-

			age compressional deformation in southwest Utah. Shinob Kibe Butte is capped by the Shinarump Member of the Chinle Formation (figure 2), here a coarse-grained, well-cemented pebbly sandstone.
1.0	6.2	MP-12	Cross the Washington fault. The Washington fault is a 42-mile-long, down-to-the-west, high-angle, late Quaternary normal fault that trends north-south through northern Arizona and southern Utah. More about this fault at Stop 1.
1.0	7.2		**Exit 13, Washington Parkway, exit I-15.**
0.2	7.4		**Top of Exit 13 off ramp, turn left on Washington Parkway.** Prior to turning, Washington Black Ridge is at 12:00. The road cut on I-15 through the ridge exposes the Washington flow, which occupies the now-inverted ancestral channel of Grapevine Wash. This is the most mafic of the volcanic flows in the St. George area. Best and others (1980) reported a K-Ar age of 1.7$\pm$0.1 Ma for this flow, but Biek (2003a) obtained two $^{40}Ar/^{39}Ar$ ages for the flow of 0.98 $\pm$0.02 Ma and 0.87$\pm$0.04 Ma. The basalt is strongly jointed and has been quarried for building stone (Biek, 2003a).
0.1	7.5		**Roundabout, negotiate carefully and continue straight on Washington Parkway.**
1.0	8.5		**T-junction and stop sign, turn right on Telegraph Street.**
1.0	9.5		**Stoplight, turn left on 300 E. Street (Washington Fields Road).**
0.8	10.3		Trace of the Washington fault; here the fault displaces the Washington flow down to the southwest.
0.2	10.5		**Passing Point of Interest: Flood of January 8-12, 2005 on the Virgin and Santa Clara Rivers** Riverine flooding along major drainages in southwestern Utah is usually regional in nature, lasts for several hours or days, typically takes place on perennial streams, has recurrence intervals of from 25 to more than 100 years, and usually can be predicted days to weeks in advance. Riverine floods commonly

result from the rapid melt of a winter snowpack or from periods of prolonged heavy rainfall associated with major frontal storms, or from both conditions simultaneously. Where uncontrolled, riverine floods can inundate large areas along flood plains and cause extensive erosion and flood damage over a wide area.

Measurements or careful estimates of historical peak flows on the Virgin River date to 1909 (U.S. Army Corps of Engineers, 1973), but are not available for every year. Similarly, records of historical peak flows for the Santa Clara River and Fort Pearce Wash (figure 1) contain gaps. The largest recorded natural flood on the Virgin River occurred in January 2005. The U.S. Geological Survey (USGS, 2006a) reported a peak discharge of 21,000 cubic feet per second (cfs) on the Virgin River at Hurricane, Utah. The largest recorded flow on the Santa Clara River was 6390 cfs near the city of Santa Clara in 1966 (USGS, 2006a), a flow nearly equaled with the peak flow of 6200 cfs on the Santa Clara River at St. George in January 2005 (USGS, 2006a). The 2005 flood resulted from a prolonged rain event on heavy snowpack at low elevations, and is the most damaging flood recorded in the St. George area. Both the regional 1966 and 2005 floods were winter rain-on-snow events that occurred when a strong El Niño was subsiding.

In the January 2005 flood as many as 50 homes were destroyed or condemned, chiefly along the Santa Clara River (figure 4), and damage exceeded $180 million dollars (USGS, 2006b). Washington County

***Figure 4**. Damage to homes caused by flooding in January 2005.*

received a federal disaster declaration following the flood. The majority of the damage occurred as a result of bank erosion and channel migration. This behavior is a common occurrence along rivers in the arid Southwest, but not typically addressed in flood-plain mapping. Long stretches of stream banks along both the Virgin and Santa Clara Rivers were armored with riprap following the 2005 flood.

1.0	11.5	Washington Dome at 11:00, Nichols Peak at 3:00.
1.1	12.6	**Turn left on Majestic Drive.**
0.3	12.9	**STOP 1: WASHINGTON FAULT**

The Washington fault is a down-to-the-west normal fault that stretches from northern Arizona into southern Utah (figure 1). Displacement decreases northward along the fault, from 2200 feet about 6 miles south of the border, to about 1650 feet at the state line (figure 5), to about 700 feet near Washington City (Billingsley, 1992; Hayden, 2005). The fault may link up with the Washington Hollow fault near the west edge of the Pine Valley Mountains (Cordova, 1978; Willis and Higgins, 1995; Biek and others, 2007).

Figure 5. View northwest to the Washington fault, about four miles south of Stop 1. Mixed alluvial and colluvial deposits (Qaeo) on the hanging wall are in fault contact with the Shnabkaib Member (TRms) of the Moenkopi Formation exposed in the footwall (from Biek and Hayden, 2007).

Fault drag along the Washington fault has created narrow, anticlinal footwall folds in the Moenkopi Formation and the Shinarump Conglomerate Member of the Chinle Formation from Washington Dome south into Arizona.

Three fault scarps provide data to bracket ages of movement on the Washington fault. One scarp, about 2.75 miles to the south, cuts highly dissected, gently sloping, mixed colluvial and alluvial sediments that, based on scarp profiling and comparison to dated scarps elsewhere, Anderson and Christenson (1989) considered to be latest Pleistocene in age. Equidistant to the north, several scarps on splays of the fault cut the 900,000-year-old Washington lava flow (Biek, 2003a; Hayden, 2005). Other prominent scarps in the quadrangle seem to be the result of differential erosion, a conclusion reached by Peterson (1983) and Anderson and Christenson (1989).

Recent trenching by Applied Geotechnical Engineering Consultants, Inc. (AGEC) across the low scarp visible to the southeast has exposed the main trace of the Washington fault (figure 6). This was AGEC's third attempt in the past several years to locate the fault in this area prior to residential development. With limited time available to study the trenches, the UGS conducted a brief reconnaissance investigation of the exposed fault. The northernmost trench exposed a 4-meter-wide fault zone consisting of at least three splays that dip steeply to the west. Colluvial-wedge deposits provide evidence for three surface-faulting earthquakes that displace mixed alluvial-colluvial-eolian deposits by amounts ranging from about 35 cm to just less than 1 m. The most recent earthquake displaces the modern soil Bk horizon and an overlying weakly indurated sand deposit. The fault rupture extends to within 25 cm of the ground surface where it is buried by modern, actively accumulating eolian sand. Based on these structural and stratigraphic relations, we conclude that the most recent surface-faulting earthquake on the Washington fault is no older than latest Pleistocene and likely occurred in Holocene time.

The UGS collected several samples of colluvial/eolian sand from within, above, and below the colluvial wedges (figure 6) and submitted them to the Optically Stimulated Luminescence (OSL) Geochronology Laboratory at Utah State University for analysis to constrain the ages of the surface-faulting earthquakes. The OSL age results are expected in the summer of 2007.

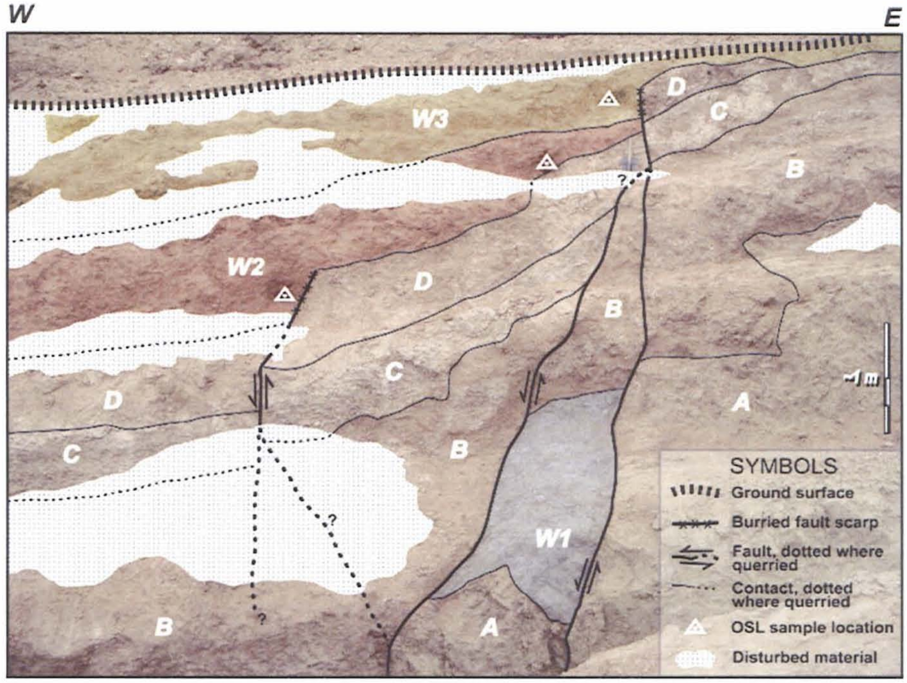

Figure 6. Reconnaissance photolog of AGEC trench across the Washington fault zone near the south end of Washington Dome. Unit descriptions from oldest to youngest: A = highly weathered Virgin Limestone Member of the Moenkopi Formation, W1 = colluvial wedge consisting mostly of eolian sand, B = slightly to moderately indurated mixed alluvial and eolian sandy sediments, C = alluvial sandy gravel with a moderately developed Bk soil horizon, D = moderately indurated mixed alluvial and eolian sand, W2 = colluvial wedge consisting of slightly indurated eolian sand, W3 = colluvial wedge consisting of loose eolian sand.

3.4	16.3	**Return to intersection of 300 E. Street and Telegraph Street. Turn right on Telegraph Street.**
1.3	17.6	Road begins to ascend Washington Black Ridge.
0.4	18.0	Road cut on the right exposes the Washington flow occupying the ancestral channel of Grapevine Wash cut on the Triassic Chinle Formation.
1.0	19.0	Cross Grapevine Wash, note new homes built in flood plain.
1.8	20.8	**Stoplight, turn right and proceed east on State Route 9 (SR 9).**

0.5	21.3	Road cut exposes the northwest limb of the Virgin anticline. Beneath this fold is a blind, west-dipping thrust fault (Davis, 1997). The rim rock surrounding the eroded center of the anticline is the resistant Shinarump Conglomerate of the Chinle Formation. Colorful Moenkopi Formation beds lie beneath the Shinarump.
0.4	21.7	View to the east toward the town of Hurricane. West limb of the Virgin anticline at 11:00; Volcano Mountain, a large Quaternary cinder cone at 1:00; east limb of the Virgin anticline at 12:00; the Hurricane Cliffs, which mark the trace of the Hurricane fault, in the middle ground at 2:00; and the sandstone spires and temples of Zion National Park in the far distance at 1:00.
1.1	22.8	On the left, the west limb of the Virgin anticline exposes the upper members of the Moenkopi Formation, and the Shinarump Conglomerate of the Chinle Formation (yellow) caps the ridge.
0.6	23.4	**Passing Point of Interest: Quail Creek South Dam and Reservoir**

Quail Creek Dam and Reservoir are owned and operated by the Washington County Water Conservancy District (WCWCD). The Quail Creek Water Treatment Plant treats 20 million gallons of water per day and supplies drinking water to the towns of St. George, Ivins, Hurricane, and Washington.

Quail Creek reservoir has a 40,000 acre-foot capacity and is formed by two dams, known as the main and south dams (11:00). Construction of the south dam's 78-foot-high, 1980-foot-long earthen embankment was completed in April 1984. The main dam was completed in January 1985, and reservoir filling began in April 1985. The dike began experiencing severe leakage almost immediately and grouting programs were undertaken three different times between 1986 and 1988. However, after undergoing repeated episodes of increased seepage, discolored seepage, and development of small sinkholes during the preceding three years, the south dam failed catastrophically (figure 7) a few minutes after midnight on January 1, 1989. Downstream evacuation prevented fatalities and injuries, but flooding caused millions of dollars of damage and disrupted major highways and bridges. Peak discharge at the Bloomington Gage on the Virgin River several miles downstream was estimated by the USGS at 60,000 cfs.

Figure 7. View looking north at the Quail Creek south dam failure, January 1989. Photo courtesy of Benjamin Everitt.

The south dam was constructed approximately perpendicular to the axis of the doubly-plunging Virgin anticline in thin-bedded sediments of the gypsiferous Shnabkaib Member of the Triassic Moenkopi Formation. Gypsum content exceeds 50 percent in some Shnabkaib beds. Due to the folding, bedrock within the anticline is highly fractured, and both the fractures and the strike of the bedrock were oriented normal to the axis of the dam (O'Neill and Gourley, 1991; Gourley, 1992).

The failure resulted from seeping water removing embankment material and/or in-situ soils at the dam/foundation contact. As the seepage and erosion accelerated, a process of backward erosion caused caving and the eventual breach of the dike embankment. Several factors contributing to the failure: (1) erodible materials existed or were placed at the dike/foundation contact, (2) the rock foundation was extensively jointed and weathered with discrete seepage paths, particularly near the ground surface where open cavities caused by expansion, dissolving, and erosion of gypsum were common, and (3) participation of an engineering geologist was limited during all phases of the project (Gourley, 1992). Lacking critical geologic information, errors contributing to the dike's failure included an underestimation of the gypsum content in the foundation, a mistaken assumption of low foundation permeability, and inadequate preparation and treatment of the foundation (O'Neill and Gourley, 1991; Gourley, 1992).

The WCWCD retained Morrison Knudsen Engineers of San Francisco and James M. Montgomery Consulting Engineers of Salt Lake City to design a structure to replace the failed dam. Geotechnical investigations began in June 1989 to evaluate foundation conditions and borrow materials. The consultants used rock quality, the amount of gypsum present, hydraulic conductivity, rock core recovery, and previous grouting records to select the type and depth of a cutoff trench (Payton, 1992).

A 2000-foot-long concrete cutoff trench was constructed with a maximum depth of approximately 75 feet in the breach area and tapering to 50 feet at the left abutment and 25 feet at the right abutment (figure 8). The volume of material excavated for the cutoff was 68,000 yd^3. The rebuilt dam is a concrete gravity dam constructed using 176,000 yd^3 of roller-compacted concrete. The new dam has a crest length of approximately 2000 feet, a width of 16 to 86 feet, and ranges in height from 6 to 78 feet.

Figure 8. The Quail Creek south dam cutoff trench during reconstruction.

0.5	23.9		At 10:00 is the flood path created by the Quail Creek dam failure (see figure 7 for an aerial view). The floodwater stripped away all soil and vegetation in its path and exposed Moenkopi bedrock.
0.2	24.1		East limb of the Virgin anticline. During the Quail Creek south dam failure, floodwater was tens of feet deep as it passed through this road cut.
0.2	24.3		New bridge across the Virgin River – the old bridge was destroyed by the flood following the Quail Creek south dam failure.
0.6	24.9		Road cut exposes a lava flow sourced from cinder cones near the town of Hurricane.
0.2	25.1		Main Quail Creek dam at 9:00. Volcano Mountain at 2:00 is the source for several mafic lava flows in the Hurricane area. Two flows from Volcano Mountain dated by Sanchez (1995) yielded $^{40}Ar/^{39}Ar$ ages of 0.258 ± 0.024 Ma and 0.353 ± 0.045 Ma.
1.5	26.6	MP-6	Road cut exposes a mafic lava flow overlying the Jurassic Navajo Sandstone.
2.0	28.6		Entering the town of Hurricane. The Cinder Pits (9:00) and Radio Tower (10:00) cinder cones are part of the Hurricane volcanic field (Biek, 2003b).
0.5	29.1		Stoplight at 1150 W. Street, continue straight.
0.5	29.6		Stoplight at 700 W. Street, continue straight.
0.4	30.0		Stoplight at 300 W. Street, continue straight.
0.3	30.3		Stoplight at Main Street, continue straight. The Hurricane Cliffs are at 12:00; the Hurricane fault lies at the base of the cliffs. The lava flow remnant stranded near the midpoint of the cliffs yielded a $^{40}Ar/^{39}Ar$ age of 0.353 ± 0.045 Ma (Sanchez, 1995). SR 9 will soon bear to the left and begin paralleling the Hurricane Cliffs and fault.
1.1	31.4		**Just before the bridge across the Virgin River turn right on the access road to Pah Tempe Hot Springs.**

0.3 31.7

STOP 2. TIMPOWEAP CANYON: LAVA FLOWS, HURRICANE FAULT ZONE, AND PAH TEMPE HOT SPRINGS.

Volcano Mountain lava flow: The lava flow visible in the surrounding cliffs and to the west along the Virgin River erupted from Volcano Mountain, the large cinder cone just southwest of Hurricane. Biek (2003b) mapped this flow, which traveled both north and then southwest toward and down the ancestral Virgin River, and also east and northeast, where it blocked the Virgin River and crossed the Hurricane fault. Remnants of the flow are preserved here on the both the footwall and hanging wall of the Hurricane fault.

The lava flow is an olivine basalt that is typically 35 to 45 feet thick, but it thickens greatly where it fills paleotopography. Exposures here reveal a single cooling unit about 170 feet thick that reaches to current river level (figure 9). The base is marked by a rubbly zone; 20 to 40 feet thick that contains pillow basalts (figure 10). This rubbly zone is overlain by about 10 feet of dense, fine-grained basalt with prominent, widely spaced columnar joints (the lower colonnade), which in turn is overlain by about 100 feet of similar basalt that is prominently and chaotically jointed (the entablature). The upper roughly 20 feet of this

Figure 9. Volcano Mountain lava flow and SR 9 bridge over the Virgin River. This cliff reveals a single lava flow about 170 feet thick; at its base is a 20- to 40-foot-thick rubbly zone with pillow basalts, indicating that the flow once blocked the ancestral Virgin River, creating a small lake into which lava flowed (from Biek and Hayden, 2007).

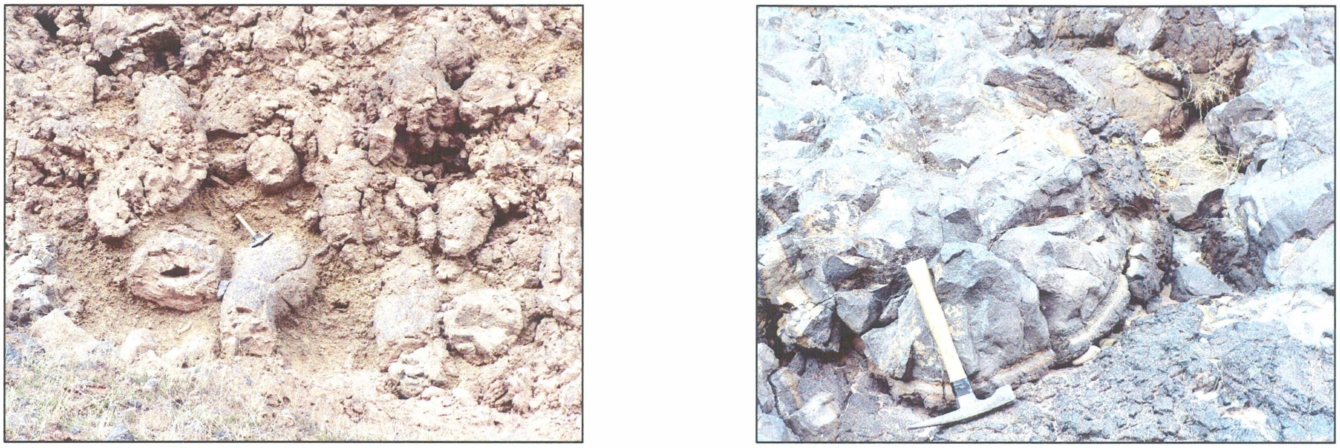

Figure 10. Close-up of pillow basalt near the SR 9 bridge (from Biek and Hayden, 2007).

exposure consists of vesicular basalt with few columnar joints (the upper colonnade).

This lava flow yielded an $^{40}Ar/^{39}Ar$ isochron age of 0.353 ± 0.045 Ma (Sanchez, 1995) and a K-Ar age of 0.289 ± 0.086 Ma (Best and others, 1980). Paleomagnetic studies show that this flow has a normal polarity, which is consistent with the radiometric age determinations, and that there is less than 10E of reverse drag on the hanging-wall flow (Hozik, 1999; Lund and others, 2007).

Hurricane fault zone: The Hurricane fault is a major, active, steeply west-dipping normal fault that extends from south of the Grand Canyon northward to Cedar City. In the Hurricane area, the Upper Cretaceous Iron Springs Formation is down to the west against the Lower Permian Toroweap Formation (figure 2), resulting in an apparent, or stratigraphic, separation across the fault in this area of nearly 9000 feet (Biek, 2003b). However, by subtracting the effects of previous Sevier-age folding, reverse-drag flexure in the footwall, and rise-to-the-fault flexure in the hanging wall, the true tectonic displacement across the fault near Hurricane is about 3600 feet (Anderson and Christenson, 1989).

Here, where the Virgin River crosses the fault, the 350,000-year-old lava flow is displaced about 240 feet across three strands of the fault zone (figure 11). Lund and others (2001, 2007) calculated an average slip rate of about 0.21 mm/yr for this part of the Hurricane fault since about 350,000 ka.

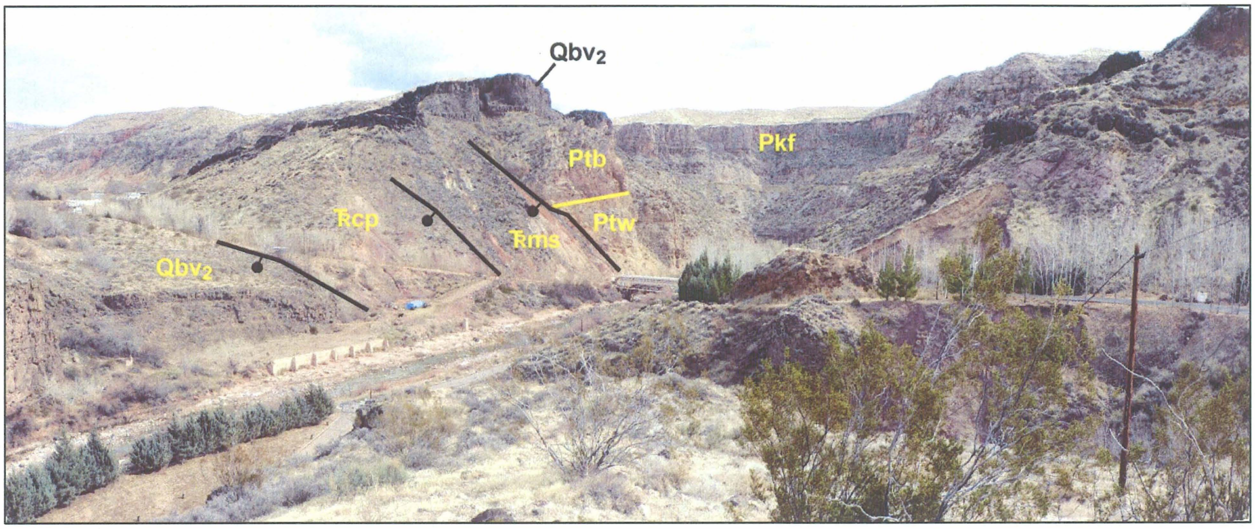

Figure 11. View northeast to the entrance of Timpoweap Canyon. Three main strands of the Hurricane fault zone are shown. Here, the 350,000 ka Volcano Mountain lava flow (Qbv_2 of Biek, 2003b) is displaced about 240 feet, yielding an average slip rate of about 0.21 mm/yr for this part of the fault. The fault zone is characterized by a west-dipping panel of Triassic strata caught between splays of the fault; these red beds act as a barrier to ground water flow, causing warm water to rise through permeable Permian strata in the footwall and emerge as Pah Tempe Hot Springs. TRcp = Petrified Forest Member of the Chinle Fm.; TRms = Shnabkaib Member of the Moenkopi Fm.; Ptw and Ptb = Woods Ranch and Brady Canyon Members of the Toroweap Fm., respectively; Pkf = Fossil Mountain Member of the Kaibab Fm. (from Biek and Hayden, 2007)

Pah Tempe Hot Springs: Pah Tempe Hot Springs (also known as LaVerkin or Dixie Hot Springs) (figure 12) has the highest recorded spring-water temperature in the St. George area (Budding and Sommer, 1986). The springs average about 104 °F, have a pH of 6.3, and discharge sodium-chloride-type water with an average of 9600 to 9900 mg/L TDS. They issue from and immediately above the bed of the Virgin River (from near the base of the Brady Canyon Member of the Toroweap Formation) for a distance of nearly 1500 feet upstream of the Hurricane fault. Mundorff (1970) and Yelken (1996) summarized physical and chemical parameters of the Pah Tempe Hot Springs. They noted that the average annual dissolved-solids discharge at the springs is about triple that of the Virgin River just upstream of the springs. The high TDS of the spring water contributes to poor downstream water quality, and is the reason Virgin River water is collected above the springs and piped to Quail Creek and Sand Hollow Reservoirs.

The west-dipping panel of Triassic red beds caught in the Hurricane fault zone acts as a barrier to

Figure 12. Pah Tempe Hot Springs average about 104 °F (40 °C) and issue from and immediately above the bed of the Virgin River, just upstream from the Hurricane fault (from Biek and Hayden, 2007).

Ground-water flow, whereas the fractured and cavernous Permian carbonates east of the fault act as conduits to ground-water flow. Dutson (2005) studied the springs and noted that the hydrogen and oxygen isotopic composition of the spring water suggested a minimum circulation depth of 2300 to 4300 feet. It seems reasonable that as ground water encounters the Hurricane fault at depth, it is forced laterally and upward, eventually discharging along the Virgin River. The source of the hot water is thus structurally controlled and is not related to Pleistocene volcanic activity. Basalts in the region originated at far greater depth, rising to the surface though narrow conduits, thus precluding the basaltic magmas from being a significant heat source (Budding and Sommer, 1986).

0.3	32.0		**Return to SR 9 and turn left toward the town of La Verkin.**
0.2	32.2	MP-11	Bridge over the Virgin River – enter the town of La Verkin.
1.4	33.6		**Junction, turn right at stoplight by Chevron station and continue on SR 9 toward Springdale and Zion National Park.**

The Hurricane Cliffs and Hurricane fault are at

12:00. The cliffs expose the yellowish-tan Permian Kaibab Formation in the fault footwall. The Jurassic Navajo Sandstone is buried by alluvium beneath us in the fault hanging wall. As SR 9 climbs the Hurricane Cliffs we are leaving the Colorado Plateau – Basin and Range transition zone and entering the Colorado Plateau proper.

0.6 34.2 MP-13 From 10:00 to 1:00 are the Pine Valley Mountains, which are part of the eroded remnants of one of the world's largest laccoliths. The laccolith, which has a preserved maximum thickness of 3000 feet and a maximum horizontal dimension of over 20 miles in a northeast-southwest direction, was emplaced in the early Miocene, about 20.5 Ma, into the Claron Formation, where it spread out into a shallow, mushroom-shaped intrusion (Hacker, 1998; Hacker and others, 2002; Willis, 2002; figure 13). The laccolith was emplaced rapidly, which resulted in catastrophic slope

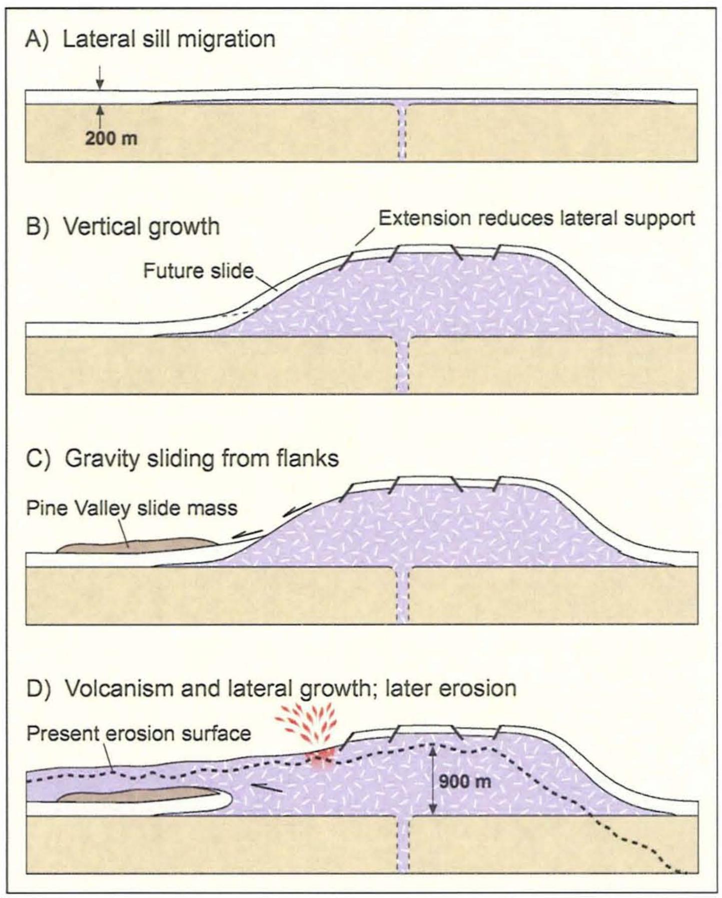

Figure 13. Four steps of intrusion of the Pine Valley laccolith, with resulting gravity slide, and post-slide volcanism (triggered by suddenly reduced pressure) and continued intrusion (from Hacker and others, 2002, and Willis, 2002).

failure on oversteepened topography. The result was enormous gravity slides – highly sheared, allochthonous rock masses soled on low-angle faults and laterally bounded by tear faults. This unroofing of the laccolith led to concomitant eruption of ash-flow tuffs, tuff breccias, and lava flows that blanket the gravity slide masses.

0.5 34.7 To the left, the strongly contrasting red color of the steeply west-dipping Moenkopi Formation in the hanging wall, and the yellowish tan color of the gently east-dipping Kaibab Formation in the footwall mark one trace of the Hurricane fault.

0.2 34.9 On the right, this road cut exposes a polished slickensided surface of a strand of the Hurricane fault. Rounding the curve ahead, the Hurricane fault, as expressed by contrasting rock colors, can be seen extending along the base of the cliff to the left.

1.2 36.1 MP-15 **Junction, turn right on the La Verkin Overlook road.**

1.5 37.6 **STOP 3. LA VERKIN OVERLOOK –THE HURRICANE FAULT ZONE**

Extending from Cedar City, Utah, to Peach Springs, Arizona, south of the Grand Canyon (figure 14), the 160-mile-long Hurricane normal fault has produced thousands of feet of vertical displacement during late Cenozoic time. The Hurricane fault is within the approximately 100-mile-wide structural and seismic transition zone between the Colorado Plateau and Basin and Range physiographic provinces. In this transition zone, the generally subhorizontal Paleozoic and Mesozoic strata of the Colorado Plateau are displaced thousands to tens of thousands of feet down-to-the-west by a series of north-trending normal faults. Geologic evidence indicates that the Hurricane fault is the most active of these faults in southwestern Utah, and displacement across the fault is recorded by the impressively steep and linear Hurricane Cliffs, which closely follow the fault trace over most of its length. Previous studies of the Hurricane fault documented displaced Quaternary lava flows and alluvium (Anderson and Mehnert, 1979; Menges and Pearthree,

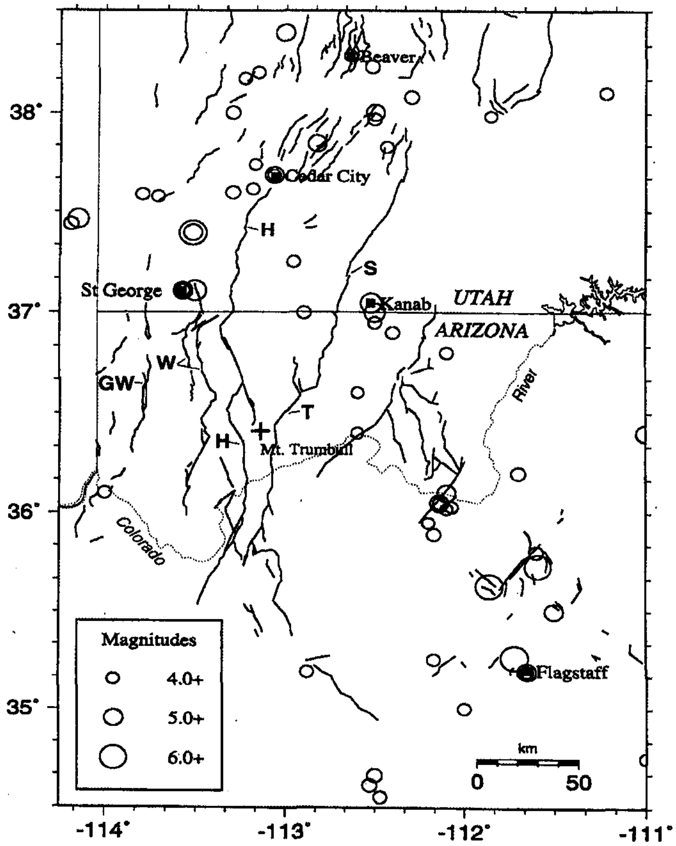

Figure 14. Quaternary faults and historical earthquakes in southwestern Utah and northwestern Arizona. H = Hurricane fault, W = Washington fault, GW = Grand Wash fault, S = Sevier fault, T = Toroweap fault. Figure courtesy of the Arizona Geological Survey.

1983; Pearthree and others, 1983; Anderson and Christenson, 1989; Hecker, 1993; Stewart and Taylor, 1996; Stewart and others, 1997; Black and others, 2003; Lund and others, 2007).

Historical seismicity: Historical seismicity in southern Utah and northern Arizona has generally been diffuse (figure 14), with several concentrations of activity and a few moderately large earthquakes. The Colorado Plateau-Basin and Range transition is coincident with the Intermountain seismic belt (Smith and Sbar, 1974). Although surface rupture has not occurred along the Hurricane fault historically, the area surrounding it has a moderate record of seismicity. Most notable of past seismic events are the 1902 M ~6 Pine Valley, Utah, earthquake, and the 1992 M_L 5.8 St. George earthquake (Smith and Arabasz, 1991; Pechmann and others, 1995). Both of these earthquakes are thought to have been on or near the Hurricane fault. Based on hypocentral location, aftershock distribution, nodal plane orientation, and other data, Pechmann and others (1995) concluded that the St. George earthquake was caused by slip on the Hurricane fault.

Segmentation: The Hurricane fault almost certainly ruptures in segments, as has been observed historically for long normal faults in the Basin and Range Province (Schwartz and Coppersmith, 1984; Schwartz and Crone, 1985; Machette and others, 1992). The Anderson Junction segment (AJS) on which this field-trip stop is located is one of six fault segments identified along the Hurricane fault (Pearthree and others, 1998; Lund and others, 2001; Lund and others, 2002; Black and others, 2003; Lund and others, 2007). The AJS is near the center of the fault zone and extends approximately 28 miles from north of Toquerville in Utah to south of Cottonwood Canyon in Arizona. The fault trace follows the high, north-trending, west-facing escarpment in Paleozoic bedrock visible both to the north and south from this vantage point (figure 15). In Arizona, scarps up to 100 feet high on late Pleistocene colluvium and alluvium mark the fault along the base of the escarpment.

Earthquake timing: Stenner and others (1999) excavated two trenches on the AJS at Cottonwood Canyon in Arizona, and identified two surface-faulting earthquakes on the basis of stratigraphic displacement, shear fabric, and fault drag. Additionally, Stenner and others (2003) excavated a trench across a single fault scarp formed on an alluvial fan at Rock Canyon, approximately 2.5 miles south of Cottonwood Canyon where they found evidence for three surface-faulting earthquakes.

Stratigraphic relations in the Cottonwood Canyon trenches indicated that event Z (most recent surface-faulting earthquake) occurred 5-10 thousand years ago (ka). The timing of event Y (penultimate surface-faulting earthquake) could not be determined other than bracketed as > 5-10 ka and < 25-50 ka (estimated age of the faulted fan surface). No carbon or other material suitable for dating was recovered from the trenches.

The trench at Rock Canyon revealed evidence for three surface-faulting earthquakes of variable displacement based on stratigraphic displacement, shear fabric, fault drag, fissuring, and minor graben formation. Laboratory results from bulk samples collected from the trench for ^{14}C dating are not yet available, so the timing of the three earthquakes is unknown.

Because the timing of surface-faulting earthquakes on the AJS is poorly constrained, the Utah Quaternary Fault Parameters Working Group (UQFPWG; Lund, 2005) limited the surface-faulting chronology for the AJS to broad time intervals:

Event Z	5-10 ka
Event Y	> 5-10 ka and < 25-50 ka
Event X	> 25-50 ka?

Surface-faulting recurrence: Stenner and others (1999, 2003) did not report recurrence intervals for the AJS at either the Cottonwood Canyon or Rock Canyon sites. However, the surface-age estimates at Cottonwood Canyon imply one surface-faulting earthquake since 5-10 ka and two earthquakes since 25-50 ka. Age estimates are presently not available for the surface of the alluvial fan or for the three surface-faulting earthquakes at Rock Canyon. However, if events Y and Z at Rock Canyon are the same as at Cottonwood Canyon, then the timing of event X at Rock Canyon must be >25-50 ka, since it was not recognized in the second trench at Cottonwood Canyon only 2.5 miles away.

Because the timing of surface faulting on the AJS is poorly constrained, the UQFPWG (Lund, 2005) reported a consensus recurrence interval for the AJS of 5-50 thousand years to reflect the large uncertainty associated with the data.

Vertical slip rate: From scarp profiles measured at Cottonwood Canyon, Stenner and others (1999) calculated vertical slip rates of 0.1-0.3 mm/yr in ~70-125 ka deposits, and 0.1-0.4 mm/yr in ~25-50 ka deposits. Lund and others (2001, 2007) geochemically correlated and $^{40}Ar/^{39}Ar$ dated displaced mafic lava flows at four locations on the AJS. The flows indicate a vertical slip rate since the middle Quaternary of $\geq$0.45

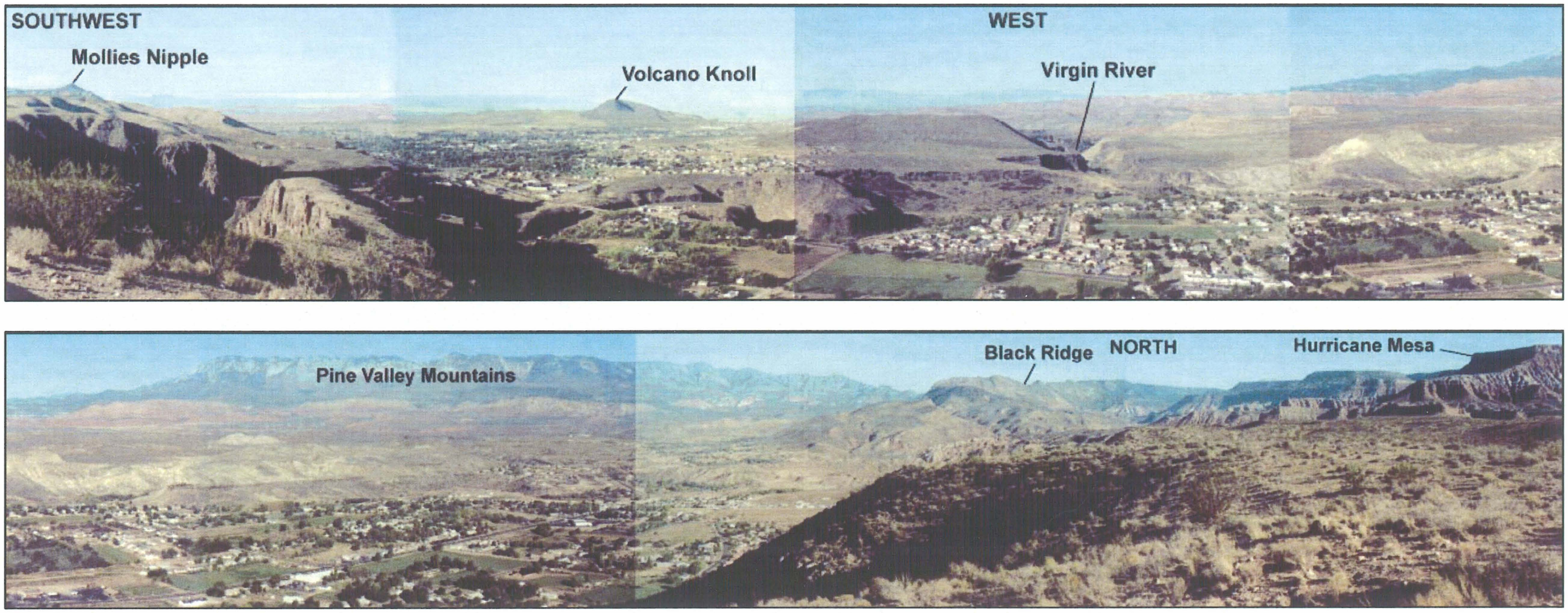

Figure 15. Panoramic view west from the LaVerkin Overlook. Beginning at the lower right, a complete section of the Moenkopi Formation is exposed below the Shinarump Conglomerate, which caps Hurricane Mesa; the overlook itself is on the Timpoweap Member of the Moenkopi Formation. Black Ridge is carved from the east limb of the Kanarra anticline and is locally capped by the 850,000-year-old Pintura lava flow. This lava flow had its principal source west of the Hurricane fault and has since been displaced over 1000 feet (300 m) by down-to-the-west movement on the Hurricane fault. The Pine Valley Mountains, an early Miocene laccolith intruded into the Claron Formation, form the skyline to the northwest. To the west and southwest, the Virgin River cuts across the north end of the Hurricane volcanic field. The basalt flow exposed in the footwall of the Hurricane fault zone, just south of the Virgin River, yielded an $^{40}Ar/^{39}Ar$ age of 353 $\pm$ 45 ka (Sanchez, 1995); it has been displaced about 240 feet (73 m) by the Hurricane fault. Pillow basalt at the base of this flow, exposed on both the upthrn and downthrown blocks, shows that the flow temporarily blocked the Virgin River. Mollies Nipple, on the skyline at left, is capped by a basaltic lava flow that erupted at Ivans Knoll, immediately south of Volcano Knoll. The Ivans Knoll flow is about 1,000,000 years old and has been displaced about 1300 feet (400 m) by the Hurricane fault (from Biek and Hayden, 2007).

mm/yr, slowing to ≤0.2 mm/yr since about 350 ka.

Based on available information, the UQFPWG (Lund, 2005) consensus vertical slip-rate estimate for the AJS is 0.2 mm/yr, but could reasonably be as low as 0.05 or as high as 0.4 mm/yr.

1.5 39.1 MP-15 **Return to the intersection of La Verkin Overlook road and SR 9 and turn right toward the town of Virgin.**

Prior to turning, Hurricane Mesa is at 12:00. Hurricane Mesa is the site of a commercial (formerly Air Force) rocket-sled facility used to test various kinds of materials. The side of the mesa exposes an almost complete section of the Moenkopi Formation (figure 16).

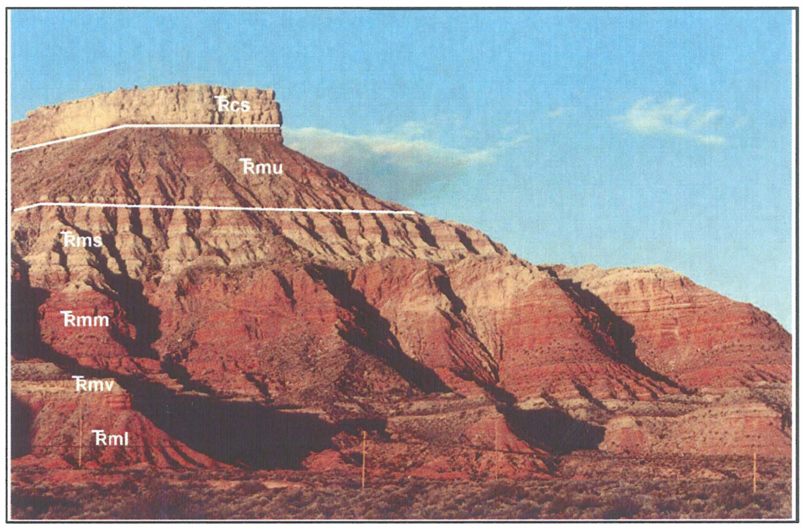

Figure 16. View northeast to Hurricane Mesa. Hurricane Mesa is capped by the Shinarump Conglomerate Member of the Chinle Formation (TRcs), below which is a striking section of the Moenkopi Formation, including the upper red (TRmu), Shnabkaib (TRms), middle red (TRmm), Virgin Limestone (TRmv), and lower red (TRml) members. Note old landslide (area of disrupted bedding) in the middle red and Shnabkaib Members (from Biek and Hayden, 2007).

1.9 41.0 Entering the town of Virgin. The Virgin lava flow caps the mesa at 11:00. Willis and Biek (2001) obtained a $^{40}Ar/^{39}Ar$ age of 1.06±0.01 Ma for this flow. The flow traveled down an ancestral North Creek channel to near the Virgin River. The river has downcut the landscape 1,300 feet in the million years since emplacement of the lava flow, for a rate of 1.3 ft/1,000 years (Biek and others, 2007).

1.6	42.6		Crossing North Creek, a tributary to the Virgin River and site of a proposed dam.
0.6	43.2	MP-20	Crater Hill lava flow on the left. Utah Geological Survey unpublished $^{40}Ar/^{39}Ar$ ages (Bob Biek, UGS, personal communication, 2007) indicate that the flow is about 300,000 years old. Note basalt-talus-covered landslides for the next several miles on the left side of SR 9.
5.0	48.2	MP-25	On the left, a view of the Crater Hill lava flow and cone.
1.8	50.0		Entering the town of Rockville and lower Zion Canyon.
0.4	50.4	MP-27	Numerous large rock-fall boulders on both sides of SR 9; most are from the Shinarump Conglomerate Member of the Chinle Formation, which crops out on the canyon wall to the left.
0.8	51.2		**Passing Point of Interest: Home Damaged by a Rock Fall**

On October 18, 2001, at approximately 5:30 a.m., a large boulder dislodged from a cliff face along the south side of the Rockville Bench in lower Zion Canyon, rolled and bounced down slope, and struck and severely damaged a private residence (Lund, 2002; Rowley and others, 2002; figure 17).

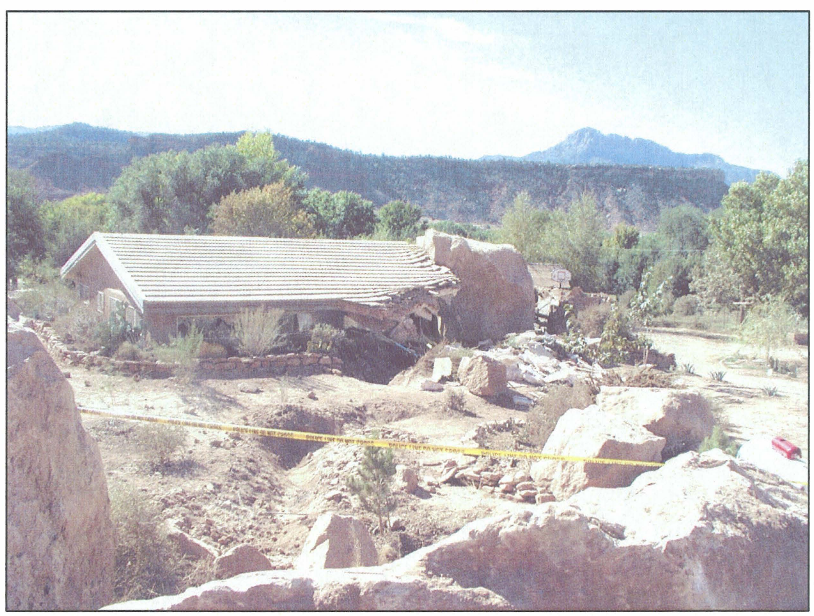

Figure 17. Home struck by an estimated 300-ton Shinarump Conglomerate boulder in October 2001. The boulder dislodged from an adjacent cliff; note the gouge where the boulder traveled across the yard.

The boulder, measuring approximately 16 by 16 by 12 feet and weighing an estimated 300 tons, broke loose from an outcrop of the Shinarump Conglomerate Member of the Chinle Formation, which caps the Rockville Bench north of the Virgin River. The well-indurated Shinarump sandstone and conglomerate beds rest upon less resistant shale, mudstone, and silty sandstone beds of the upper red member of the Moenkopi Formation. The Shinarump outcrop stands about 200 feet above the adjacent valley floor and the damaged home (figure 18).

The boulder was part of a larger rock fall that consisted of several boulders, at least one of which was even larger than the boulder that hit the home. Fortunately, the other boulders came to rest on a dirt road at the base of the slope. However, the damaging boulder continued to roll and bounce across the road and the yard of the home, leaving deep gouges in the yard and at one point bouncing completely over an approximately 24-inch-high rock wall, before hitting the house. The boulder crashed through the outside wall

Figure 18. Shinarump Conglomerate overlying the upper red member of the Moenkopi Formation above the damaged home. Note the fresh scar where the rock fall detached from the cliff.

of the home and entered the bedroom, narrowly missing the (no longer) sleeping homeowner. In addition to the bedroom, the boulder destroyed the adjoining bathroom, service area, and living room.

Other fresh-appearing rock-fall scars on the Rockville Bench cliff face, and numerous boulders on and at the base of the steep slope capped by the Shinarump Conglomerate, attest to the frequency of rock falls in the area. Even so, this rock fall was unusual in that it lacked an obvious triggering event. The weather was dry and had been for some time, so storm-related or above-average precipitation was not a factor in the failure. Similarly, no earthquakes were recorded at the time of the failure and none occurred in the area for some time prior to the rock fall. Therefore, this rock fall apparently resulted from the cumulative effects of gradual erosion and gravity. The Moenkopi strata that underlie the Shinarump sandstones and conglomerates (figure 2) are more susceptible to erosion than the overlying harder rocks. Over time, erosion of the softer Moenkopi strata undercut the Shinarump beds until the force of gravity was sufficient to cause the cliff face to fail. Similar rock falls can be expected at any time anywhere along the south edge of the Rockville Bench where the Shinarump Conglomerate stands in a near-vertical cliff face above the adjacent canyon floor. Note many other houses in Rockville built among, and in some cases around Shinarump boulders.

1.1	52.3	MP-29	On the left, contact between the upper red member of the Moenkopi Formation and the overlying Shinarump Conglomerate Member of the Chinle Formation is exposed in the canyon wall.
0.5	52.8		Shinarump Conglomerate at road level. As we proceed up Zion Canyon, we will continue to drive progressively up-section through the gently east-dipping Mesozoic rocks exposed in the canyon walls (figure 2).
0.3	53.1		Enter the town of Springdale.
2.4	55.5	MP-32	**Junction, turn left on Balanced Rock Road.**
0.1	55.6		**STOP 4. SPRINGDALE LANDSLIDE**

The most damaging effect of the September 2, 1992, St. George earthquake (M_S 5.6, **M** 5.7, M_L 5.8; Arabasz and others, 1992) was the Springdale landslide (figure 19), which destroyed three homes (see road log cover), two water tanks, and several storage buildings. The landslide also blocked SR 9 leading to Zion National Park, ruptured both buried and above-ground utility lines, and caused a condominium complex and several businesses around the periphery of the slide to be temporarily evacuated. The earthquake also triggered a smaller slope failure west of the Springdale landslide, called the Paradise Road landslide (figure 19), which caused no damage.

The Springdale landslide is a complex block slide that involves both rotational and translational elements (Black, 1994). Although ground shaking initiated the movement, the landslide moved slowly and continued to move for several hours after the earthquake. The

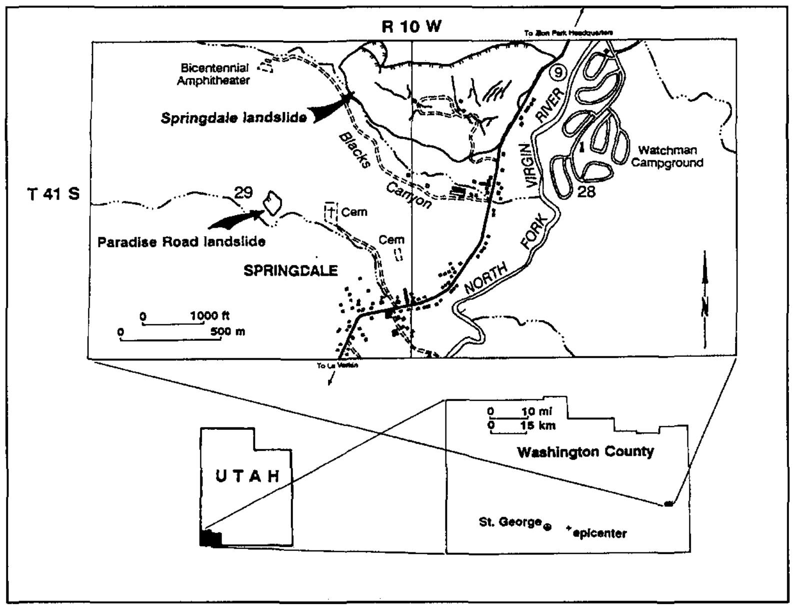

Figure 19. Springdale landslide and the epicenter of the 1992 St. George earthquake (after Black and others, 1995).

slide measures approximately 1600 feet from the main scarp to the toe, has a width of about 3600 feet, and a surface area of 4.4 million square feet. The total volume of the slide is about 18 million cubic yards (Black and others, 1995). The landslide has a clearly defined main scarp as well as numerous fissures and minor scarps that form a broken irregular topography within the slide mass (figure 19). The spacing and orientation of the scarps and fissures indicate that the landslide likely moved as several coherent blocks. Several smaller landslides also developed on the oversteepened toe of the main slide mass.

The landslide surface of rupture was in the Petrified Forest Member of the Triassic Chinle Formation, and also involved lower units of the Jurassic Moenave Formation, as well as overlying alluvium and colluvium derived from the Jurassic Kayenta Formation (Lucas and Tanner, 2006). Prehistoric landslides in the Petrified Forest Member are common in the Springdale area (Solomon, 1996), and this unit is involved in many deep-seated landslides throughout southwestern Utah (Harty, 1992).

The landslide is exceptional because it occurred 27 miles from the earthquake epicenter. Worldwide data (Keefer, 1984) indicate that the previous maximum recorded epicentral distance for a coherent landslide of this size in a M_S 5.6 earthquake was only 11 miles. The Springdale landslide may be the largest historical landslide triggered by an earthquake of this magnitude (Jibson and Harp, 1995).

Slope-stability analysis indicates that the static factor of safety for the landslide before the earthquake may have been as low as 1.30 (Jibson and Harp, 1995), near the threshold where general slope failure might be expected to occur. The earthquake likely triggered enough deformation to elevate pore-water pressure in the clays of the Petrified Forest Member in which the basal surface of rupture then formed. The elevated pore-water pressure probably reduced the factor of safety below 1.0 leading to a general failure of the slope (Jibson and Harp, 1995). Precipitation at Zion National Park was high in February and March preceding the slide, but near average during the next 5 months.

0.1 55.7 **Turn vehicles around and return to SR 9, turn left toward Zion National Park.**

Note exposure of Petrified Forest Member of the Chinle Formation and overlying landslide deposits on the left. Landside deposits continue on the left as we proceed up canyon on SR 9.

0.2 55.9 **Turn right into Giant Screen Theatre Complex.**

0.1 56.0 **Sol Foods Restaurant, end of field trip and lunch.**

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