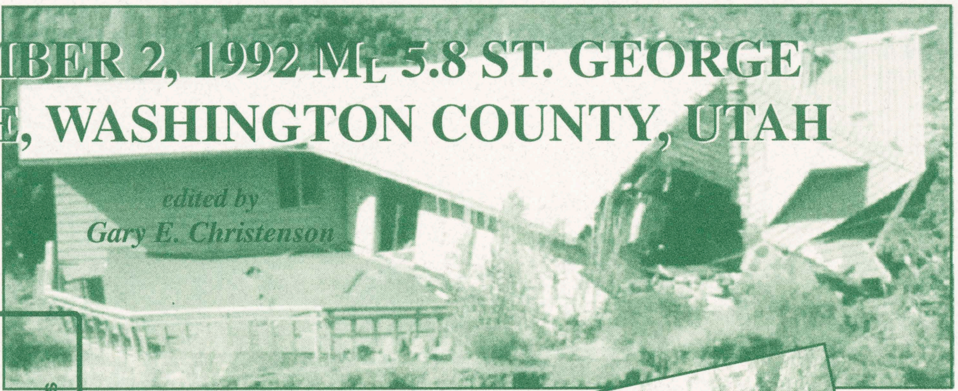
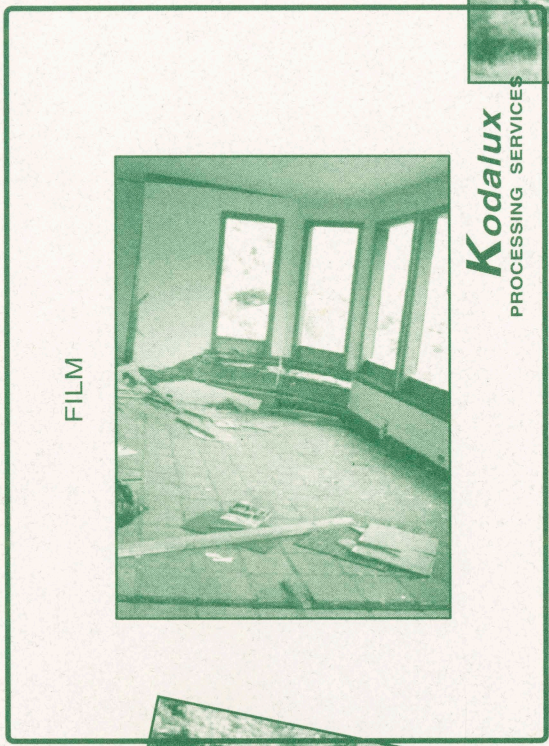
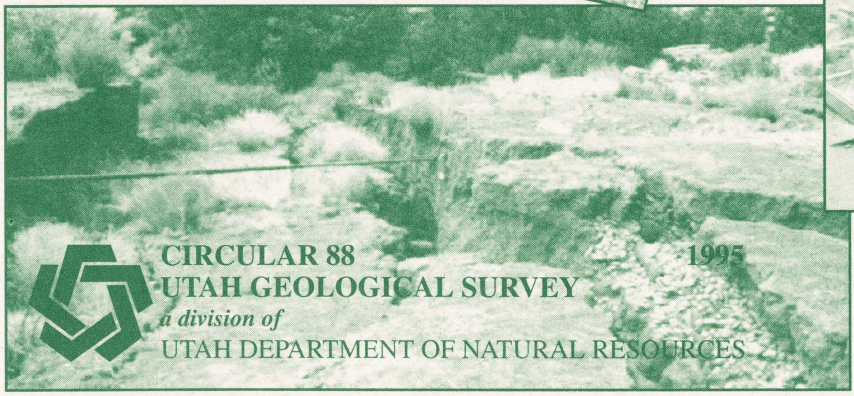
THE SEPTEMBER 2, 1992 M_L 5.8 ST. GEORGE EARTHQUAKE, WASHINGTON COUNTY, UTAH

edited by
Gary E. Christenson







CIRCULAR 88 1995
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES

UTAH CENTENNIAL 1896-1996

Christenson

THE SEPTEMBER 2, 1992 M_L 5.8 ST. GEORGE EARTHQUAKE, WASHINGTON COUNTY, UTAH

Utah Geological Survey Circular 88

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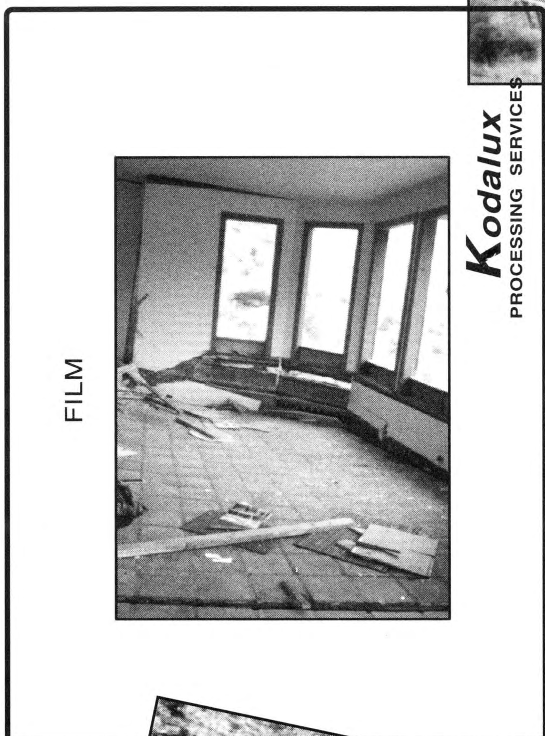

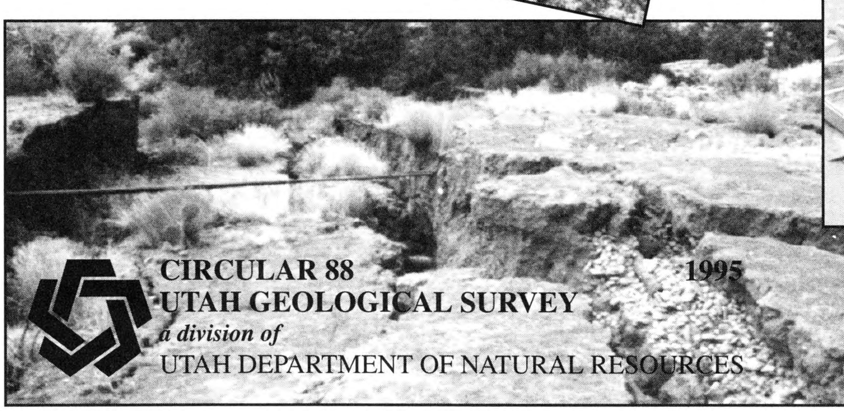

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PREFACE

by
Gary E. Christenson
Utah Geological Survey

Many state and federal agencies share interest and responsibility for scientific documentation and emergency response following a significant earthquake in Utah. In the September 2, 1992 M_L 5.8 St. George earthquake, many state agencies responded immediately. The University of Utah Seismograph Stations which operates the state's seismograph network located the epicenter, assigned a preliminary magnitude, and sent field crews with portable instruments to the area to monitor aftershocks. The Utah Geological Survey (UGS) sent crews to look for geologic effects (surface faulting, liquefaction, slope failures, hydrologic changes) and advise emergency-response personnel regarding geologic hazards. The Utah Division of Comprehensive Emergency Management responded to coordinate and assist local government emergency responders and to evaluate the need for state and federal aid. The Utah Division of Water Rights, Dam Safety Section, inspected dams for earthquake-related damage.

Federal agencies responding included the U.S. Natural Resources Conservation Service (NRCS), then the U.S. Soil Conservation Service, and U.S. Geological Survey (USGS). The NRCS inspected their dams and water-conveyance structures, and the USGS studied the earthquake-caused Springdale landslide and advised state and local officials regarding landslide hazards. The USGS also retrieved a strong-motion record from an instrument in Cedar City.

This circular presents scientific observations and documents damages and losses from the St. George earthquake. Each agency listed above contributed a report summarizing their findings. These reports are edited to remove duplication where possible and are formatted to conform to UGS editorial standards. However, all conclusions and recommendations are those of the agency and author contributing the report.

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SEISMOLOGY

by
James C. Pechmann, Walter J. Arabasz, and Susan J. Nava
University of Utah Seismograph Stations

Modified from:
Pechmann, J.C., Arabasz, W.J, and Nava, S.J., 1994 [abs.], Refined analysis of the 1992 M_L 5.8 St. George, Utah, earthquake and its aftershocks: Seismological Research Letters, v. 65, p. 32.

An M_L 5.8 earthquake occurred in southwestern Utah at 4:26 a.m. MDT on September 2, 1992, 8 ± 2 kilometers (5 ± 1.2 mi) ESE of the city of St. George. The shock was the largest in the Utah region since 1975 and the largest in the St. George area since 1902. The earthquake caused surprisingly little damage in St. George (population ~28,500) and other nearby communities, although it triggered a massive, destructive landslide about 45 kilometers (28 mi) away. No surface faulting was observed. Using the focal depth of 15 ± 2 kilometers (9.3 ± 1.2 mi) determined by others from analysis of teleseismic waveforms, we computed an epicenter of 37° 4.8′ N, 113° 29.2′ W. Our focal mechanism for this earthquake indicates normal slip on a north-striking fault dipping 46° ± 5° E or 46° ± 6°W.

The main shock had no foreshocks ($M_C \geq 2.0$) and remarkably few aftershocks for an event of this size. Only two aftershocks of $M_C \geq 2.0$ occurred, the largest of which was an $M_C \geq 2.7$ event eight days after the main shock. To supplement the sparse station coverage provided by regional seismic networks in this area (nearest station 60 kilometers [37 mi]), the University of Utah operated portable seismographs, including five telemetered stations and one three-component digital station, for six months following the main shock. Hypocenters of 40 microaftershocks, constrained by data from the portable seismographs, define a zone 20 kilometers (12 mi) long extending from 4 to 18 kilometers (2.5 - 11 mi) depth which becomes shallower to the east of the main shock focus. This aftershock distribution implies that the west-dipping nodal plane of the focal mechanism is probably the slip plane. The surface projection of the west-dipping plane lies close to the surface trace of the Hurricane fault. This major, west-dipping normal fault has a late-Quaternary slip rate of 0.30 to 0.47 mm/yr (0.01 - 0.02 in/yr) (Anderson and Christenson, 1989) and lies along the western margin of the Colorado Plateau. Our data suggest, but do not prove, that the St. George earthquake resulted from buried slip on the Hurricane fault.

On-scale P waves recorded at a distance of 60 km (37 mi) suggest that the main shock rupture was simple and had a length of 0.8 to 5.5 kilometers (0.5 - 3.4 mi), much smaller than the length or width of the aftershock zone. Stress-drop estimates are poorly constrained but range from moderate to high, with a minimum value of 25 bars. Neither the stress drop of the main shock nor the radiation pattern predicted from our location and mechanism provide any simple explanation for the relatively light damage in the city of St. George.

REFERENCE

Anderson, R.E., and Christenson, G.E., 1989, Quaternary faults, folds, and selected volcanic features in the Cedar City 1° x 2° quadrangle, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 89-6, 29 p.

GEOLOGIC EFFECTS

by
Bill D. Black, William E. Mulvey[1], Mike Lowe,
and Barry J. Solomon
Utah Geological Survey

INTRODUCTION

Ground shaking and slope failures were the dominant geologic effects associated with the September 2, 1992 St. George earthquake. Ground shaking caused damage to buildings in Hurricane, La Verkin, Washington, St. George, and other communities (Olig, this volume). A destructive landslide in the town of Springdale, called the Springdale landslide (previously termed the Balanced Rock Hills landslide) (figure 1), destroyed three homes in the Balanced Rock Hills subdivision and forced the temporary evacuation of condominiums and businesses around the periphery of the slide. Numerous rock falls throughout the region caused minor damage. The earthquake also produced liquefaction along the Virgin River and changes to the springs at Dixie Hot Springs (figure 1).

On September 2-3, UGS geologists (B.J. Solomon, M. Lowe, and B.D. Black) inspected the Springdale landslide, examined the Washington and Hurricane faults for evidence of surface fault rupture, and advised Washington County, Springdale Town, Utah Department of Transportation, and Utah Division of Comprehensive Emergency Management officials regarding potential dangers from the landslide. On September 9-10, W.E. Mulvey (UGS) examined liquefaction features along the Virgin River and with M. Lowe performed additional reconnaissance of the Hurricane fault. On September 15-16, B.D. Black assisted the town of Springdale in establishing survey-monitoring stations on the landslide, examined changes to the springs at Dixie Hot Springs, and performed a more detailed field inspection of the Hurricane fault.

In this report, measurements and distances are in English units followed by metric equivalents in parentheses. However, where measurements were reported in metric units or equations required metric units, these units are given first.

WASHINGTON AND HURRICANE FAULTS

Although no surface-faulting earthquakes have occurred in the St. George area in historical time, two faults near the epicenter have evidence of Quaternary movement: (1) the Washington fault, and (2) the Hurricane fault (figure 1). It has been estimated that up to 1 foot (0.3 m) of surface displacement may accompany a magnitude 6.0 earthquake on these faults, with an expected recurrence interval on each fault of 200 to 300 years (Earth Science Associates, 1982). Both faults are considered capable of generating earthquakes of magnitude 7.0 to 7.5 (Earth Science Associates, 1982). Seismological and isoseismal data suggest that the probable source of the St. George earthquake was the Hurricane fault (see Pechmann and others, this volume; Olig, this volume).

We examined the Washington and Hurricane faults for surface fault rupture following the earthquake. The investigation was conducted by driving and walking the fault traces. The Washington fault was followed for approximately 5 miles (8 km) south and 2 miles (3 km) north of the epicenter (figure 1). The Hurricane fault was followed south approximately 12 miles (18 km) from where it crosses the Virgin River to the Utah-Arizona border, which is the nearest approach of the fault to the epicenter (figure 1). No evidence of surface cracks or displacement was found on either fault.

GROUND SHAKING

Ground shaking is typically the most widespread and damaging earthquake hazard. For details of effects of ground shaking on structures, see Olig (this volume). Geologic effects of ground shaking for this event included slope failures, liquefaction, and hydrologic changes.

Unfortunately, only one strong-motion record of the St. George earthquake was obtained (see appendix). However, Campbell (1987) has developed an empirical relation to estimate peak horizontal acceleration (PHA). Using this relation, estimates of PHA are about 0.2 g for St. George and 0.07 g for Springdale (Susan Olig, Utah Geological Survey, verbal communication, September, 1992). These estimates assume a dipping fault, a focal depth of 15 kilometers (9 mi), and a sediment depth of less than 10 meters (30 ft) at each location. St. George is in seismic zone 2B of the 1991 Uniform Building Code (UBC) and has a Z-factor of 0.2, which is roughly equivalent to the estimated PHA of 0.2 g. Based on Campbell's (1987) relation, the earthquake should have subjected St. George to approximately the PHA presently used in engineering design in the area.

SLOPE FAILURES

Springdale (Balanced Rock Hills) Landslide

The most damaging effect of the St. George earthquake was the Springdale (Balanced Rock Hills) landslide (figures 2 and 3) which destroyed two water tanks (one was abandoned), several storage buildings, and three homes in the Balanced Rock Hills subdivision (figure 4). The landslide also blocked State Route

[1]*Presently at Raleigh, North Carolina*

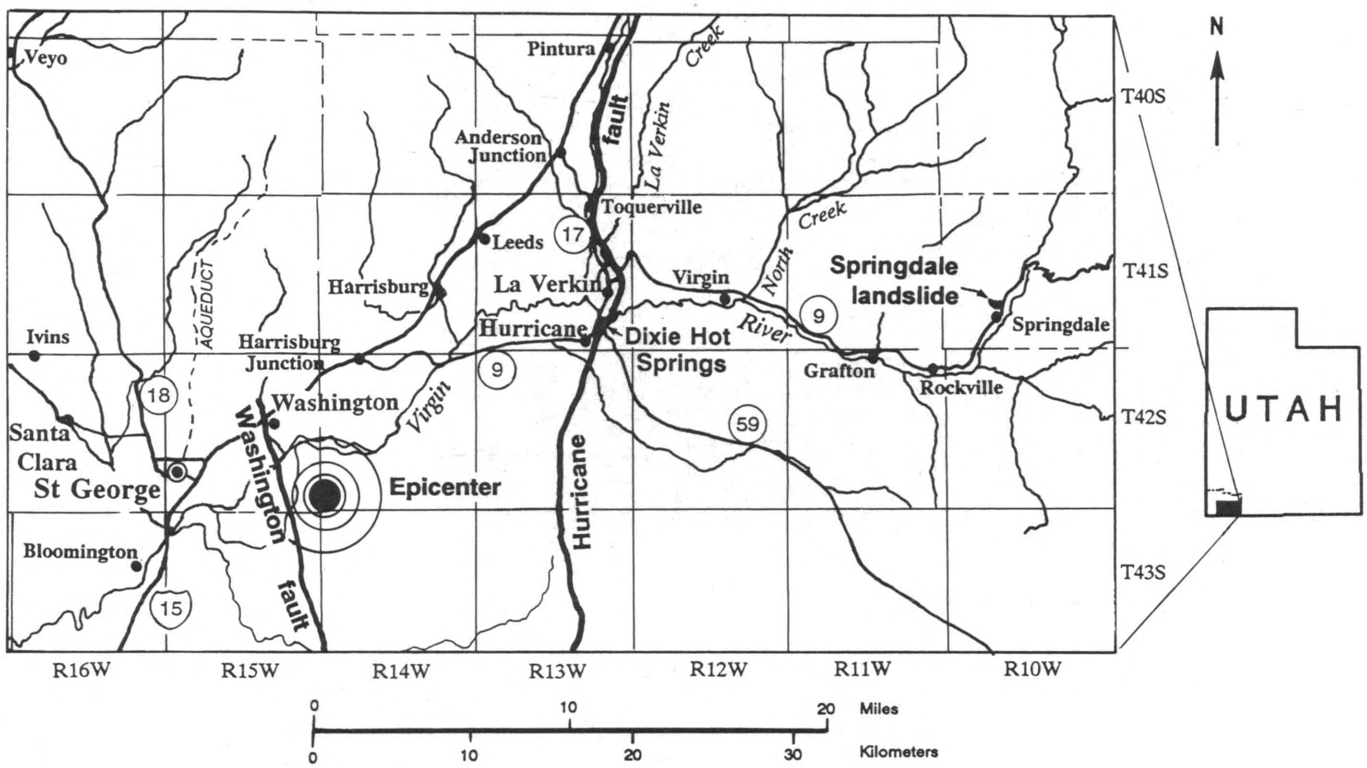

Figure 1. Location map.

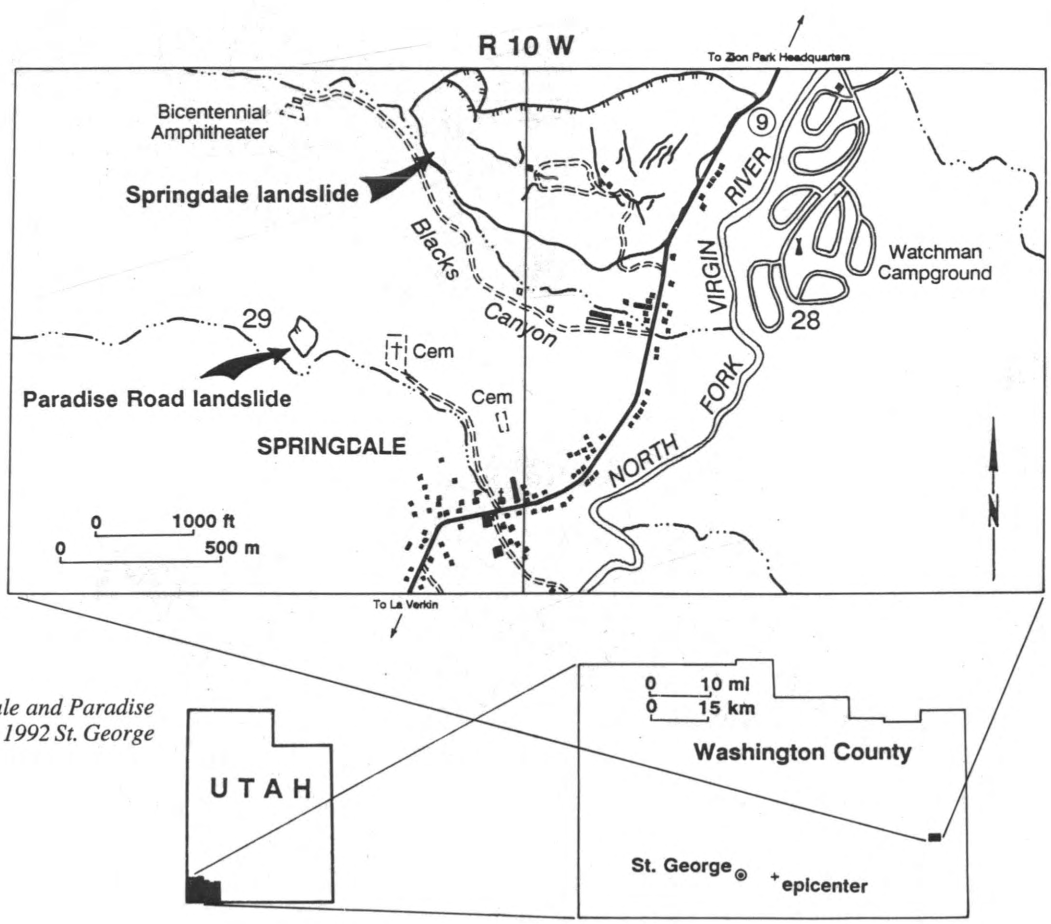

***Figure 2.** Location of the Springdale and Paradise Road landslides and epicenter of the 1992 St. George earthquake.*

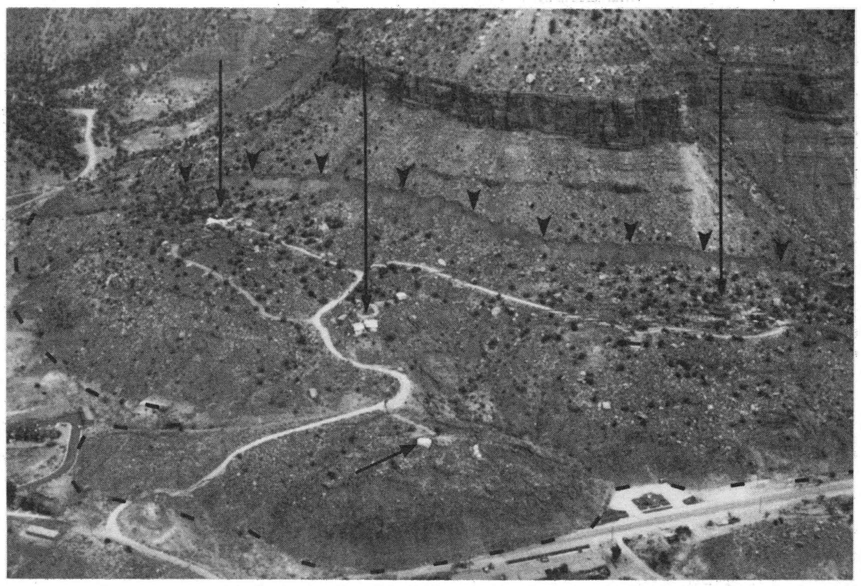

Figure 3. Aerial view of the Springdale landslide. State Route 9 is at the bottom; short arrows show the main scarp of the landslide, long arrows indicate three houses damaged, medium arrow locates the abandoned water tank, and dashed line outlines landslide toe. Photo by B.J. Solomon.

Figure 4. House in the Balanced Rock Hills subdivision destroyed by landsliding. Photo by B. D. Black.

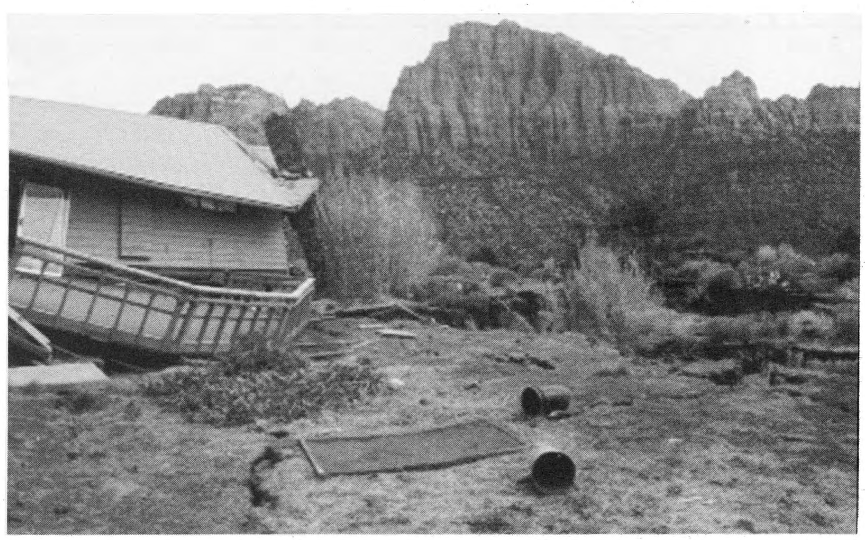

Figure 5. Toe of the Springdale landslide near State Route 9. Note ruptured utility lines in the toe of the slide. Photo by B.D. Black.

(SR) 9 leading to Zion National Park, and ruptured both buried and above-ground utilities in the subdivision and along SR 9 (figure 5); condominiums and businesses around the periphery of the slide were temporarily evacuated. A smaller slope failure west of the Springdale landslide, called the Paradise Road landslide (figure 2), was also triggered by the earthquake but caused no damage.

The Springdale landslide is a complex block slide that likely involves both rotational and translational elements. Although ground shaking initiated the movement, the landslide moved slowly and continued moving for several hours following the earthquake. The slide measures roughly 1,600 feet (488 m) from the main scarp to the toe, with a width of about 3,600 feet (1,097 m) and a calculated surface area of 4.4 million square feet (409,000 m^2). The total volume of material is about 18 million cubic yards (14 million m^3). Prior to the slope failure, the average gradient of the slope from the crown of the slide to the toe was 30 percent (17 degrees). The landslide has a clearly defined main scarp (figure 6), as well as numerous fissures and minor scarps that form a broken, irregular topography within the slide mass. These scarps and fissures indicate that the landslide likely moved in several coherent blocks. Smaller discrete landslides also developed on the oversteepened toe.

Three geologic units are mapped by Cook (1960) in the area of the Balanced Rock Hills subdivision: (1) the Jurassic Kayenta Formation, (2) the Triassic Moenave Formation, and (3) the Triassic Chinle Formation (Petrified Forest Member). The Springdale Sandstone Member of the Moenave Formation (Harshbarger and others, 1957) forms a prominent cliff north of the subdivision, above the main scarp of the landslide (figure 3). The landslide involved lower units of the Moenave Formation and upper units of the Petrified Forest Member of the Chinle Formation, and included colluvium containing rock-fall debris from the Kayenta and Moenave Formations. Previous investigators (Kaliser, 1975; Christenson and Deen, 1983; Harty, 1990) have noted slope instability in the Petrified Forest Member in the Springdale area. Also, a significant number of deep-seated landslides in Utah occur in this unit (Harty, 1991).

A combination of failure-prone geologic materials, long-term marginal stability, and earthquake ground shaking is the most likely cause of the landslide. Slope movement in the subdivision was first studied in the mid-1970s by Wayne Hamilton, a geologist with Zion National Park, who reported differential movement in the hill on which the Springdale water tank rests, now at the toe of the 1991 landslide (figure 3; Kaliser, 1975). Hamilton (1984) noted 1.3 inches (3.3 cm) of movement from August 1974 to June 1975, and noticed that other areas nearby were also moving. Although the slide is beyond the maximum distance predicted by Keefer (1984) for coherent landslides to occur from the epicenter of a M_L 5.8 earthquake (see Jibson and Harp, this volume), distant slopes that are only marginally stable before an earthquake can fail even from minor ground shaking (Keefer, 1984).

Although no water was observed issuing from the landslide, water probably contributed to the failure. Precipitation was about 120 percent of normal for the water year in the region at the time of the earthquake (Utah Climate Center, 1992). Also, other sources of water such as effluent from wastewater disposal systems or possible leaking water lines or tanks in the subdivision may have contributed. However, the role of water from these sources is unknown, particularly considering the nearby Paradise Road landslide which is in an undeveloped area lacking these sources.

Where possible, Electronic Distance Measuring (EDM) reflector stations were established and surveyed on each landslide block based on mapping of prominent minor scarps and fissures (figure 7). The EDM stations were placed to monitor movement and response of the landslide to future precipitation and earthquakes. Surveys in the month following the earthquake showed no evidence of renewed movement (Doug Schneider, Alpha Engineering, written communication, October, 1992).

Rock Falls

Numerous rock falls were observed along the steep cliffs above SR 9 from La Verkin to Zion National Park, in the Hurricane Cliffs along the Hurricane fault, and in St. George along the Red Hills and West Black Ridge. In most cases, the rock falls either occurred in uninhabited areas (causing no damage) or fell onto roads and were quickly cleared away (figure 8). However, at an unreported location a truck was hit by a boulder, and in St. George a boulder crashed through a wall and damaged a car (unpublished Utah Division of Comprehensive Emergency Management final field report). Rock falls also caused damage to footpaths and irrigation lines at Pah Tempe Resort in La Verkin (figure 9), and blocked an unused section of the Hurricane Canal east of Hurricane. Numerous fresh rock-fall scars, probably from rock falls caused by the earthquake, are present in cliffs of the Moenkopi Formation near the Arizona border (figure 10).

LIQUEFACTION

Liquefaction from the St. George earthquake occurred in alluvium along the Virgin River from roughly 1 mile (1.6 km) south of Bloomington to 4 miles (6 km) west of Hurricane (figure 11). No documented damage occurred from liquefaction. Sediments involved were poorly graded channel sands, commonly covered by thin overbank deposits of silt and clay. Liquefaction features observed were lateral spreads, sand blows, and caved stream banks. Lateral spreads were most common.

Lateral spreads result when liquefaction of a shallow subsurface layer causes overlying intact layers to crack and "raft" downslope. They were common on gentle (0.5 - 3 degree) slopes underlain by alluvial sands along the modern flood plain of the Virgin River (figure 12). Most cracks were arcuate, extending up to 20 meters (65 ft) parallel and 8 meters (25 ft) perpendicular to the river. The largest lateral spread extended along the river for 60 meters (196 ft) and perpendicular to the river for 20 meters (65 ft) (no. 5, figure 11). Cumulative crack width, which indicates the total amount of lateral movement, was more than 48 centimeters (19 in).

Small "sand volcanoes" (commonly called sand blows) form as liquefied material is forced upward and flows onto the ground surface. Sand blows were small, commonly 1 to 5 centimeters

Figure 6. Main scarp of the Springdale landslide. Photo by S. Olig.

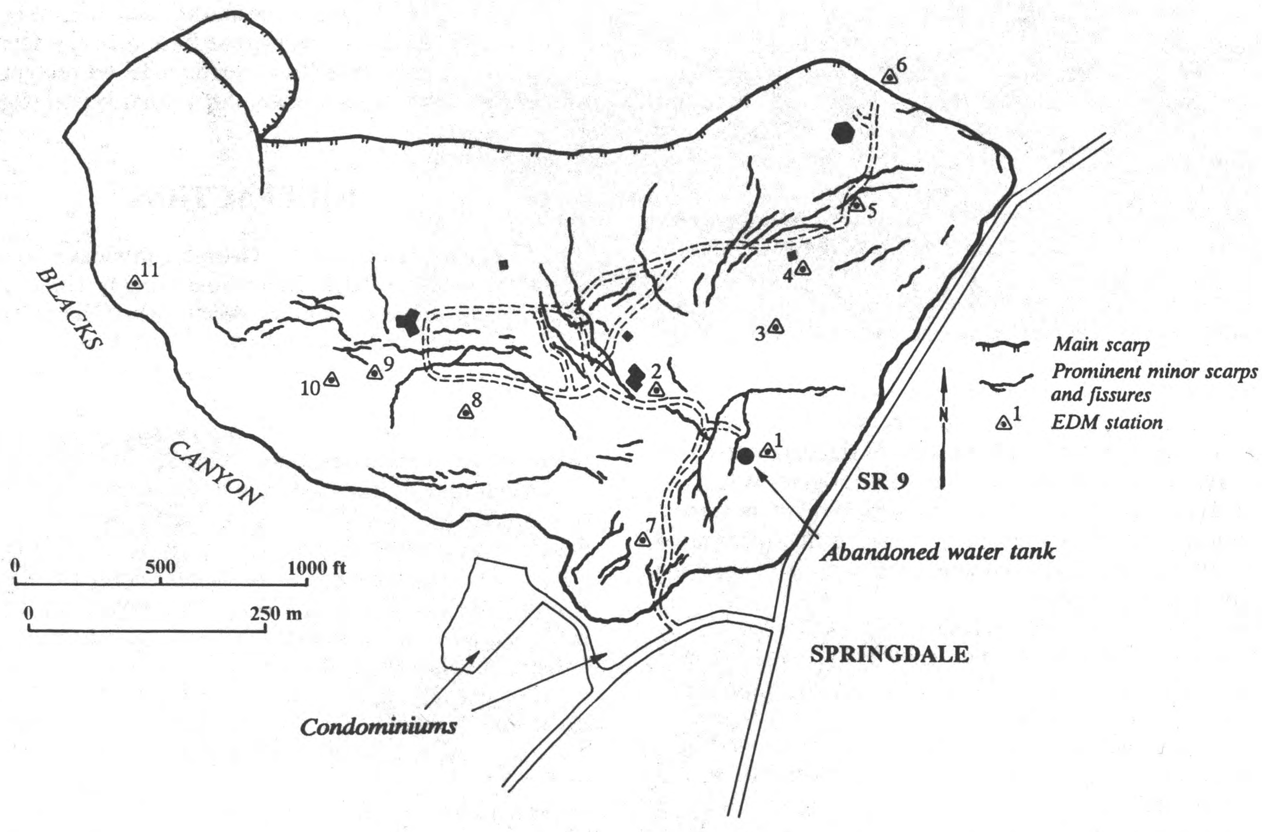

Figure 7. Main scarp, prominent minor scarps and fissures, and location of EDM stations on the Springdale landslide.

Figure 8. Rocks that fell from West Black Ridge onto Ridgeview Drive in St. George. Photo by B.D. Black.

Figure 9. Rock fall on a footpath at Pah Tempe Resort in La Verkin. Photo by B.D. Black.

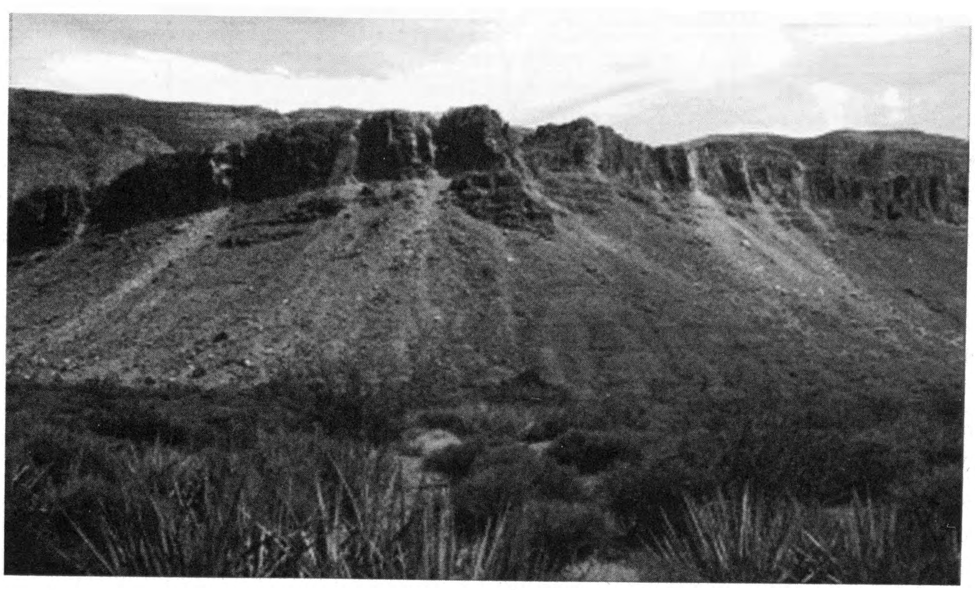

Figure 10. Rock-fall scars in cliffs of the Moenkopi Formation near the Arizona border. Photo by W.E. Mulvey.

Base map from ST. GEORGE, U.S.G.S.
30' x 60' topographic quadrangle

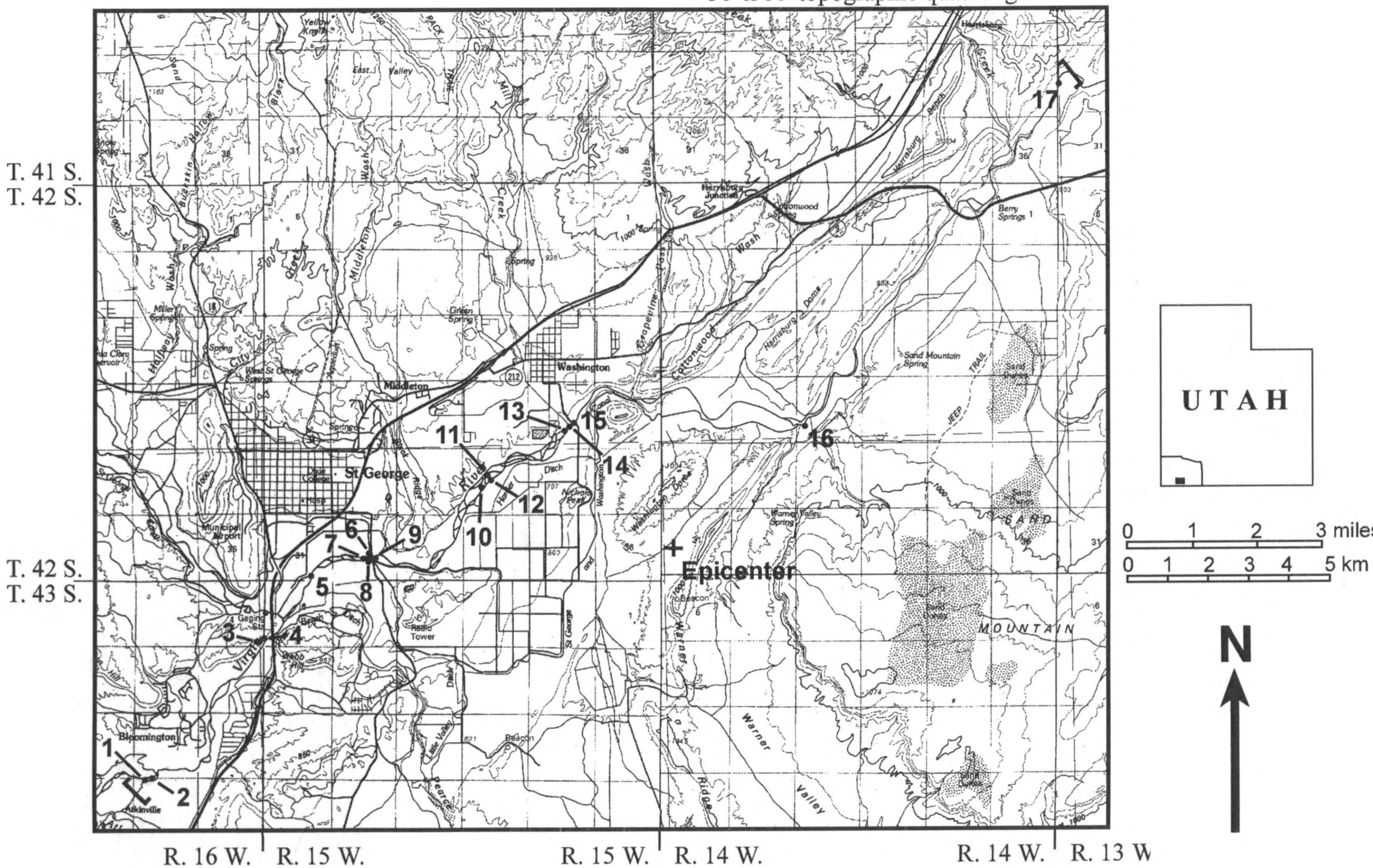

Figure 11. Extent of liquefaction along the Virgin River (between brackets) and locations of lateral-spread features investigated.

Figure 12. *Lateral-spread cracking from liquefaction along the Virgin River. Photo by W.E. Mulvey.*

(0.4-2 in) in diameter, and occurred singly, in groups, and along cracks associated with lateral spreads (figure 13). The largest sand blow was 50 centimeters (20 in) in diameter. Coalescing sand blankets from the sand blows were as large as a meter (3 ft) across, and contained pea-size gravel at one location. Sand blows were most numerous where a thin layer (1-2 centimeters [0.4-0.8 in]) of overbank deposits (silt and clay) covered the sands that liquefied.

Measurements from 17 lateral-spread features were used to determine Liquefaction Severity Index (LSI) values in the area affected by the earthquake. The LSI quantifies the amount of ground displacement due to liquefaction-induced lateral spreading caused by earthquake ground shaking (Youd and Perkins, 1987). Mabey and Youd (1989) developed an equation to calculate LSI in Utah (see equation, table 1). It calculates the maximum lateral displacement likely to occur in gently sloping Holocene flood-plain deposits such as those along the Virgin River. The LSI relates the maximum displacement that is not likely to be exceeded in a given earthquake, to earthquake magnitude and distance from the earthquake source (Mabey and Youd, 1989). In this investigation, the distance from the epicenter is used in the LSI calculation.

Table 1 compares measured lateral displacements (column 2, cumulative crack widths) with calculated LSI values (column 4). Values in table 1 indicate that the calculated LSI values more closely predicted measured displacements at greater distances from the epicenter. At lesser distances, the measured values were generally less than the calculated values. One unusual lateral spread with a large displacement was south of St. George (table 1, no. 5; figure 11), and may relate to thickness of alluvium and amplified effects of ground shaking. The area of this lateral spread has the thickest alluvium near St. George (Christenson and Deen, 1983).

Table 1.
Liquefaction Severity Index (LSI) values for the St. George earthquake.

$$\log(\mathrm{LSI}) = -3.53 - 1.60 \log(R^1) + 0.96\, M_w$$

Site (figure 11)	Cumulative crack width in inches	Distance from epicenter in kilometers	Calculated LSI
1	1.4	13	1.4
2	1.5	13	1.4
3	6.4	10	2.2
4	3.7	10	2.2
5	19.4	8	3.1
6	0.9	7	3.9
7	10.6	7	3.9
8	3.5	7	3.9
9	1.3	7	3.9
10	1.8	4	9.5
11	1.8	4	9.5
12	10.0	4	9.5
13	0.3	4	9.5
14	2.1	4	9.5
15	0.4	4	9.5
16	0.7	5	6.7
17	0.1	17	0.9

[1]R is the distance in kilometers from the epicenter; Mw is moment magnitude of the earthquake (5.7 for the St. George earthquake).

OTHER EFFECTS

An additional effect of the St. George earthquake was a change in the hydrology of Dixie Hot Springs at Pah Tempe Resort, 2 miles (3 km) north of Hurricane (figure 1). The springs are along the Hurricane fault and issue from cavities in the Kaibab Limestone and from rock along the bed of the Virgin River, where joints and faults of small displacement provide outlets for ground water (Gregory, 1950; Mundorff, 1970). The source of heat is probably an abnormally high geothermal gradient resulting from volcanic activity during Quaternary time (Mundorff, 1970). Combined spring flow was measured in 1966 at 5,206 gpm, with a temperature ranging from 100° to 108° F (Mundorff, 1970).

Following the St. George earthquake, flow from the springs decreased dramatically (figure 14). Water now emerges from new sources at a lower elevation and closer to the river; no flowing spring is more than one foot (0.3 m) above the elevation of the river (Everitt, 1992). Changes in the springs may have occurred when the earthquake cracked natural or artificial barriers between the aquifer and the river bed, creating new outlets at a lower elevation and causing water levels to drop below the elevation of the resort (Everitt, 1992).

SUMMARY

The dominant geologic effects of the September 2, 1992, St. George earthquake were ground shaking and slope failures. Ground shaking caused damage in several communities; however, estimated PHAs from the earthquake do not exceed values presently required for engineering design in UBC seismic zone 2B in the area. The most damaging effect of the St. George earthquake was a large, destructive landslide in Springdale, which destroyed several structures in the Balanced Rock Hills subdivision in Springdale, temporarily blocked SR 9 leading to Zion National Park, and disrupted utilities in the subdivision and along SR 9. Ground shaking also triggered numerous rock falls throughout the region. Other geologic effects of the earthquake were liquefaction and lateral spreading in the Virgin River flood plain and changes in flow in the springs at Dixie Hot Springs. No evidence of surface fault rupture was found.

ACKNOWLEDGMENTS

The authors wish to thank Denny Davies and Larry Wiese of Zion National Park, who donated a copy of "Sculpturing of Zion" by Wayne Hamilton. Randall Jibson and Edwin Harp of the U.S. Geological Survey provided helpful assessments of the Springdale landslide. The Utah Department of Transportation allowed us to participate in their aerial reconnaissance. Several people

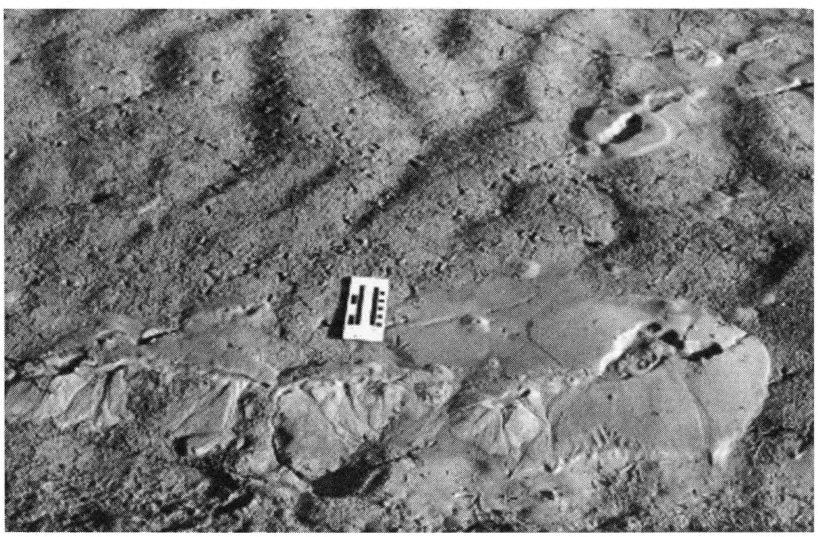

Figure 13. Sand blows from liquefaction along the Virgin River. Photo by W.E. Mulvey.

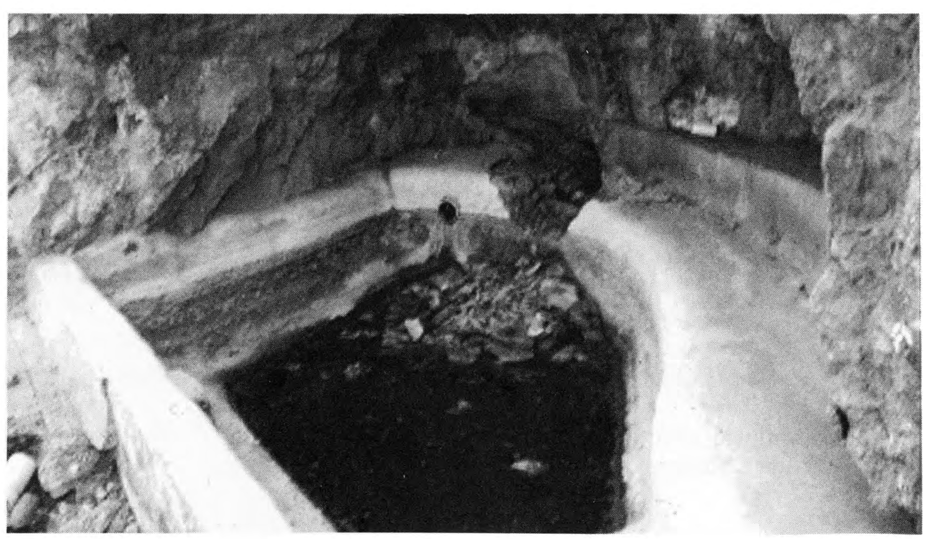

Figure 14. Dry spring in Pah Tempe Resort roughly 6 feet (1.8 m) above the river. Photo by B.D. Black.

with experience in the area provided valuable information, including Wayne Hamilton, Jim Fraley (Town of Springdale), and local residents James Roberts and Al Warneke. Matthew Mabey (Oregon Department of Geology and Mineral Industries) reported on his reconnaissance of geologic effects, particularly liquefaction, and provided advice regarding interpretations of the Liquefaction Severity Index.

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GROUND SHAKING AND MODIFIED MERCALLI INTENSITIES

by
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INTRODUCTION

Ground shaking, either directly or indirectly, caused all of the damage associated with the September 2, 1992 St. George earthquake. Unfortunately, strong-motion records were obtained at only one site, in Cedar City, Utah (appendix), so it is difficult to quantitatively evaluate the factors affecting ground motions. To qualitatively evaluate these factors and the patterns of damage, I documented site-specific observations and assigned corresponding Modified Mercalli intensities (MMI) for the St. George earthquake.

The MMI scale relates physical observations and effects of an earthquake to ground shaking intensity, varying from I (barely felt) to XII (total destruction) (table 1). Since the MMI scale was first published in 1931 (Wood and Neumann, 1931), many revisions and additions have been suggested to update the scale to make it more suitable to modern environments (see for example, Stover's [1989] caveat on using observations from people in modern cars, Nason's [1982] addition of physical effects in grocery and furniture stores, and Richter's [1958] caveats on considering different types of construction). Many of these revisions were considered in assigning the intensities for this study. Observations of structural damage, interior damage, or interior disturbance were given the most weight in assigning intensities and locating isoseismals, whereas observations of geologic effects were weighted the least.

The intensities in this study are based on three sources of data. The Utah Geological Survey distributed a survey (figure 1) in local newspapers and received responses for 141 sites. Over half of these sites were in St. George. To supplement the newspaper survey, I interviewed numerous structural engineers, building and emergency-response officials, architects, contractors, and property owners to record their first-hand observations of damage and physical effects caused by the earthquake. Additionally, the National Earthquake Information Center (NEIC) provided preliminary MMIs for 85 communities in the epicentral region (L. Brewer, NEIC, verbal communication, 1993). They assigned preliminary intensities for each community based on Earthquake Reports (questionnaires mailed to local postmasters). Although Richter (1958) recommends that the dominant MMI observed in an area should be the value assigned to the area, I generally drew isoseismals based on the maximum MMI observed. I chose this convention because it is used by NEIC in developing their intensity database for United States earthquakes (L. Brewer, verbal communication, 1993).

RESULTS

Intensities for 242 sites form the basis for the preliminary isoseismal map for the St. George earthquake (figure 2). The map is preliminary because I used preliminary NEIC intensity determinations in some areas.

Felt Area

Ground shaking during the St. George earthquake was felt over an area of at least 143,000 square kilometers (55,212 mi^2). There are few observations from sites in southeastern Utah and northern Arizona so the isoseismals are poorly constrained in these areas. Given the uncertainties, the felt area for the St. George earthquake compares favorably with the felt area of roughly 168,000 square kilometers (64,865 mi^2) estimated for the 1962 M_L 5.7 Richmond earthquake (Lander and Cloud, 1964). The St. George event was felt as far south as Lake Mohave on the Nevada-Arizona border and as far north as Delta, Utah. It was felt as far west as Las Vegas, Nevada, and as far east as Tuba City, Arizona. Unconfirmed newspaper reports of a man who felt shaking in his trailer in Blanding suggest that motions were barely discernible 350 kilometers (217 mi) east of the epicenter. However, postmasters in Blanding, Monticello, and Bluff did not report that anyone felt the shaking in their communities (M. Black, R. Bumcrot, and S. Cannon, U.S. Postal Service, verbal communications, 1993).

Maximum Intensity

The maximum intensity was a weak VII in the Hurricane-Toquerville-Virgin area (figure 2). Many older, unreinforced masonry buildings showed minor structural damage, including walls separating from roofs and ceilings, partial collapse of masonry infill walls, extensive cracks in walls and foundations, and chimney damage (figures 3, 4, and 5). Most older, unreinforced chimneys were cracked, shifted, or sheared as a result of the earthquake, although none were known to be completely sheared off (R. Bezette, contractor, verbal communication, 1993). Interior damage included extensive cracking and falling of plaster, and overturning of bookshelves and filing cabinets. Lots of bottles and cans were knocked from shelves and filled the aisles at Lins Market in Hurricane (L. Imlay, Hurricane city councilman, verbal communication, 1992). Because the earthquake occurred very early in the morning (4:26 a.m. MDT; Pechmann and others, this volume), many people were asleep and were awakened by the shaking and loud noise. Many reported hearing loud rumbling noises or booms, and some reported feeling the floor drop before the shaking started. Geologic effects in the area of maximum intensity included many rock falls along the Hurricane Cliffs and side canyons, and dramatic

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Table 1. *MODIFIED MERCALLI INTENSITY SCALE [1] (modified from Case, 1988).*

Intensity (Magnitude[2])	Personal Reactions	Vehicle Response	Response of Buildings	Miscellaneous Effects	Geologic Effects
I (1-2)	Barely felt by sensitive few, some dizziness, nausea.			Animals restless. Trees, structures, liquids, bodies of water may sway. Doors may swing very slowly.	
II (2-3)	Felt by few indoors, especially on upper floors or while lying down.			Delicately suspended objects may swing. Effects noticed in I are more obvious.	
III (3)	Felt by several while indoors. Similar to passing of light truck.	Parked cars rock slightly.		Hanging objects may swing.	
IV (3-4)	Felt by many indoors, a few outdoors, light sleepers awakened, a few frightened. Similar to passing of heavy truck or heavy object jolting.	Parked vehicles rock.	Wooden walls and frame creak.	Dishes, windows, doors, glassware, and crockery rattle, clash, clink. Hanging objects swing. Liquids in open vessels slosh back and forth.	Threshold for disrupted slides and falls, chiefly rock falls.
V (4-5)	Felt by almost everybody, indoors and outdoors. Most sleepers awakened, some are frightened and run outdoors. Shaking direction estimated. Buildings tremble throughout.		Some plaster walls, and rarely, windows crack.	Small, unstable objects (glassware, dishes, objects of art) are displaced, upset, broken. Pictures are skewed or thrown against wall. Doors/shutters open or close abruptly. Liquids disturbed/spill. Pendulum clocks change rate or stop/start. Hanging objects swing greatly. Slight shaking of trees and bushes.	Threshold for coherent slides (slumps, translational slides) and liquefaction (including lateral spreads and flows).
VI (5)	Felt by all, many are frightened and run outdoors. Walking is unsteady. Some loss of life possible near epicenter.		Masonry D: plaster and brick walls crack and pieces fall.	Many small objects such as dishes, glassware, knickknacks, or books are broken or thrown off shelves. Pictures fly off walls. Heavy furniture moved, lighter pieces overturned. Small bells ring. Trees and bushes rustle and shake.	Disrupted slides and falls likely.
VII (5-6)	Difficult to stand.	Drivers notice ground movement.	Masonry D damaged: cracks, falling of plaster, stucco, loose bricks/stones/ tiles, cornices, parapets, and ornaments fall. Some cracks in Masonry C walls and foundations.	Hanging objects quiver. Furniture is overturned and broken. Large bells ring. Trees and bushes rustle moderately to strongly. Concrete irrigation ditches are damaged.	Seiches are produced, water can become turbid with mud. Small slumps and slides along sand and gravel banks. Coherent slides and liquefaction likely.
VIII (6-7)		Steering is affected.	Masonry C buildings may partially collapse. Some damage to Masonry B, none to Masonry A. Stucco and some masonry walls fall. Chimneys, factory stacks, monuments, tombstones, towers, elevated tanks may twist or fall. Unbolted frame houses shift on foundation, loosely attached panels are thrown from frame. Solid stone walls are cracked and broken.	Branches are broken from trees. Decayed pilings are broken off.	Spring or well water may change flow rate, odor, turbidity, or temperature. Dry wells may renew flow. Cracks develop in wet ground or steep slopes. Sand boils may eject small amounts of mud/sand. Threshold of surface fault rupture.
IX (7)	General panic. Extensive loss of life possible.		Masonry D buildings destroyed. Masonry C heavily damaged, sometimes with total collapse. Masonry B structures are seriously damaged. General foundation and frame damage. Unbolted structures shift off foundations.	Underground pipes may be broken.	Conspicuous ground cracks. Sand boils, earthquake fountains, sand craters in alluvial areas. Serious damage to reservoirs. Fractures 20-30 km (12-19 mi) long breach ground surface along fault.
X (7-8)			Most masonry and frame structures, and their foundations are destroyed. Some well-built wooden buildings and bridges collapse. Serious damage to dams.	Rails bent. Underground pipelines crushed or separated.	Serious damage to dams. Large landslides are triggered. Water is thrown onto banks of water bodies. Lateral spreading of sand/mud occurs on beaches and flat land. Fissures occur on wet banks.
XI (8-9)			Well-built bridges collapse due to failure of ground at pillars, footings, and piles.	Rails are bent greatly. Underground pipelines are completely out of service.	Ground disturbances are abundant and widespread, particularly if ground is soft and wet.
XII (8-9)	Lines of sight and level are distorted.		Damage nearly total.	Objects are tossed into the air.	Large rock masses are displaced. Significant landslides are numerous and extensive.

Note: 1: The effects given with each intensity level are taken from Wood and Neumann (1931), Richter (1958), Keefer (1984), and Smith and Arabasz (1991).
2: Approximate earthquake magnitude which may produce the intensity effects near the epicenter.

CONSTRUCTION TYPES:

Masonry A: The building shows good workmanship using good materials, the design includes reinforcement specifically intended to withstand lateral forces.

Masonry B: The building is reinforced and shows good workmanship using good materials, but the reinforcement was not designed to withstand lateral motion.

Masonry C: The unreinforced building shows ordinary workmanship with standard materials. The building has no extreme weaknesses, like failing to tie-in at corners, but it is not designed to resist lateral forces.

Masonry D: The building is constructed of weak materials, such as adobe or poor mortar, with low standards of workmanship, and the design is weak against horizontal forces.

The Utah Geological Survey is investigating the magnitude 5.8 earthquake that occurred on September 2, 1992 near St. George, Utah, and requests your assistance. The information will be used in the scientific research of earthquakes in your area and your response is appreciated.

Please complete the following questionnaire and mail it to:

Earthquake Survey
Utah Geological Survey
2363 S. Foothill Drive
Salt Lake City, UT 84109-1491.

Name ________________ Daytime phone ____________

Where were you during the earthquake?

Address ___________________

City ___________________ Zip __________

If address is a rural route or post-office box, it is approximately _____ miles _____ (north, northeast, etc.) of _____________ (city). Include map if possible.

If driving, give approximate location ___________________________________

1) I did feel ___/did not feel ___ this earthquake (check one). Please respond even if you did not feel the earthquake.
2) I was awake ___/asleep ___ during the earthquake (check one).
3) If asleep, I was ___/ was not ___ awakened by the earthquake (check one).
4) I was indoors___/outdoors ___ (check one).
   If indoors, what floor were you on ___.
   If indoors, did you notice any of the following:
   ___ Hanging objects swung
   ___ Windows, doors rattled
   ___ Dishes, glassware rattled
   ___ Dishes, glassware displaced, upset, or broken
   ___ Doors/shutters open or close
   ___ Hanging pictures swung out of place
   ___ Hanging pictures fell off wall
   ___ Heavy furniture moved
   ___ Plaster or brick walls cracked
   ___ New cracks in foundation __, driveway _, patio __, or road __ (check one)
   ___ Chimney cracked __, twisted __, or fell __ ; no chimney __ (check one)
   If outdoors (or driving), did you notice any of the following:
   ___ Parked cars rocked
   ___ Trees and bushes shook slightly
   ___ Trees and bushes shook and rustled
   ___ Ground shaking noticed while driving
   ___ Steering affected while driving
5) Describe any major damage to home and estimate repair cost:

   Building is wood frame __/ wood frame with brick or stucco veneer __/ brick __/ adobe __/ other ________________________________ (describe) (check one).
6) Describe any other personal observations:

Figure 1. *Example of the survey distributed through local newspapers following the September 2, 1992, St. George earthquake.*

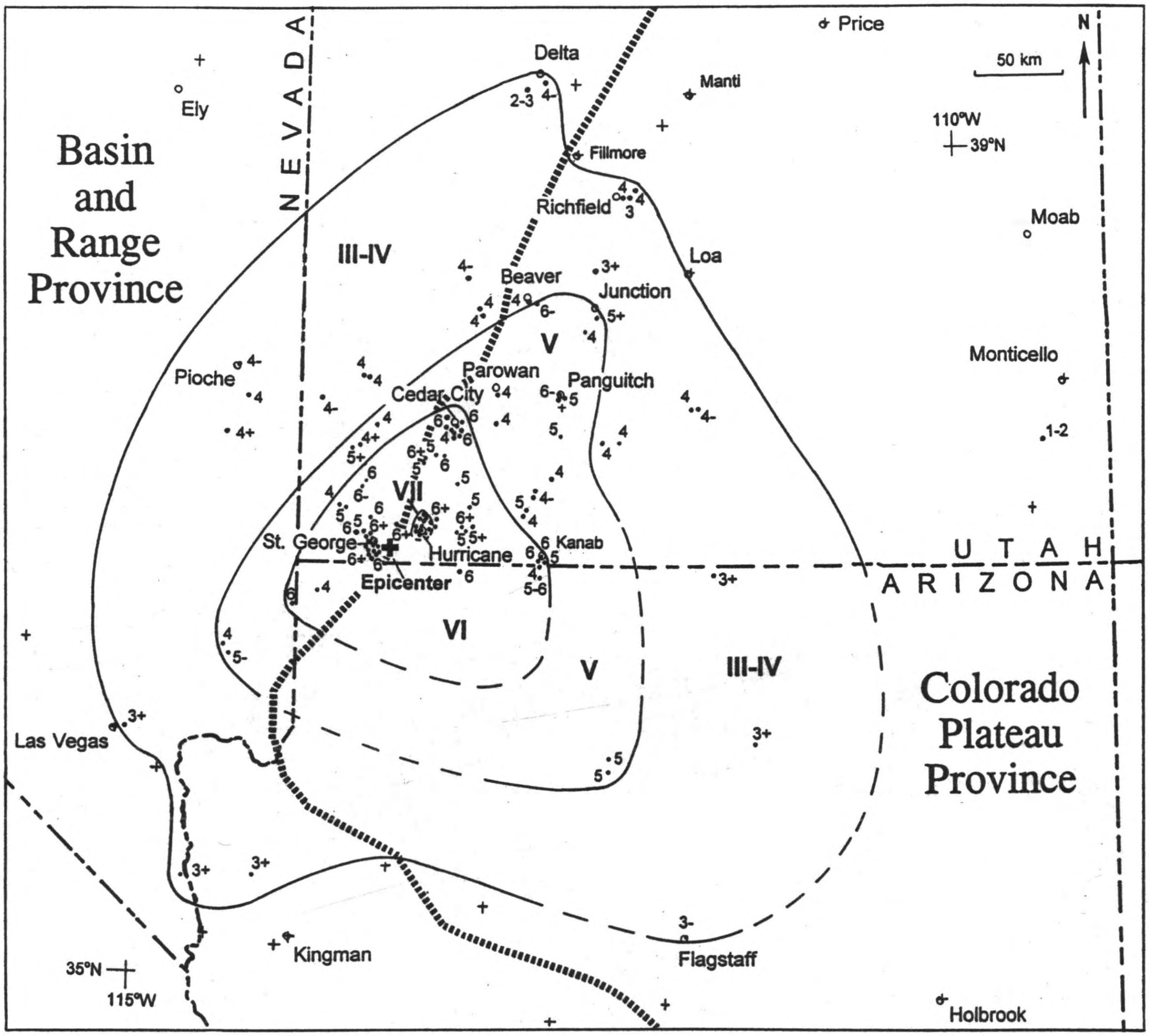
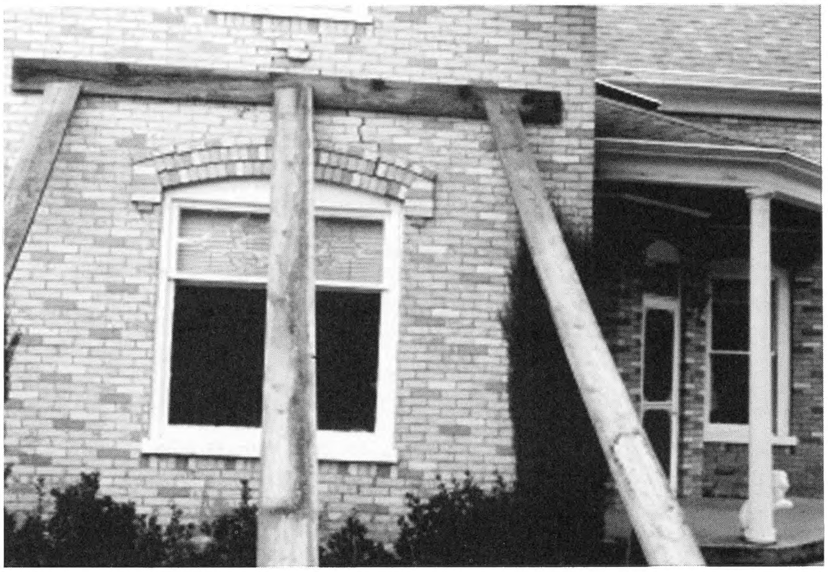


Figure 2. Preliminary isoseismal map for the M_L 5.8 September 2, 1992, St. George earthquake. The map was developed from observations at 242 sites (not all are shown). Preliminary intensities from 85 sites were provided by the National Earthquake Information Center and have not yet been finalized (L. Brewer, NEIC, verbal communication, 1992). Sites where shaking was felt are marked by solid circles with a number (given in arabic numerals) for the intensity assigned (where sites are clustered a single label for the predominant intensity is given); crosses mark sites where shaking was not felt. Location of the epicenter is marked by a bold cross (epicenter symbol obscures 5 sites of intensity VI). Isoseismal lines are dashed where poorly constrained.

A



B

Figure 3. *(A) Damage to an unreinforced 2-story brick house in Hurricane historically referred to as the Stanworth home. Chimneys were twisted and partially fell, the walls and foundation were severly cracked, and two walls partially separated from the first-story ceiling, necessitating bracing and eventually structural repair (shown in figures 3B and 3C) to prevent collapse. (B) Anchor bolts used to repair one of the damaged walls in the Stanworth home. (C) Tie rod used to repair one of the damaged walls in the Stanworth home. Photos provided by Charles M. Sheperd, Utah State Historical Society.*

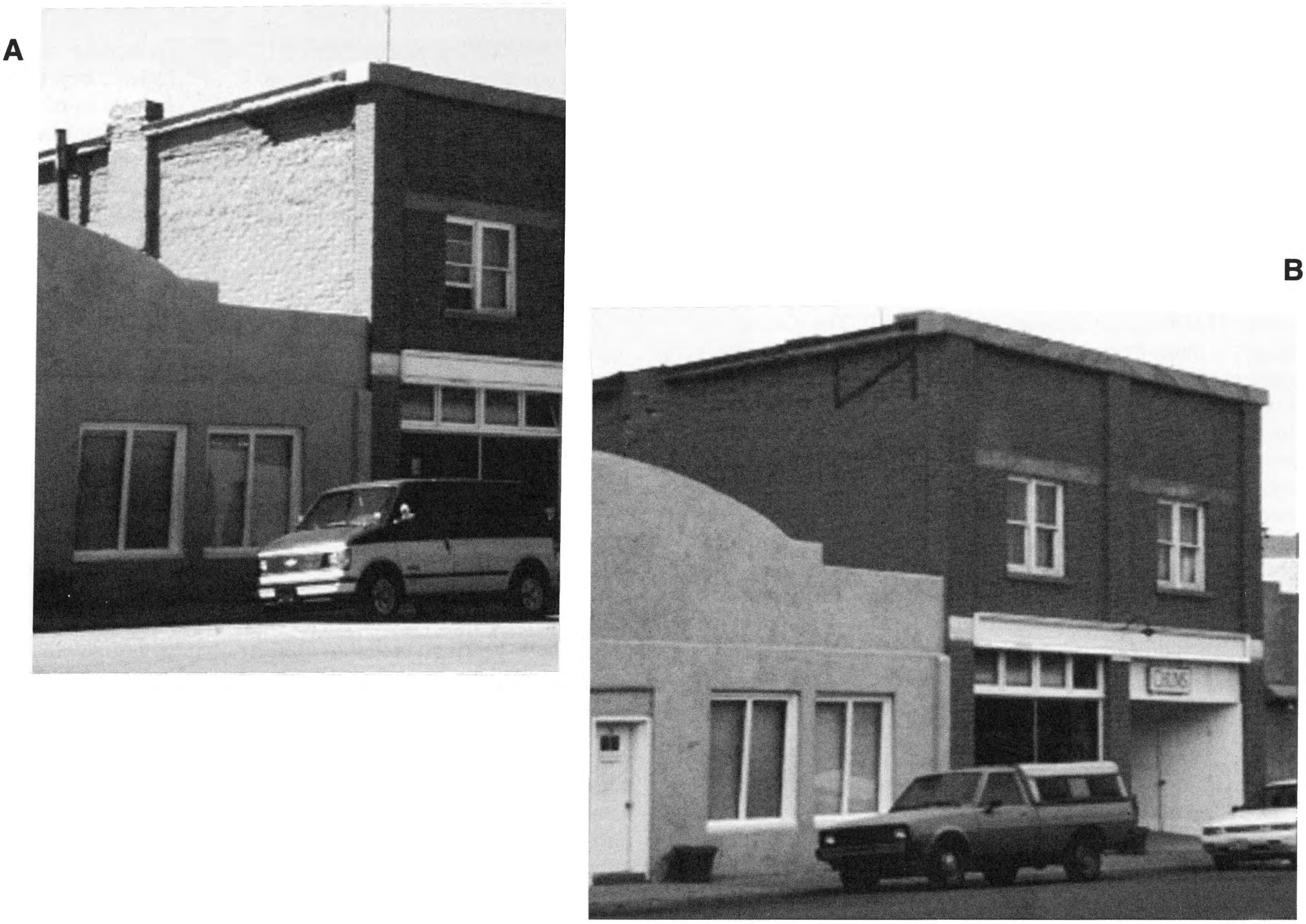


Figure 4. (A) Damage to the Chums' factory building in downtown Hurricane. Masonry infill partially collapsed near the roofline. (B) Repairs to the Chums' building. Photos provided by Charles M. Sheperd, Utah State Historical Society.

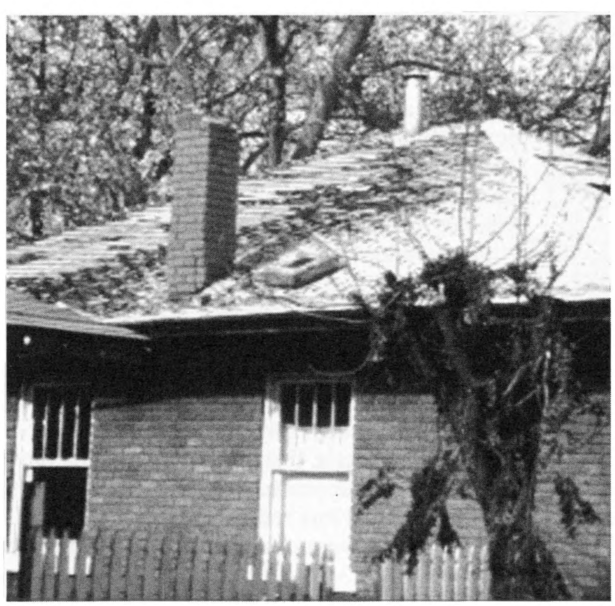


Figure 5. Chimney damaged in Hurricane. Photo provided by Charles M. Sheperd, Utah State Historical Society.

changes in the flow of hot springs at Pah Tempe Resort (Black and others, this volume).

MMI VI

Very minor structural damage, including small cracks in masonry walls, foundations, and patios, occurred as far east as Kanab, as far north as Cedar City, and as far west as Mesquite, Nevada, indicating intensities of at least VI over an area of roughly 17,000 square kilometers (6,564 mi^2). The Kanab City Library, a multi-story brick building with a stone foundation, experienced extensive cracking but did not need structural repairs (S. White, Kanab building inspector, verbal communication, 1992). Severe cracking and partial separation of a large unreinforced masonry wall occurred in the gymnasium at Beaver High School (built in the early 1900s) in Beaver, Utah (L. Reaveley, Reaveley Engineers and Associates, verbal communication, 1993). However, because much of this damage appeared to be pre-existing and simply enhanced by the St. George earthquake, the intensity VI isoseismal was not extended north to Beaver. Many rock falls were reported throughout the intensity VI area, including St. George, Zion National Park, and near Kanab.

Although the epicentral area near St. George and Washington did not appear to experience damage as extensive as the Hurricane area, observations of cracked chimneys and fallen plaster indicate a strong VI MMI for the epicentral region (figures 6 and 7). Damage to a few, early 1900s and older, multi-story, adobe and stone structures was the most severe. In downtown St. George, a pioneer-vintage two-story adobe home was severely cracked and had to be condemned (J. Empy, St. George building official, verbal communication, 1993) and a large gable-end wall made of sandstone was partially separated from the ceiling in the Latter-day Saints Tabernacle (L. Reaveley, verbal communication, 1993). In downtown Washington, the gable ends of an adobe home, with brick veneer, also buckled and the roof was severely damaged. Also in Washington, an old granary made of stone was cracked severely and condemned by the city. The local Historical Society will relocate and reconstruct the structure (R. Lee, architect, verbal communication, 1993).

Dramatic non-structural damage occurred at a KDXU radio facility in Washington Fields, a little over 4 kilometers (2.5 mi) from the epicenter. A 2-ton (1,814 kg) transmitter moved about ¼ inch (0.6 cm), a 500-pound (227 kg) transformer "walked" off a shelf, and lots of smaller equipment was knocked off the shelves; the heavy equipment appeared to have "vibrated and rotated clockwise" (J. Wilkonson, KDXU radio station engineer, verbal communication, 1993). Several grocery and department stores in Washington and St. George reported items knocked from shelves and into the aisles, indicating intensities of V to VI, using the guidelines of Nason (1982). An improperly braced ceiling-tile and light-fixture system collapsed in one supermarket in downtown St. George (R. Reaveley, verbal communication, 1993). In addition to the rock falls mentioned previously, geologic effects in the epicentral area included small liquefaction-induced lateral spreads and sand blows at numerous sites along the Virgin River (Black and others, this volume).

The greatest losses from the St. George earthquake were associated with the landslide triggered in Springdale (Carey, this volume). The triggering of this massive slide suggests an intensity of at least VI. However, it should be noted that landslides can be unreliable indicators of intensities due to the variable effects of site conditions. For comparison, observations from other sites in Springdale, such as items falling from shelves and out of cupboards, and damage to merchandise in a souvenir shop, suggest an intensity V.

CONCLUSIONS

A weak, VII maximum MMI was observed in the Hurricane-Toquerville-Virgin area, coincident with the trace of the Hurricane fault and approximately 15 kilometers (9 mi) east of the epicenter. Intensities in the epicentral area appear slightly less at an MMI of VI. Although surface fault rupture did not occur in the St. George earthquake (Black and others, this volume), the distribution of aftershocks and the location, depth, and focal mechanism of the main shock suggest that it occurred on a north-south-striking, moderately west-dipping normal fault, probably the Hurricane fault (Pechmann and others, this volume). This is also supported by the fact that maximum intensities occurred along the surface trace of the Hurricane fault. These intensities suggest that focusing of energy along the rupture plane could have had a significant effect on the ground shaking associated with the earthquake. Theoretical studies of ruptures on dipping normal faults suggest that focusing or directivity effects can result in larger ground motions along the fault trace (Benz and Smith, 1989; Hill and others, 1990; Wong and Silva, 1993); the isoseismal patterns for the St. George earthquake suggest this could be true even for earthquakes not large enough to cause surface rupture.

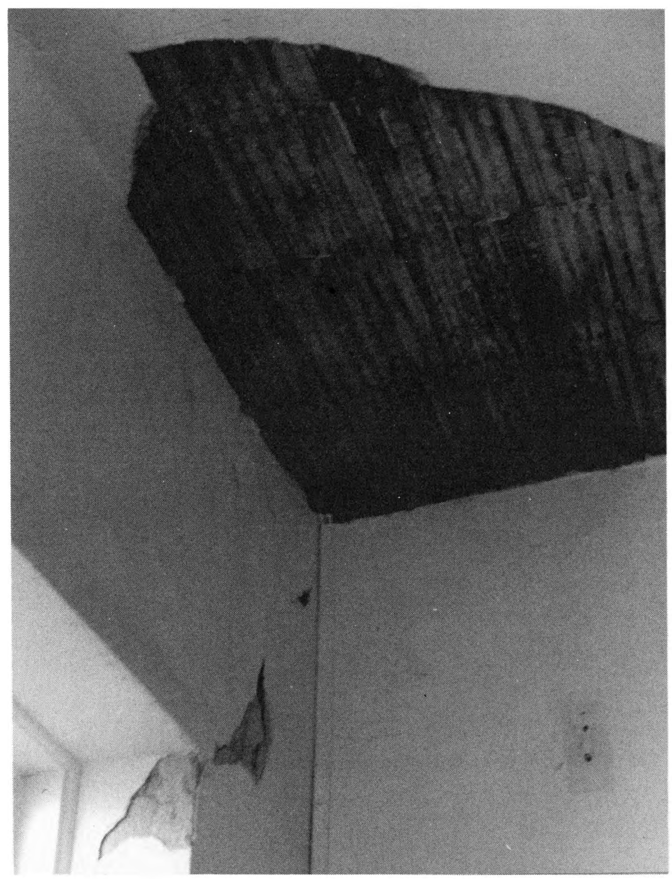
The isoseismals for the St. George earthquake are not symmetric about the epicenter but are skewed to the east (figure 2). This suggests that ground motions did not attenuate as rapidly in the Colorado Plateau to the east as they did in the Basin and Range Province to the west. Unfortunately, the sparsity of data east of Kanab precludes a quantitative comparison of intensity attenuation to the east and west of the epicenter. This pattern for intensities associated with southern Utah earthquakes has been previously noted; preliminary MMI data from the M_L 5.3 1988 San Rafael Swell earthquake also suggested that ground motions attenuated more rapidly to the west in the Basin and Range Province than to the east in the Colorado Plateau (Case, 1988).

Observations in the Springdale area indicate intensities of V to VI occurred near the landslide. This supports the findings of Jibson and Harp (this volume) that site conditions rather than unusually strong ground motions probably triggered such a large landslide 44 kilometers (27 mi) from the epicenter.

Reconnaissance by structural engineers (Reaveley, 1992), findings of this study, and estimates of damage costs (Carey, this volume) all indicate that structural damage directly caused by ground shaking appeared relatively minor for the St. George earthquake. Total loss estimates are $1 million, and the majority of these losses were associated with the Springdale landslide

Figure 6. *Shear cracks in chimney at a house in St. George. Photos provided by Charles M. Sheperd, Utah State Historical Society.*

Figure 7. *Damage to plaster in the women's restroom in the St. George Art Center (formerly Dixie Academy) in St. George. This is a large, two-story, unreinforced masonry building. Photo provided by Glen Blakey via Deedee O'Brien.*



(Carey, this volume). For comparison, total loss for the 1962 M_L 5.7 Richmond earthquake was nearly $1 million in 1962 dollars (Lander and Cloud, 1964); the 1987 M_L 5.9 Whittier Narrows, California earthquake caused $358 million of damage; and losses estimated (as of May 1993) for the March 25, 1993, Scotts Mill, Oregon, earthquake (M_L 5.6) are nearly $30 million (Madin and others, 1993).

Despite the relatively minor structural damage directly caused by ground shaking during the St. George earthquake, there is no clear evidence in the MMI data for unusually weak ground motions. Using McGuire's (1983; equation #46) relation for estimating MMIs in Utah, a hypocentral distance of 21 kilometers (13 mi), and an M_L of 5.8, the estimated site intensity for the Hurricane area during the St. George earthquake is about 6.6, in good agreement with the observed intensity of weak VII. Gutenberg and Richter's (1956) relation for estimating magnitude based on maximum intensity indicates that a maximum intensity of VII yields an estimated magnitude of about 5.7.

Observations from the one set of strong-motion records obtained from Cedar City also suggest that the St. George earthquake did not generate unusually weak ground motions. The peak horizontal ground motion measured on accelerograms recorded in Cedar City by the U.S. Geological Survey (R. Maley, written communication, 1992) is approximately 0.03 g (appendix). This compares favorably with an estimate of 0.02 g calculated using Campbell's (1987) empirical relation, a distance of 75 kilometers (47 mi), and an M_L of 5.8.

I emphasize that neither these observations, nor the MMI data, are conclusive as to whether or not the St. George earthquake caused unusually weak ground motions, particularly in the St. George area. The degree of damage caused by shaking is dependent on the frequency, duration, and amplitude of the motions as well as the type of structures present. Thus, evaluating ground motions based on observed damage is difficult at best. However, the MMI data do suggest one possible explanation for the relatively small amount of total loss associated with the St. George earthquake; the maximum intensities occurred in a sparsely populated rural area, roughly 15 kilometers (9 mi) east of the epicenter and 25 kilometers (16 mi) east of the more densely populated St. George area.

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THE SPRINGDALE LANDSLIDE

by
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INTRODUCTION

The most dramatic geologic effect of the 1992 St. George, Utah, earthquake (M_S 5.6, **M** 5.7, M_L 5.8; Arabasz and others, 1992) was the triggering of the 14,000,000-cubic-meter (18,000,000-yd^3) Springdale landslide, 44 kilometers (27 mi) from the earthquake epicenter. Landslide movement destroyed three homes, threatened several condominiums, disrupted utility lines, and temporarily closed State Route 9, the southwest entrance to Zion National Park. For an earthquake of such small magnitude, both the size and great epicentral distance of this landslide are extraordinary when compared to observations of landslides triggered by earthquakes worldwide.

In the sections that follow, we describe the geologic setting and physical characteristics of the landslide, analyze its static and seismic stability, interpret the conditions leading to failure, consider the implications of the great epicentral distance, and briefly discuss continuing hazards posed by the slide.

SETTING AND PHYSICAL DESCRIPTION OF THE LANDSLIDE

The landslide is located directly north of downtown Springdale and just south and west of the Zion National Park boundary (figure 1). The slide occurred on a convex-outward slope at the confluence of the valley of the North Fork Virgin River with Blacks Canyon, a small tributary valley extending northwestward from the Virgin River. The steep valley walls above the landslide consist of Lower Jurassic sandstone of the Kayenta Formation capped by Navajo Sandstone. Underlying the base of the Kayenta is a prominent ledge of Springdale Sandstone Member (Harshbarger and others, 1957), which locally is the uppermost member of the Lower Jurassic Moenave Formation. The head of the landslide is some distance below the ledge in the less-resistant part of the Moenave, and most of the landslide mass consists of permeable Moenave sandstone sliding on the weak Petrified Forest Member of the Upper Triassic Chinle Formation (Stewart and others, 1972). The Petrified Forest Member is a structureless, variegated claystone formed by alteration of redeposited volcanic debris. We collected surface samples of the Petrified Forest Member exposed at the toe of the landslide. X-ray diffraction shows that the samples consist of mixed-layer clays that are 70 percent montmorillonite and 30 percent illite. Landslides in the Chinle Formation are abundant in the region (Christenson and Deen, 1983; Harty, 1992).

The landslide is somewhat irregular in plan view (figure 2). In maximum dimension, the slide is about 1,100 meters (3,600 ft) wide and 500 meters (1,640 ft) long (from main scarp to toe) and covers an area of about 400,000 square meters (4.3 million ft^2) (Black, 1992). Estimated average depth to the slip surface is 35 meters (115 ft), which yields a volume of about 14,000,000 cubic meters (18,000,000 yd^3).

The landslide has a spectacular main scarp consisting of a single fracture dipping 57 to 77 degrees that is 8 to 15 meters (25-50 ft) high along most of its length (figure 3). The central two-thirds of the scarp is linear in plan view, and the east and west ends curve to follow the convex topography at the site. Multiple scarps developed on the west end where the main scarp intersected a separate smaller slide higher on the slope. Slickensides are well developed along the main scarp (figure 4), and in most places they indicate purely dip-slip displacement. However, evidence of oblique slip in the western half of the scarp reflects complex internal displacement within the landslide mass.

The landslide mass moved about 10 meters (33 ft), primarily by translation along a fairly planar, gently dipping, basal slip surface; parts of the landslide also rotated. The slide mass contains numerous internal scarps and extension fractures as deep as 6 meters (20 ft) (figure 5). The orientations of these fractures and relative displacements along them confirm that the slide moved as several large, coherent blocks. Near the head of the slide, fractures primarily trend parallel to the scarp and bound deep grabens resulting from longitudinal extension. In the central part of the slide mass, some fractures trend parallel to the direction of slide movement and form longitudinal grabens, indicating transverse extension (figures 2 and 6). This extension perpendicular to the direction of slide movement probably resulted from the convex shape of the landslide, which allowed the slide mass to spread outward as it moved downslope. Preexisting gullies in the slide mass also enhanced the formation of these longitudinal grabens. Differential displacement of the ground surface on the landslide destroyed the only three homes on the slide (figure 7).

The toe of the landslide consists of a very steep, bulging front that moved laterally outward several meters (figure 8). The southeast part of the toe moved part way across State Route 9, temporarily blocked access to Zion National Park, and destroyed utility lines. The southernmost lobe of the toe moved to within a few meters of a condominium complex that had to be temporarily evacuated. The western part of the toe moved into and partially blocked the stream draining Blacks Canyon. Landslide material at the toe was dilated and oversteepened, which gave rise to several shallow debris slides.

Residents from the two occupied homes on the landslide reported that they were awakened by the predawn earthquake shaking but returned to bed soon after the shaking stopped. Within 15 to 30 minutes, they heard "snapping and popping" noises and began to feel the ground shifting beneath them. As they left their houses and tried to escape to safety, they could feel

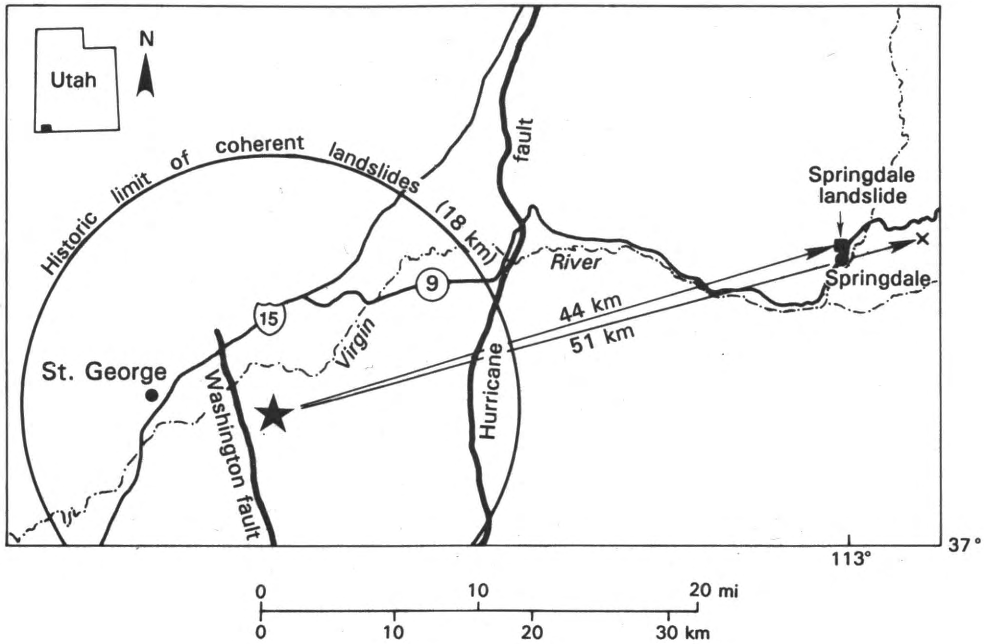

Figure 1. Map showing the epicenter (star) of the St. George earthquake, the Springdale landslide (solid square), the location of the farthest rock fall triggered by the earthquake (x), and the distance limit from worldwide historical data (Keefer, 1984) for coherent landslides.

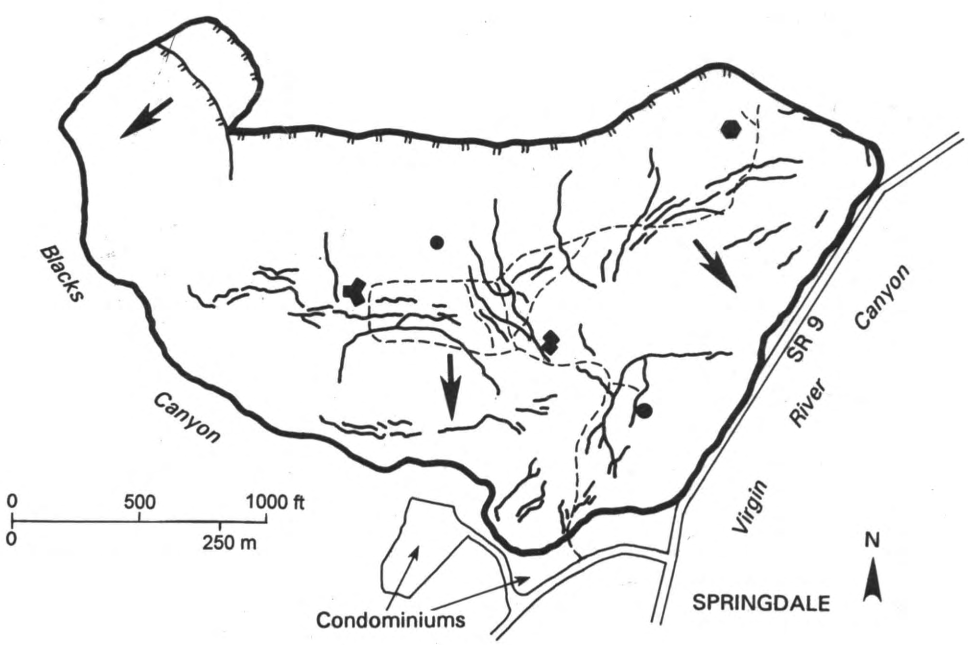

Figure 2. Map of the Springdale landslide (adapted from Black, 1992). Heavy, solid line is landslide boundary, hachured along main scarp; lighter solid lines are prominent fractures; solid double lines are paved roads; dashed lines are dirt roads; solid polygons are structures; solid circles are water tanks; bold arrows show predominant directions of landslide movement.

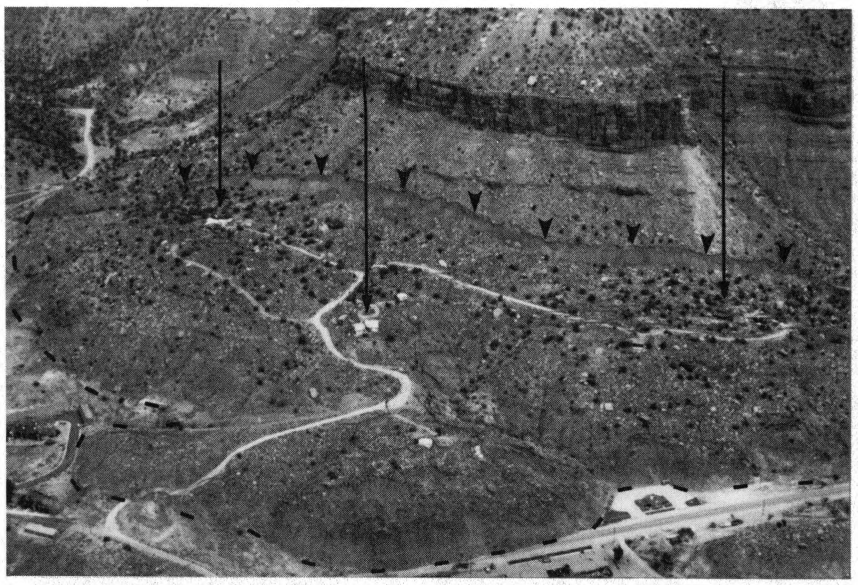

Figure 3. *Aerial oblique view of the Springdale landslide looking north-northwest. Especially striking is the well-developed main scarp of the landslide (shown by short arrows), which is as high as 15 m (50 ft). Long arrows show the three houses that were destroyed by the slide movement, and dashes outline the landslide toe.*

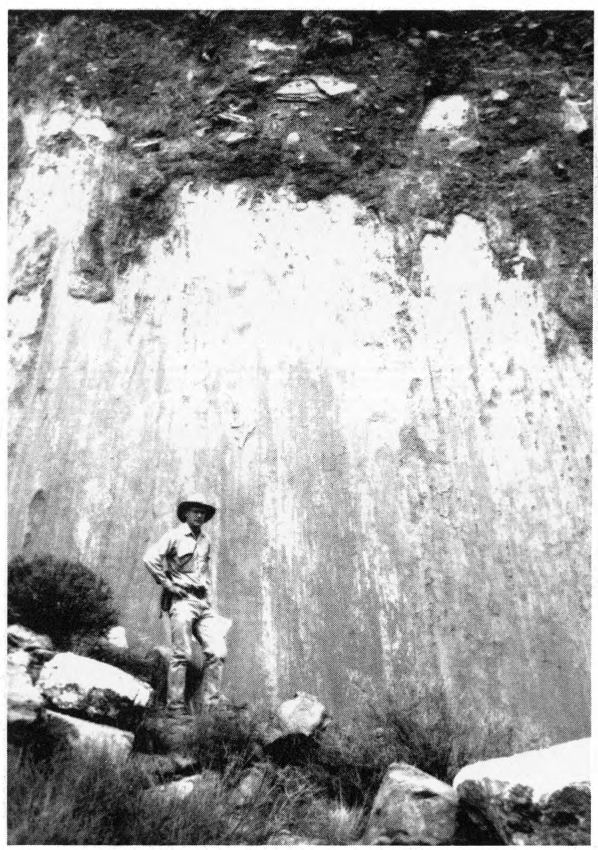

Figure 4. *Main scarp of the Springdale landslide showing well-developed slickensides.*

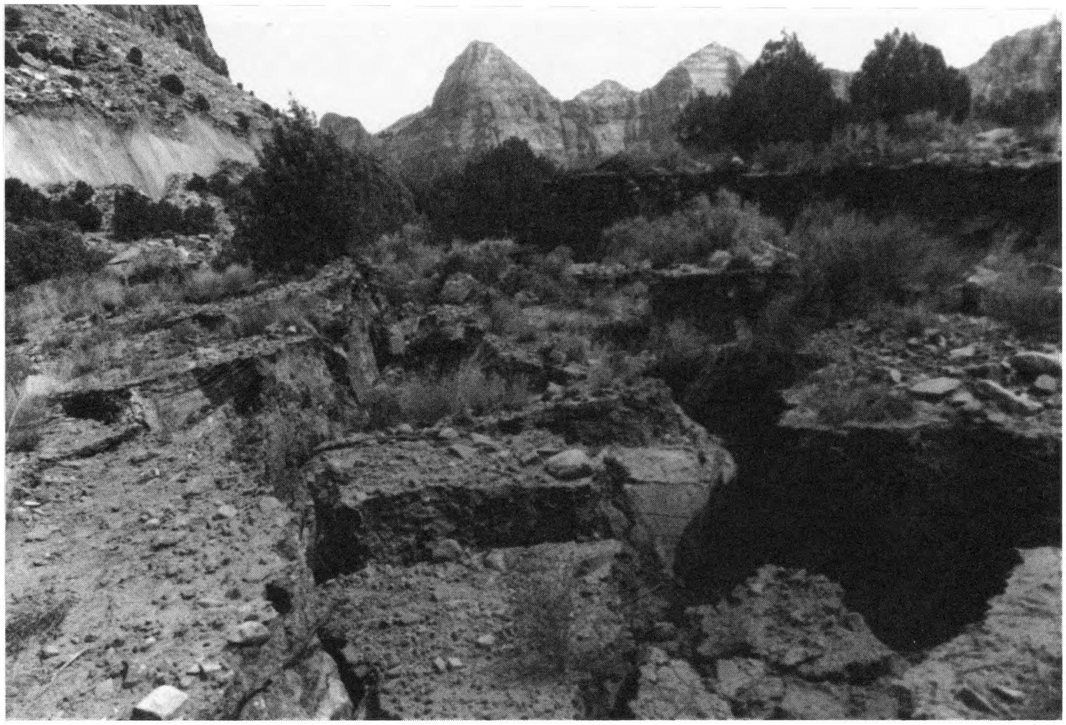

Figure 5. *Extension fractures within graben that extends parallel to main scarp (upper left).*

Figure 6. *Graben extending parallel to direction of landslide movement (right to left). The car (visible in the upper center) was abandoned by homeowners trying to escape the landslide; the road was blocked by the far wall of the graben, which must have formed before the near wall (foreground).*

Figure 7. *House on the western part of the Springdale landslide destroyed by differential movement along internal scarps and other fractures. Main scarp is visible behind the house.*

Figure 8. *Western part of landslide toe near mouth of Blacks Canyon. The toe is very steep and has dilated, also shallow slides and falls of soil and rock have formed.*

the earth shifting and watched deep fissures form as they walked down the entrance road. One resident tried to escape by car, but found the road blocked by a series of scarps several meters high (see figure 6). The landslide continued to move for about 10 hours after the earthquake. No subsequent movement has been detected.

PREVIOUS MOVEMENT HISTORY

Part of the hillside that moved as a result of the St. George earthquake also had moved within the past few decades. Hamilton (1984) monitored the slope from August 1974 to June 1975 and documented 3.3 centimeters (1.3 in) of slope movement in response to 28 centimeters (11 in) of rainfall. His monitoring clearly indicated that movement corresponded to periods of rainfall. Although Hamilton's (1984) estimated movement rate of 3.5 mm/month (0.14 in/month) is quite slow, it clearly indicates slope instability in the recent past. Sensitivity to moderate levels of rainfall suggests that the slope generally is near equilibrium, and that relatively small impulses of rainfall or earthquake shaking could initiate movement. The following sections briefly analyze the slope stability at the site.

STATIC SLOPE-STABILITY ANALYSIS

We estimated the pre-earthquake static stability of the hillside by measuring the shear strength of the materials near the basal shear surface and reconstructing the topography and shear-surface geometry, as described below. We used a PC-based slope-stability program that uses Spencer's (1967) method to calculate the average factor of safety along the shear surface.

Following the earthquake, we collected bag samples of disturbed clay from the Petrified Forest Member of the Chinle Formation near where the basal shear surface appeared at the toe of the landslide. The drained (effective) shear strength of the material was measured in fully saturated conditions in cyclic direct shear. Samples were reconsolidated at confining stresses corresponding to the depth of the shear surface, then forward and reverse shearing cycles were imposed until samples approached residual strength (no further loss of strength during shear). Test results indicate an effective friction angle (ϕ) of 7 degrees and cohesion (c) of 156 kPa (23 psi). The frictional strength of the Moenave sandstone was estimated to be 35 degrees; zero cohesion was assumed because the shear surface in the Moenave probably extends along a preexisting fracture formed by previous landslide movement. We estimated the total unit weight of the hillside material to be 23.7 kN/m^3 (150 pcf).

Figure 9 shows the slope profile constructed for stability analysis. The topographic profile was constructed from contours on the U.S. Geological Survey 1:24,000-scale topographic map of the Springdale East, Utah 7½′ quadrangle. The elevation of the top of the Petrified Forest Member is from a water-well log (James Roberts, homeowner, written communication, 1992) located on the line of profile. Strata are horizontal here, as shown by Cook (1960). Locations of the main scarp and toe of the landslide were mapped in the field, and the geometry of the basal shear surface was constrained to pass through the Petrified Forest Member, by far the weakest stratigraphic unit present. Surface features on the landslide, described above, indicate predominant translation, and so the basal shear surface probably is fairly planar. The geometry of the basal shear surface is well constrained by these data and interpretations. The piezometric surface was placed at the top of the Chinle Formation, whose montmorillonite clay probably retains ground water and is perpetually moist or nearly saturated.

The static factor of safety (FS) using these input parameters is 2.81, which appears quite high considering the movement history of the slope. A higher piezometric level would reduce the factor of safety, but we saw no evidence of water draining from the permeable sandstone above the slip surface, and we consider it unlikely that ground water was perched above the upper surface of the Chinle Formation. The high measured cohesion contributes most of the calculated stability. Because the slide has been recently active, it may be reasonable to assume a well-developed shear surface having little or no cohesion. With no cohesion, the factor of safety drops to 1.30, which appears more reasonable for an intermittently active slide. We use this range of FS=1.30 to 2.81 as lower and upper bounds for dynamic analysis in the following section.

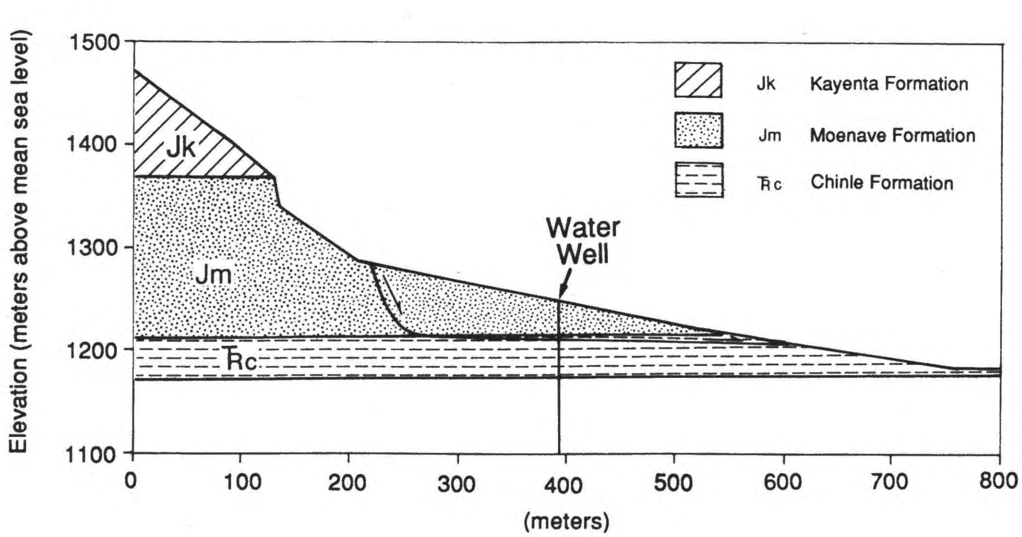

Figure 9. *Cross-sectional profile of Springdale landslide showing stratigraphic contacts and estimated location of the basal shear surface.*

SEISMIC SLOPE-STABILITY ANALYSIS

We use the seismic displacement analysis developed by Newmark (1965) to evaluate the behavior of the slope during seismic shaking. Newmark's method models a landslide as a rigid friction block on an inclined plane. The block has a certain critical acceleration (the acceleration required to overcome frictional resistance and initiate sliding) that must be exceeded for permanent downslope displacement to occur (critical acceleration is analogous to yield acceleration in pseudostatic analysis). The analysis calculates the cumulative permanent displacement of the block as it is subjected to the effects of a selected earthquake acceleration-time history by double-integrating the parts of time history that lie above the critical acceleration. The user then judges the significance of the displacement. Conducting a Newmark analysis thus requires knowing the critical acceleration of the potential landslide and selecting strong-motion records to model the ground shaking.

Critical Acceleration: Newmark (1965) showed that the critical acceleration of a potential landslide mass is a simple function of the static factor of safety and the landslide geometry, expressed as:

$$A_c = (FS - 1)g \sin \propto \qquad (1)$$

where A_c is the critical acceleration in terms of g, the acceleration of Earth's gravity; *FS* is the static factor of safety; and $\propto$ is the thrust angle, the angle from the horizontal that the center of mass of the potential landslide block first moves. For the Springdale landslide, the thrust angle is simply the inclination of the basal shear surface, about 2 degrees. Combined with this thrust angle, the range of static factors of safety given above (1.30-2.81) yields critical accelerations of 0.01 to 0.06 g. The very low thrust angle strongly affects the critical acceleration, such that even the very wide range of static factors of safety yields a fairly narrow range of critical accelerations (typically, critical accelerations of landslides triggered by earthquakes range from 0.10 to 0.30 g). Thus, for a thrust angle of 2 degrees, the critical acceleration is fairly insensitive to variations in factor of safety. Critical accelerations of 0.01 to 0.06 g are rather low, which is reasonable considering the marginal instability of the site in recent years.

Strong-Motion Records: Only one strong-motion instrument was triggered by the St. George earthquake, an analog instrument in Cedar City, Utah, at about twice the epicentral distance as the landslide. The trace of the seismogram is so small that it cannot be used for Newmark analysis, so strong-motion records from other earthquakes must be used. Jibson (1993) suggests using (1) magnitude and source distance, (2) peak ground acceleration (PGA) and duration, and (3) shaking intensity (as defined by Arias, 1970), as criteria for selecting strong-motion records for Newmark analysis at a specific site.

Magnitude and source distance are easily compared, and several strong-motion records, primarily from California earthquakes, are in the magnitude range of interest and have appropriate source distances.

PGA can be estimated from attenuation equations developed for the region. Campbell's (1987) equation for Utah predicts a PGA of 0.07 g at this source distance. The most useful measure of duration for this comparison is that defined by Dobry and others (1978) as the time required to build up the central 90 percent of the Arias (1970) shaking intensity, described in the following paragraph. Dobry and others (1978) proposed an empirical relationship between this measure of duration and earthquake magnitude:

$$\log T = 0.432M - 1.83 \qquad (2)$$

where T is Dobry duration in seconds and M is unspecified earthquake magnitude (probably local magnitude, M_L). For M_L 5.8, the estimated Dobry duration is 4.7 seconds.

We use a single numerical measure of shaking intensity defined by Arias (1970) as the integral of the square of the acceleration-time history, which has units of velocity. The Arias intensity at a site can be estimated using the magnitude-distance equation of Wilson and Keefer (1985):

$$\log I_a = \mathbf{M} - 2\log R - 4.1 \qquad (3)$$

where I_a is Arias intensity in meters per second, **M** is moment magnitude, and R is earthquake source distance in kilometers. For the **M** 5.7 St. George earthquake at an epicentral distance at Springdale of 44 kilometers (27 mi), equation 3 predicts an Arias intensity of 0.021 meters/second (0.069 ft/s).

An alternate empirical method of estimating Arias intensity was developed by R.C. Wilson (U.S. Geological Survey, written communication, 1988) using 43 strong-motion records:

$$I_a = 0.9\, T\hat{a}^2 \qquad (4)$$

where I_a is in meters per second, $\hat{a}$ is PGA in g's, and T is Dobry duration in seconds. Inserting T=4.7 s and $\hat{a}$=0.07 g into equation 4 yields an estimated Arias intensity of 0.021 meters/second (0.069 ft/s), which agrees exactly with the estimate from equation 3.

Table 1 lists 10 strong-motion records from California earthquakes whose characteristics are similar to those estimated above for Springdale. By examining several records we can reasonably bracket the actual shaking conditions and examine the consistency of the results of the Newmark analysis.

Newmark Displacements: For the upper boundary critical acceleration of 0.06 g (corresponding to FS=2.81), one of the strong-motion records generates 0.2 centimeters (0.08 in) of Newmark displacement; the remainder generate none or only an infinitesimal amount. For a critical acceleration of 0.01 g (FS=1.30), Newmark displacements of 1.2 to 7.9 centimeters (0.5-3.1 in) are generated, with an average of about 4 centimeters (1.6 in). Whereas these latter displacements are not large, they approach and reach the 5- to 10-centimeter (2-4 in) range considered critical in initiating general slope failure in other studies (Wieczorek and others, 1985; Wilson and Keefer, 1985; Keefer and Wilson, 1989; Jibson and Keefer, 1993).

INTERPRETATION OF STABILITY ANALYSES

Even at a very low level of critical acceleration (0.01 g), little permanent displacement is calculated because the predicted shaking levels from a moderate earthquake at this distance are so

Table 1.
Strong-motion records used for analysis of the Springdale landslide.

Earthquake Recording site, component	M	R (km)	$\hat{a}$ (g)	T (s)	I_a (m/s)	Newmark Displacement $A_c = 0.06g$ (cm)	$A_c = 0.01g$ (cm)
1992 St. George, Utah Springdale, Utah (estimated)	**5.7**	**44**	**(0.07)**	**(4.7)**	**(0.021)**		
1957 Daly City, California Golden Gate Park, 10°	5.3	12	0.08	2.6	0.022	< 0.1	1.3
1987 Superstition Hills, Calif. Coachella Canal #3, 45°	6.5	56	0.08	13.8	0.061	< 0.1	4.7
1979 Imperial Valley, Calif. Plaster City, 45°	6.5	52	0.04	12.1	0.031	0	1.7
1979 Imperial Valley, Calif. Plaster City, 135°	6.5	52	0.06	11.4	0.057	0	4.2
1979 Coyote Lake, California San Juan Batista, 303°	5.8	28	0.09	10.2	0.051	< 0.1	4.0
1979 Coyote Lake, California Halls Valley, 240°	5.8	30	0.05	12.2	0.023	0	1.2
1979 Coyote Lake, California Salinas, 160°	5.8	50	0.10	10.7	0.049	0.2	4.3
1979 Coyote Lake, California Bear Valley, Station 12, 220°	5.8	56	0.08	12.8	0.073	< 0.1	7.9
1979 Coyote Lake, California Bear Valley, Station 14, 310°	5.8	74	0.05	14.2	0.033	0	2.4
1979 Coyote Lake, California Bear Valley, Station 14, 220°	5.8	74	0.08	12.4	0.064	< 0.1	5.9

Note: **M** *is moment magnitude, R is epicentral distance, â is peak ground acceleration, T is duration as defined by Dobry and others (1978), I_a is shaking intensity (Arias, 1970), A_c is critical acceleration.*

low. This, combined with the strong influence of the low thrust angle on the critical acceleration, indicates again that the Newmark model in this situation is rather insensitive to variations in the static factor of safety. Thus, even if the stability analyses were not well constrained, we could infer that the critical acceleration of the landslide must have been low, considering both its recent aseismic activity and its triggered movement at low levels of seismic shaking.

The critical issue is how such low levels of seismic shaking triggered enough movement to lead to catastrophic failure and 10 meters (33 ft) of displacement. The predicted Arias intensity at Springdale of 0.021 meters/second (0.069 ft/s) is an order of magnitude lower than estimated threshold Arias intensities of 0.32 to 0.50 meters/second (1.05-1.64 ft/s) for triggering landslides of this type (Wilson and Keefer, 1985; Keefer and Wilson, 1989), although recent work indicates thresholds can be as low as 0.01 m/sec (Harp and Wilson, 1995). Although the shaking intensity at Springdale may have been greater than predicted by models developed for other parts of the country (equations 2-4), virtually no earthquake damage was visible in Springdale other than the landslide, which argues against significantly greater shaking intensities there. The estimated Modified Mercalli intensity (MMI) at Springdale was V (Olig, this volume), which corresponds to the lowest minimum intensity at which landslides of this type have been triggered (Keefer, 1984). Thus, the estimated shaking intensity at Springdale is at the extreme lower boundary of intensities that have triggered landslides in other earthquakes.

Lateral displacement of the landslide along its basal shear surface averaged about 10 meters (33 ft), far more than the 1 to 8 centimeters (0.4-3.1 in) modeled in the most optimistic analysis. According to eyewitnesses, however, little or no landslide movement was noticeable during the earthquake shaking, and virtually all of the visible movement began several minutes after the earthquake and continued for about 10 hours. This indicates that the earthquake shaking induced only a small amount of coseismic displacement of the landslide, but that this displacement was sufficient to destabilize the slide mass and lead to continuing failure. The most likely mechanism by which this occurred is through an increase in pore-water pressure and a possible decrease in cohesion along the shear surface. As mentioned above, the montmorillonitic clays of the Petrified Forest Member of the Chinle Formation probably are moist or locally saturated most of the time because of low permeability and continuing recharge from percolation of ground water through the overlying permeable sandstone. Results of the shear-strength tests indicate that this saturated montmorillonite clay behaves as a visco-plastic material. The viscous response results from the low permeability of the clay and effectively retards the coseismic displacement. As the seismic waves pass through the material, its low permeability inhibits deformation and generates high pore pressures. Seismically generated pore pressures dissipate very slowly in such material and thus would likely remain elevated long after the earthquake. We surmise that the seismic shaking generated pore pressures sufficient to reduce the static factor of safety below 1.0 and initiate continuing failure. As post-seismic displacement occurred, pore pressures would continue to increase along the shear surface in the impermeable clay, which could accelerate slide movement. Such movement continued until the landslide mass moved into a more stable geometry that once again raised the factor of safety above 1.0. Also, the material at the slip surface may have regained some cohesion since the last period of landslide movement. If this was the case, even small coseismic displacements would have reduced cohesion along the slip surface and contributed to static instability.

PREVIOUS DISTANCE LIMIT EXCEEDED

The paramount question with regard to this landslide is why it occurred so far (44 kilometers [27 mi]) from the epicenter when worldwide data (Keefer, 1984) indicate that the previous maximum recorded epicentral distance for a coherent landslide of this type in a M_S 5.6 earthquake is 18 kilometers (11 mi). The recent activity of the landslide suggests that it could have been near failure at the time of the earthquake, and only a minor stimulus may have been needed to trigger movement. Several factors may have contributed to the precarious stability of the site. Records from the Utah Climate Center (1992) indicate that the Springdale area received 120 percent of its normal precipitation for the water year, and a local resident reported that eight days before the earthquake an intense storm cell dropped 2.3 centimeters (0.9 in) of rainfall in 20 minutes over the landslide area. In the 1960s, the landslide area had been subdivided for development, and two water tanks and a network of subsurface water lines are present on the slide mass. Although some of these tanks and water lines may have been leaking, detailed inspection of the deep fissures and the entire toe area near the basal shear surface failed to reveal any water draining from the slide mass or moisture due to seepage.

It is tempting to invoke extraordinary site conditions at the Springdale landslide to explain its triggering at great epicentral distance. Interestingly, however, the earthquake triggered a similar landslide, although not as fully developed, in the canyon only 1 kilometer (0.6 mi) west of the Springdale landslide. The only well-developed feature of this incipient landslide was a main scarp 300 meters (1000 ft) long with 1 to 2 meters (3.3-6.6 ft) of displacement. The location of this second landslide indicates that it, too, formed in the Petrified Forest Member of the Chinle Formation. The slope on which it formed, however, showed no evidence of previous landslide movement, which may account for the smaller amount of movement triggered by the earthquake. This second earthquake-triggered landslide on an adjacent, previously undisturbed slope indicates that the conditions that led to landsliding at this extraordinary distance are not unique to one site, but relate more broadly to slopes underlain by the Petrified Forest Member of the Chinle Formation whose geometries and geotechnical properties favor slope instability.

OTHER DISTANCE LIMITS EXCEEDED

The maximum distance limit for disrupted landslides (rock falls and rock slides) also was exceeded very slightly in the St. George earthquake. For a M_S 5.6 earthquake, Keefer's (1984) rock-fall limit is 49 kilometers (30 mi). We found rock falls triggered by the earthquake at 51 kilometers (32 mi) northeast of the epicenter. To the northwest, the farthest rock fall was located at 34 kilometers (21 mi).

Interestingly, rock falls from other recent Colorado Plateau earthquakes have exceeded Keefer's (1984) worldwide historical limits by factors of 4 to 6. The M_L 5.3 Emery County, Utah earthquake of 14 August, 1988 triggered rock falls at least as far as 113 kilometers (70 mi), and possibly as far as 129 kilometers (80 mi) from the epicenter (Case, 1988); the previous historical limit for this magnitude was 29 kilometers (18 mi) (Keefer, 1984). And the western Arizona earthquake of 29 April 1993, also a M_L 5.3 with a distance limit of 29 kilometers (18 mi), triggered a rock fall near Kanab, Utah, 169 kilometers (105 mi) from the epicenter (Harp and others, 1993).

The reason for extraordinary distance limits for both disrupted and coherent landslides in these three earthquakes in the Colorado Plateau region is unclear. Although exceeding previously established landslide magnitude-distance limits for three earthquakes in this region does not constitute a well-defined pattern or trend, it does suggest that propagation of strong shaking in the Colorado Plateau may differ significantly from propagation in areas near plate boundaries where most of the worldwide data on magnitude-distance limits for landslides have been derived (Keefer, 1984). The St. George earthquake probably occurred on the Hurricane fault (Pechmann and others, this volume), which forms the boundary between the Basin and Range Physiographic Province on the west and the Colorado Plateau on the east (Hunt, 1967). The rock-fall limit to the northeast (in the Colorado Plateau) exceeded the historical distance limit, but the rock-fall limit to the northwest (in the Basin and Range) did not.

CONTINUING HAZARDS

No detailed geotechnical analyses have been conducted on the post-earthquake landslide to determine its current stability. Future earthquakes or particularly wet periods may possibly trigger additional movement of the entire landslide mass. If initiated, such movement is likely to be similar to that triggered by the St. George earthquake: relatively slow movement of several meters. Because the toe extends onto flatter ground at the base of the slope, future deep-seated movement may well be inhibited.

Perhaps more troublesome is the shallower landsliding from the toe and flanks of the landslide. The toe is very steep, nearly vertical in places, and was deformed and dilated by the earthquake-triggered movement. Shallow debris slides or flows from the toe could be triggered by rainfall or earthquake shaking and could threaten State Route 9 and structures near the toe. Also, the western part of the toe partially blocked the stream channel that drains Blacks Canyon, and if runoff begins to pond behind this small blockage and saturates the loose slide material, debris flows could form.

SUMMARY AND CONCLUSION

The Springdale landslide was the most significant geologic phenomenon associated with the 2 September 1992 St. George, Utah earthquake. This landslide is exceptional because it occurred 44 kilometers (27 mi) from the earthquake epicenter, whereas the historical distance limit for landslides in a M_S 5.6 earthquake is only 18 kilometers (11 mi). With a volume of about

14,000,000 cubic meters (18,000,000 yd^3), it may be among the largest landslides ever triggered by an earthquake of this magnitude.

Slope-stability analysis indicates that the static factor of safety of the landslide before the earthquake may have been as low as 1.30, which is consistent with its having moved during wet periods in the last few decades. Analysis of the seismic behavior of the landslide using Newmark's (1965) method indicates maximum coseismic displacements of about 1 to 8 centimeters (0.4-3.1 in), just at the threshold where general slope failure might be expected to occur. The analyses, in conjunction with eyewitness accounts that the bulk of the landslide movement began several minutes after the earthquake, suggests that the earthquake triggered enough deformation to elevate pore-water pressures in the clays of the Petrified Forest Member of the Chinle Formation in which the basal shear surface formed. These elevated pore pressures probably reduced the factor of safety below 1.0 and led to the observed 10 meters (33 ft) of landslide movement that continued for about 10 hours after the earthquake.

Two other recent Colorado Plateau earthquakes have triggered landslides at distances far beyond previously established historical limits, which suggests that separate limits may need to be developed for some areas away from plate boundaries.

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IMPACTS ON DAMS

by
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INTRODUCTION

The Dam Safety Section of the Utah Division of Water Rights regulates dams within the state. A computerized database of over 2,000 dams is maintained; nearly 700 are routinely inspected. Following an earthquake, the Dam Safety Section is responsible for inspecting dams for damage. Routine, periodic safety inspections are coordinated through the Dam Safety Section office in Salt Lake City. In emergency post-earthquake inspections, regional office personnel respond. Following the St. George earthquake, staff from the Southwestern Regional Office in Cedar City investigated dam sites in southwestern Utah.

Shortly after the St. George earthquake, a computer program written on the ARC/INFO geographic information systems (GIS) platform was used to search the data base for dams that fell within a prescribed radius about the epicenter. The search radius is a function of earthquake magnitude and, as the magnitude increases, so does the search radius. The program generated a list of 34 dams within the search radius, including 15 high-hazard dams, 5 moderate-hazard dams, and 14 low-hazard dams.

This paper discusses two dams with noticeable changes immediately following the earthquake. They are the Ivins Bench Dam and the Main Quail Creek Dam (figure 1). The purpose of this paper is to provide pertinent background information, present field observations, and document fluctuations in piezometers. Leeflang (1992) provides a more thorough analysis of the effects of the earthquake on dams in southwestern Utah.

IVINS BENCH DAM

The Ivins Bench Dam is an off-channel structure along the Santa Clara River northwest of St. George and Santa Clara. It is 14.5 miles (23.3 km) from the epicenter of the St. George earthquake (figure 1). Initial construction took place prior to 1920, using a sluicing technique to place fill over a small concrete core wall (Sandford, 1920). Cottrell (1940) describes additional embankment material end-dumped over the sluiced fill, noting historical sloughing "... every year since the dam was constructed ... by reason of water seeping through the dam ...." Under supervision of the U.S. Soil Conservation Service, a 1943 rehabilitation project was undertaken to correct the leakage by blanketing a portion of the upstream face with clay. Construction of a rubble masonry spillway was part of the project (Utah Division of Water Rights, 1979). In 1985, the Utah State Engineer ordered the reservoir drained due to leakage, slope cracking, and other problems (Morgan, 1985). A 1986 report summarizing a geotechnical investigation of the site recommended a downstream slope filtering, collection, and drain system (Rollins, Brown, and Gunnell, Inc., 1986). These repairs were completed later that year.

On the afternoon of September 2, 1992, engineers from the Southwest Regional Office of the Utah Division of Water Rights performed the post-earthquake inspection of the Ivins Bench Dam. A sand boil approximately 5 feet (1.5 m) downstream from the toe of the dam was noted. Significant deposition of material and an estimated 25 gallons per minute (95 l/min) of flow were also noted at the location. This had not been observed during the routine annual inspection performed on June 13, 1992, and indicated either a broken outlet conduit or internal piping of the embankment and/or foundation (Morgan, 1992a).

A subsequent inspection of the dam site on October 7, 1992, determined that the sand boil was actually the outlet of one of the drains installed in 1986. Four of the seven drains were buried as a result of surface erosion prior to the earthquake. Close inspection of the exposed drains revealed significant amounts of sandy material in at least one drain, indicating possible piping of embankment material. Investigators also discovered at least two major cracks in the embankment during the inspection. Vertical displacement had occurred along the cracks. A test hole at one location exposed a void which extended horizontally for about 12 feet (3.7 m) (Morgan, 1992b).

QUAIL CREEK MAIN DAM

The Quail Creek Reservoir is located north of St. George and west of Hurricane, Utah, about 7.9 miles (12.7 km) northeast of the epicenter (figure 1). Two separate structures impound the reservoir; the Main Dam and the South Dam. In 1989, the original earthfill Quail Creek dike failed and was replaced by the South Dam, a roller-compacted concrete structure. Some fluctuations in piezometer readings occurred in the South Dam following the earthquake, but the most notable fluctuations occurred in a number of piezometers on the Main Dam.

The Quail Creek Main Dam is a zoned earthfill embankment. James and others (1989) provide the following descriptions of the embankment construction. The core, or Zone I, consists of "...generally low-plasticity silty and clayey sands." Upstream of Zone I lies Zone II, consisting of "... medium-plasticity weathered shale." Zone III is a "pitrun sandy gravel" making up the upstream shell. Finally, Zone IV, the downstream shell, consists of random fill, "enveloped by Zone III sandy gravel." Several filters and a drainage system control flow through the embankment.

James and others (1989) describe the geologic setting as "unique," and note that the bedrock is the Triassic Moenkopi Formation along the Virgin anticline. Regarding bedding, they

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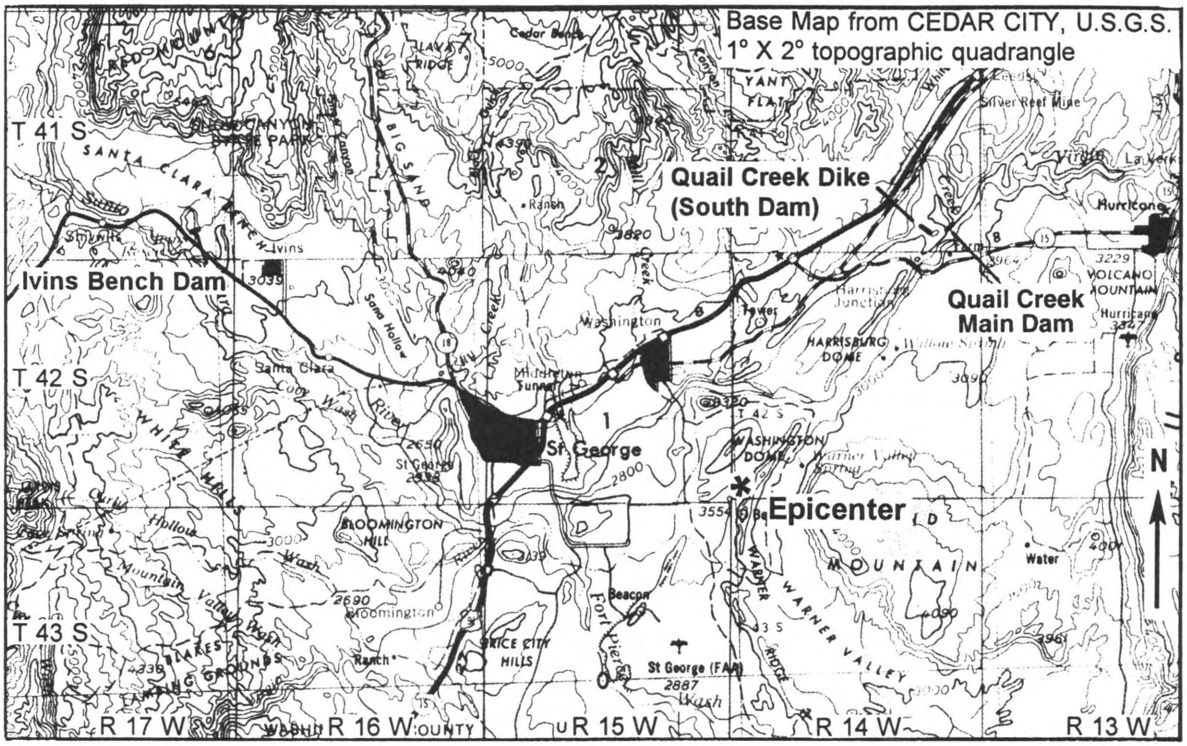

Figure 1. *Location map.*

state that "the axis of the dam [is] roughly parallel to the strike of the beds and the beds dip downstream."

The Dam Safety Section reviews all piezometer data collected by the Washington County Conservancy District for the Quail Creek dams. The district submits data on a biweekly basis for reservoir elevation and water levels in all piezometers, wells, and drain weirs. Immediately following the earthquake, district personnel collected and submitted data on a daily basis. Of the two-dozen piezometers on the Main Dam, seven displayed significant fluctuations.

Piezometers 5, 6, 8, 9, and 10 follow a cross-sectional line from the center crest of the dam downstream to the toe. Piezometers 17 and 18 are in the right abutment. Table 1 shows information for these piezometers.

Figure 2 depicts reservoir elevation and figures 3-5 depict water levels in piezometers. The general downward trend of the reservoir surface elevation preceding the earthquake reflects typical irrigation water use through the season. Piezometer levels reflect this gradual downward trend. Extrapolated points are in place to better illustrate the rise or fall in the piezometric surface at the time of the earthquake.

Figure 3 shows that water levels in piezometers 5 and 6 behaved as expected until the earthquake. At the time of the event, the level in piezometer 5 in the embankment dropped nearly 2.5 feet (0.8 m) while the level in piezometer 6 in the foundation rose nearly 5 feet (1.5 m). With time, changes in levels returned to the pre-earthquake trend but not to pre-earthquake levels.

The piezometers in figure 4 displayed the same behavior; a general downward trend, abrupt change following the earthquake, and a return to equilibrium. The spike in piezometer 9 several days after the earthquake is interpreted as a faulty reading.

The most dramatic response to the earthquake is shown in figure 5. Piezometer 17, in the right abutment (foundation), dropped nearly 17 feet (5.2 m) following the earthquake. No accompanying increase in drain discharge was recorded. As with the other piezometers, the general post-earthquake trend approximates the original downward trend, maintaining nearly the same relationship with reservoir head.

Table 1
Piezometer information in feet above mean sea level.

Piezometer #	Type	Top Elev. (feet)	Bottom Elev. (feet)	Depth (feet)	Zone
5	Embankment	2,997.5	2,810	187.5	I
6	Foundation	2,997.5	2,770	227.5	N/A
8	Embankment	2,935.8	2,800	135.8	III
9	Embankment	2,904.7	2,795	109.7	III
10	Foundation	2,904.7	2,745	159.7	N/A
17	Foundation	2,987.5	2,908.5	79	N/A
18	Foundation	2,987.5	2,801.5	186	N/A

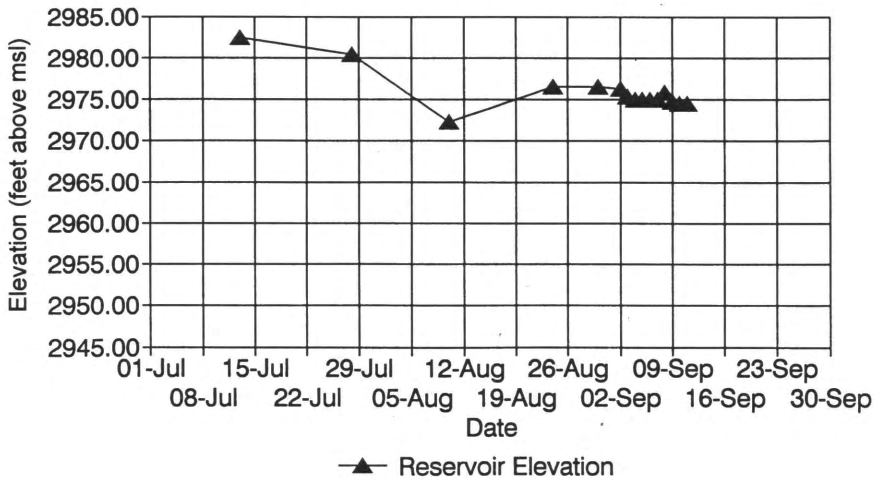

Figure 2. *Quail Creek Reservoir level.*

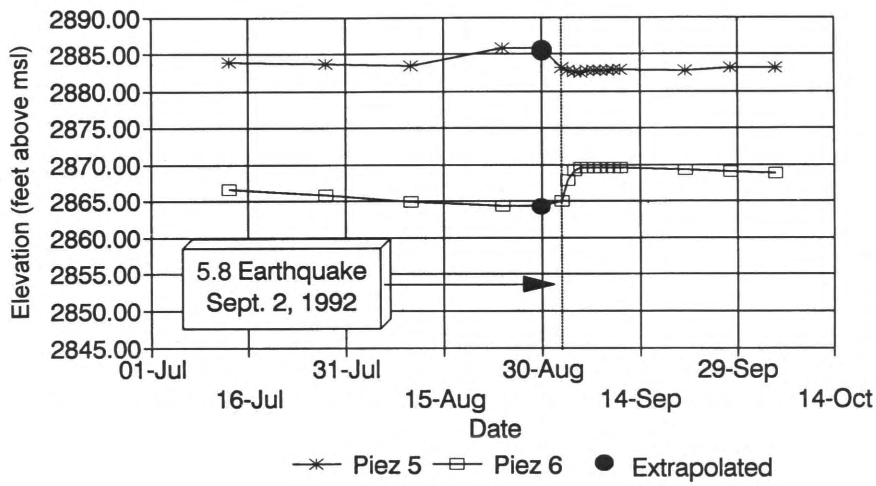

Figure 3. *Quail Creek ground-water levels (piezometers 5 and 6).*

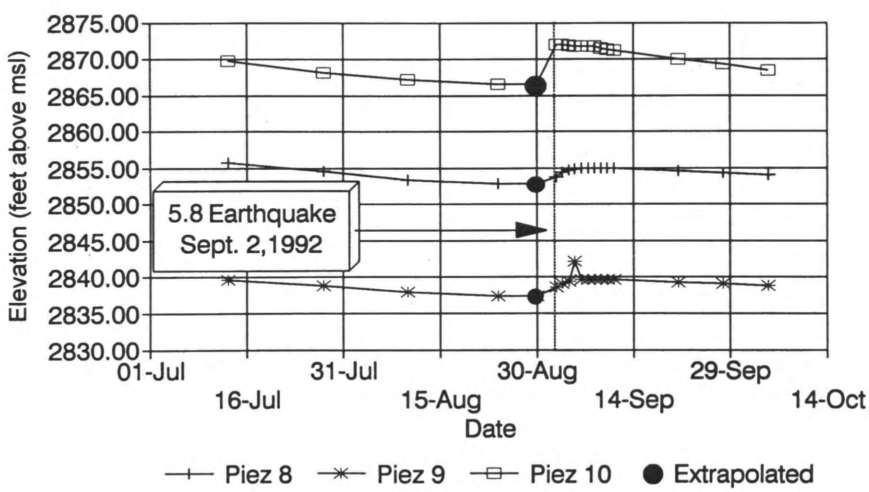

Figure 4. *Quail Creek ground-water levels (piezometers 8, 9, and 10).*

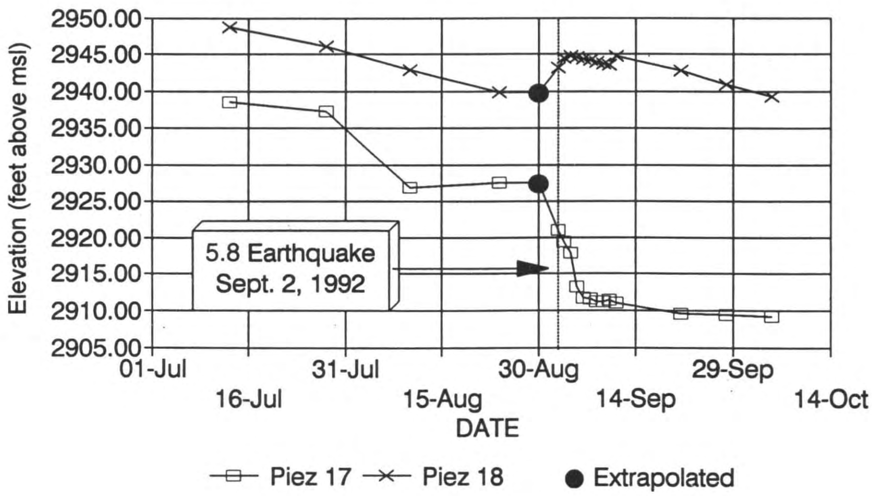

Figure 5. Quail Creek ground-water levels (piezometers 17 and 18).

CONCLUSIONS

Due to its unsafe condition, the Ivins Bench Reservoir was ordered drained by the State Engineer. An engineering study will be completed to assess the extent of the piping and other embankment problems. Repairs must be made to the dam before water can be stored in the reservoir (Morgan, 1992b).

Piezometer data from the Quail Creek Main Dam indicate significant water-level fluctuations caused by the earthquake. However, none of the design parameters were exceeded by the piezometric surface. The dam was considered safe and regular monitoring will continue.

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IMPACT ON WASHINGTON FIELDS IRRIGATION STRUCTURES

by
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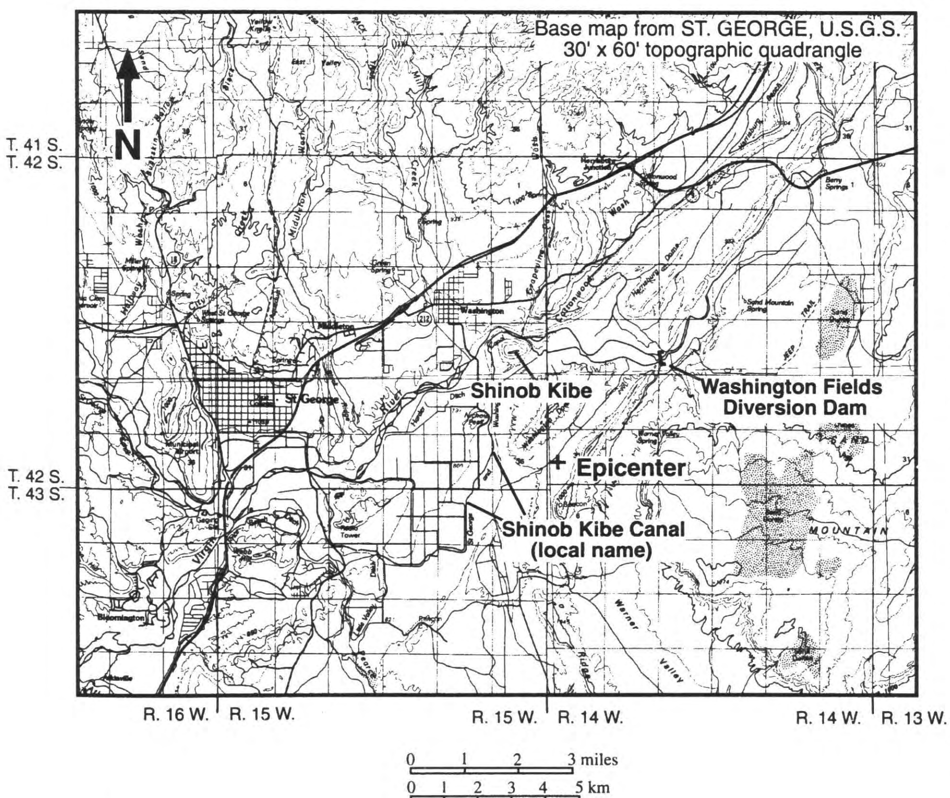
BACKGROUND

The epicenter of the 1992 St. George earthquake was near Shinob Kibe, a mesa in the Washington Fields area south of Washington, Utah (figure 1). The U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service) has constructed or designed debris basins, a diversion dam, and irrigation canals in this area. Inspection after the earthquake indicated that there were no effects on the debris basins, the Washington Fields diversion dam on the Virgin River, or the Shinob Kibe canal (legally named the St. George and Washington Canal) (figure 1). A subsequent inspection of these facilities was conducted about five months after the earthquake to determine if initially subtle, unrecognized damage had occurred that would become obvious with time.



The Washington Fields diversion dam (figure 2) and the Shinob Kibe canal (figure 3) are concrete-and-earth structures close to the epicenter of the St. George earthquake. The diversion is an earth-fill dam across the Virgin River approximately 2.5 miles (4 km) upstream of Shinob Kibe hill. The canal is a concrete-lined ditch that runs from the diversion to the west along the Virgin River and then south around Shinob Kibe hill.

No earthquake damage to either structure was noted during inspections by the NRCS and Utah Dam Safety personnel immediately following the earthquake. In a subsequent inspection during the week of February 8-12, 1993, no earthquake damage was visible in the debris basin dams or riser pipes, but damage was noted on the diversion and canal.

WASHINGTON FIELDS DIVERSION DAM

This structure was rebuilt after it was washed out in the 1989 Quail Creek dike breach. The rebuilt diversion was designed to withstand a Richter magnitude 6.0 earthquake on the Washington or Hurricane faults. It was built on approximately 40 feet (12 m) of alluvial sands that overlie conglomerate of the Moenkopi Formation (Triassic age).

No ground cracks, pipe holes, sand blows, displacement, or settlement were observed on or in the area of the diversion structure as a result of the earthquake. The vertical concrete main wall exhibited extensive micro-cracking in polygonal shapes about 0.5 inches (1.3 cm) in diameter (figure 4). These may have been formed by natural weathering of the concrete but, because no other walls were cracked, no cracks had been previously reported, and the wall faces the epicenter, this phenomenon was probably earthquake related. No spalling or displacement along cracks was observed along the wall. A wing wall of the diversion structure had a dominant crack that penetrated the wall (figure 5). There was no spalling or displacement on the wall crack, which appeared fresh. This crack was probably also earthquake caused. Annual inspection of both the main and wing walls was recommended.

Liquefaction damage was not apparent at the Washington Fields Diversion. This is interesting because during preconstruction investigations a track-hoe was buried about 5 feet (1.5 m) due to liquefaction of the river sands caused by motor vibrations. The sands were determined to be potentially liquefaction prone by soil testing of undisturbed samples and splitspoon blow-count testing. The lack of earthquake-induced liquefaction is supported by the lack of damage to the concrete-lined canal on the downstream left side (facing downstream) of the embankment. Although the embankment is covered by large rocks (upstream) and gravel (downstream), in which ground cracks may not be apparent, the lack of damage to the canal indicates a probable lack of significant liquefaction in the area of the embankment.

Figure 2. *Washington Fields diversion dam.*

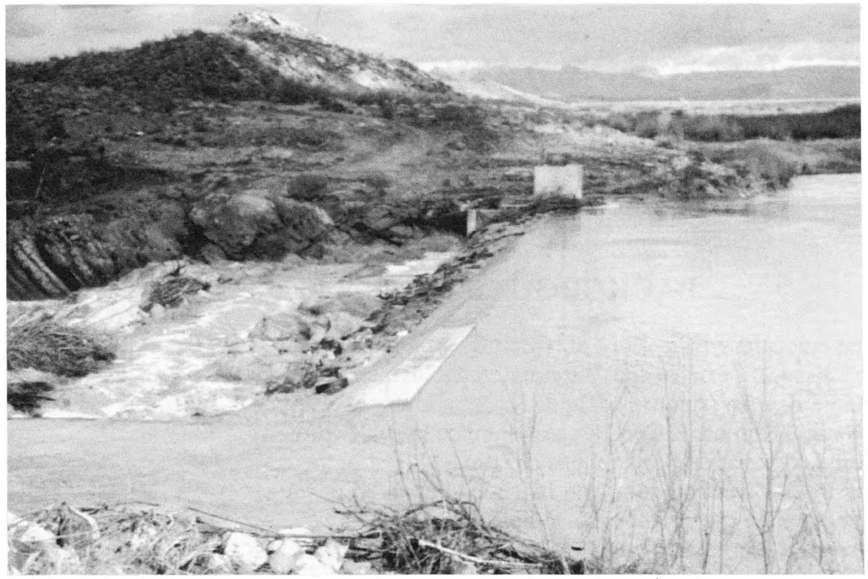


Figure 3. *Shinob Kibe canal.*

Figure 4. *Cracking in concrete main wall of the Washington Fields diversion dam.*

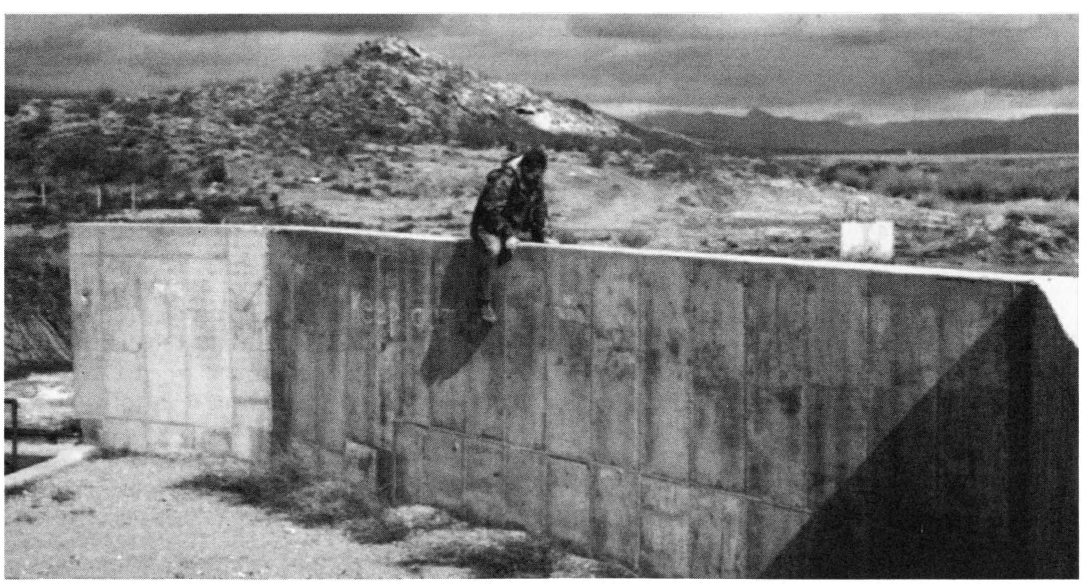
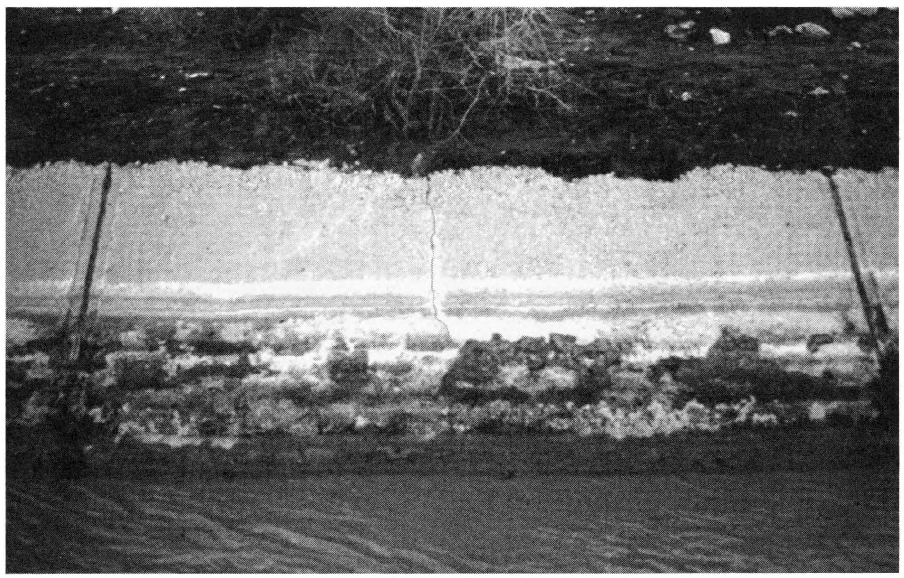


Figure 5. Crack in a wing wall of the Washington Fields diversion dam.

Figure 6. Cracks in the concrete lining of the Shinob Kibe canal.



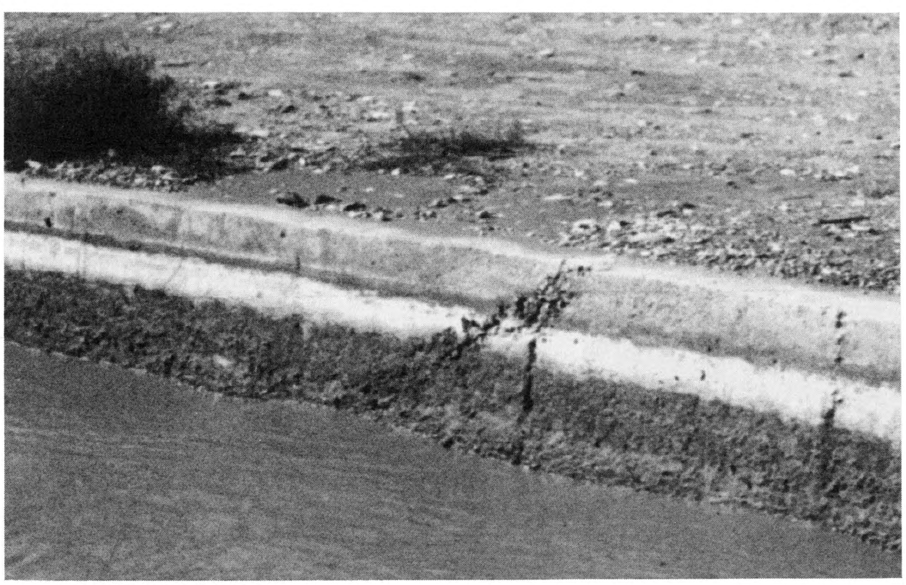


Figure 7. Cracks in the concrete lining of the Shinob Kibe canal.

Figure 8. Cracked lining and piping along the Shinob Kibe canal.

Figure 9. Rock fall adjacent to the Shinob Kibe canal.

Figure 10. Rock fall into the Shinob Kibe canal.

SHINOB KIBE CANAL

A portion of this canal is at or very near the epicenter of the earthquake (figure 1). It is a non-reinforced, concrete-lined canal (2.5 inches [6.4 cm] thick) along the north face of Shinob Kibe hill, and it transports water from the Washington Fields diversion dam. The canal was not damaged in the area of the diversion. In the area of Shinob Kibe hill, however, about every fourth slab of concrete along the canal had a visible crack that was nearly vertical in the middle of the slab. This cracking is probably earthquake related. Some of these cracks showed differential settlement (figures 6 and 7). One slab had seriously cracked and failed by foundation piping and displacement (figure 8) and will need repair. The other cracks will require frequent inspection, especially in the late winter and spring. The damage extends for the entire length of the concrete-lined portion of the canal near Shinob Kibe hill. Displacement and piping failure also occurred along joints in the concrete-slab lining. The cracking-piping damage represents a significant increase in normal annual concrete maintenance problems on the canal.

Rock fall into the canal has always been a problem because it is cut into steep, unstable colluvial slopes. During the earthquake, rocks fell into and adjacent to the canal (figures 9 and 10), and rock falls will continue to be a maintenance problem in the future, particularly during earthquakes.

SUMMARY AND CONCLUSIONS

Earthquake damage was noted on the Washington Fields diversion dam main wall (micro-cracking) and wing wall (major crack), and in canal concrete slabs (cracking and piping failure). The damage to the diversion and canal will necessitate increased inspection and maintenance. Rock fall into the canal also occurred but caused little damage.

No conclusions are warranted regarding the safety of the design of the Washington Fields diversion dam with respect to liquefaction and ground shaking in an earthquake of Richter magnitude 6.0. The St. George earthquake was apparently anomalous in that it did relatively little damage to urban and earthwork structures in the epicentral region (Pechmann and others, this volume; Olig, this volume). The lack of significant damage to NRCS structures in the area may be due to the character of this particular earthquake. The specific characteristics that may have minimized the damage are: (1) the earthquake energy appeared to be focused away from the epicentral area (Olig, this volume), and (2) the shaking may have been of short duration for an earthquake of its magnitude.

ESTIMATED ECONOMIC LOSSES

by
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Utah Division of Comprehensive Emergency Management

INTRODUCTION

This report addresses four types of losses in the St. George earthquake: (1) damage to structures, (2) equipment and human-resource costs for response, including debris removal, (3) property devaluation, and (4) replacement and repair costs. In some instances, the four types of losses are not easily separable. The purpose of this report is to identify monetary loss and document expenditures that resulted from earthquake-related damage and earthquake-related response activities. To collect the data, I contacted municipalities (public-works offices, city managers, mayors), utilities, and other local government and state agencies. Most of the communities in the epicentral area that experienced a Modified Mercalli intensity VI and greater (Olig, this volume) were contacted. This is not a comprehensive listing of all losses, but rather an attempt to quantify the major losses to determine the cost of the earthquake.

LOSSES

The most damage and economic loss was in the Springdale-Zion National Park area. The town of Springdale reported about $2,000 damage to its water system. Three homes in the Balanced Rock Hills subdivision were destroyed by the Springdale landslide and were valued by the Washington County Assessor's Office at $187,730. In addition to the monetary loss to the individual homeowners, property values dropped on the remaining land parcels in the subdivision. According to the County Assessor's Office, the total taxable properties of Balanced Rock Hills subdivision were valued at $346,530 prior to the earthquake. Following the earthquake, the taxable properties were valued at $24,500, a $322,030 loss of property value for landowners and tax base for the town.

Removal of the slide material from State Route 9 and replacement of the power lines damaged by the slide cost over $63,300 as reported by the Utah Department of Transportation (UDOT) and Utah Power and Light Company. Early UDOT estimates of the cost of rebuilding the highway ranged from $250,000 to $400,000. Several years have passed and the slide appears to be stable, so UDOT has no immediate plans to rebuild the highway. Zion National Park spent $17,000 in debris removal inside the Park and assisted homeowners from the Balanced Rock Hills subdivision in opening the road on the slide and removing personal belongings.

Hurricane City had one home damaged beyond repair, a church with some internal nonstructural damage, and some water-system damage to a local business for a total cost of about $57,500. La Verkin, north of Hurricane, reported spending $300 for an evaluation of water samples from the city water system for sedimentation problems caused by the earthquake.

St. George City spent approximately $10,000 for debris removal. Reported damage to local businesses was about $35,000 and significant private damage was about $100,000. State facilities in the area reported about $2,000 damage. Washington School District placed work orders for about $6,000 in repairs. However, one school may require $50,000 to $70,000 to repair an interior adobe wall that was damaged. Historic buildings in St. George were also damaged. Current damage estimates are about $75,000, with part of that money being spent on strengthening the structures. It must be noted that, with time, additional damage to these older structures may be recognized.

Many households experienced some type of damage such as cracks in dry wall, plaster that broke loose or cracked, and/or broken glass. This type of damage is incidental and generally goes unreported. However, if all such losses were summed as a category of damage it would likely be significant.

The library in Kanab was under renovation at the time of the earthquake. Damage to the library was significant and caused the city building inspector to consider condemning the structure. Because the library is being replaced, the city manager did not believe it appropriate to include damage estimates to the existing building in the total earthquake costs.

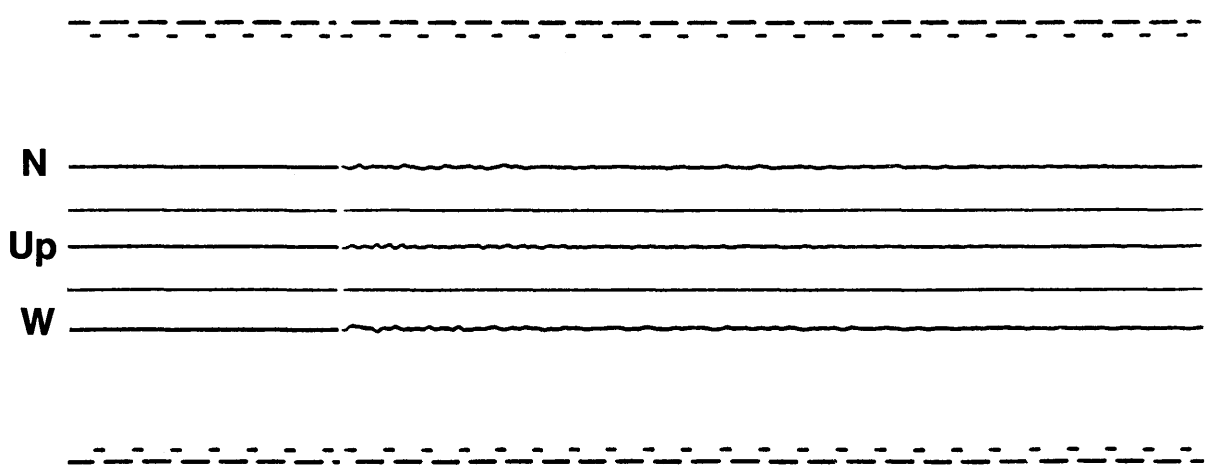
CONCLUSIONS

This brief look at damage and economic loss from the St. George earthquake indicates that it was one of the most costly earthquakes in Utah history. Total losses from direct damage, response costs, and lost property values documented in this report approach $1 million, but this is likely a minimum value. If the estimated costs to rebuild the highway were included, the total cost meets or exceeds $1¼ million. As new losses are discovered and more comprehensive estimates are made, loss estimates could rise even higher.

Appendix

Accelerograph Record - Cedar City

The U.S. Geological Survey operates a Kinemetrics SMA-1 (#1509; trigger threshold 0.01 g) analog instrument mounted on a seismic pier on the bottom floor of the Southern Utah University library in Cedar City (USGS station number 2267), 75 kilometers (47 mi) from the epicenter of the September 2, 1992 St. George earthquake. The library is a large, multi-story building at 37.67556° N. latitude and 113.06833° W. longitude on deep, Quaternary-age flood-plain alluvium (Olig and Christenson, 1993). The record is shown below; film speed - 2 time marks/second, sensitivity 18.5 millimeters/g. Peak ground acceleration was in the east-west component at about 0.03 g.



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