BRIGHAM YOUNG UNIVERSITY

GEOLOGY STUDIES

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FIELD TRIP GUIDE BOOK

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PART 2 TWO

EDITED BY PAUL KARL LINK AND BART J. KOWALLIS

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MESOZOIC TO RECENT GEOLOGY OF UTAH

Edited by
Paul Karl Link and Bart J. Kowallis

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Cover photos taken by Paul Karl Link.

Top: Upheaval Dome, southeastern Utah.
Middle: Lake Bonneville shorelines west of Brigham City, Utah.
Bottom: Bryce Canyon National Park, Utah.

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Preface

Guidebooks have been part of the exploration of the American West since Oregon Trail days. Geologic guidebooks with maps and photographs are an especially graphic tool for school teachers, University classes, and visiting geologists to become familiar with the territory, the geologic issues and the available references.

It was in this spirit that we set out to compile this two-volume set of field trip descriptions for the Annual Meeting of the Geological Society of America in Salt Lake City in October 1997. We were seeking to produce a quality product, with fully peer-reviewed papers, and user-friendly field trip logs. We found we were bucking a tide in our profession which de-emphasizes guidebooks and paper products. If this tide continues we wish to be on record as producing "The Last Best Geologic Guidebook."

We thank all the authors who met our strict deadlines and contributed this outstanding set of papers. We hope this work will stand for years to come as a lasting introduction to the complex geology of the Colorado Plateau, Basin and Range, Wasatch Front, and Snake River Plain in the vicinity of Salt Lake City. Index maps to the field trips contained in each volume are on the back covers.

Part 1 "Proterozoic to Recent Stratigraphy, Tectonics and Volcanology: Utah, Nevada, Southern Idaho and Central Mexico" contains a number of papers of exceptional interest for their geologic synthesis. Part 2 "Mesozoic to Recent Geology of Utah" concentrates on the Colorado Plateau and the Wasatch Front.

Paul Link read all the papers and coordinated the review process. Bart Kowallis copy edited the manuscripts and coordinated the publication via Brigham Young University Geology Studies. We would like to thank all the reviewers, who were generally prompt and helpful in meeting our tight schedule. These included: Lee Allison, Genevieve Atwood, Gary Axen, Jim Beget, Myron Best, David Bice, Phyllis Camilleri, Marjorie Chan, Nick Christie-Blick, Gary Christenson, Dan Chure, Mary Droser, Ernie Duebendorfer, Tony Ekdale, Todd Ehlers, Ben Everitt, Geoff Freethey, Hugh Hurlow, Jim Garrison, Denny Geist, Jeff Geslin, Ron Greeley, Gus Gustason, Bill Hackett, Kimm Harty, Grant Heiken, Lehi Hintze, Peter Huntoon, Peter Isaacson, Jeff Keaton, Keith Ketner, Guy King, Mel Kuntz, Tim Lawton, Spencer Lucas, Lon McCarley, Meghan Miller, Gautam Mitra, Kathy Nichols, Robert Q. Oaks, Susan Olig, Jack Oviatt, Bill Perry, Andy Pulham, Dick Robison, Rube Ross, Rich Schweickert, Peter Sheehan, Norm Silberling, Dick Smith, Barry Solomon, K.O. Stanley, Kevin Stewart, Wanda Taylor, Glenn Thackray and Adolph Yonkee. In addition, we wish to thank all the dedicated workers at Brigham Young University Print Services and in the Department of Geology who contributed many long hours of work to these volumes.

Paul Karl Link and Bart J. Kowallis, Editors

Neotectonics, fault segmentation, and seismic hazards along the Hurricane fault in Utah and Arizona: An overview of environmental factors in an actively extending region

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ABSTRACT

Long normal fault zones are in, and form the eastern boundary of, the transition zone between the Colorado Plateau and highly extended Basin and Range physiographic provinces. Seismicity in the transition zone of southwestern Utah and northwestern Arizona is believed to be influenced by earthquake rupture segment boundaries. Two geometric fault segment boundaries are identified on the active Hurricane fault. Fault geometry, scarp morphology, structures, and changes in amount of offset are used to define the boundaries. The seismic-risk implication of defining earthquake rupture segments and boundaries is significant in southwestern Utah, a region experiencing rapid population growth. The 1992 St. George M 5.8 earthquake probably occurred on the Hurricane fault, triggering a large and damaging landslide and other seismic hazards. Isolated Quaternary fault scarps are observed along the Hurricane fault. These fault scarps indicate that the fault is active, although no historical surface ruptures have occurred.

INTRODUCTION

The transition zone between the Basin and Range and Colorado Plateau physiographic provinces (fig. 1) displays tectonic features common to both provinces. In southwestern Utah and northwestern Arizona the zone is transected by four long normal fault zones—Toroweap-Sevier, Hurricane, Washington, and Gunlock-Grand Wash—each greater than 100 km long. The transition zone is an ideal location to study normal faulting. Important data may be obliterated by multiple-overprinting-faulting events in more highly extended regions such as the Basin and Range, but the transition zone experienced less strain and shows a higher degree of data preservation.

Within the Basin and Range Province and the transition zone, ongoing extension is typically accommodated by seismically active, long normal fault zones. Through detailed studies, long normal faults can be divided into geometric fault segments differentiated by faulting history, geometry, and seismicity. Boundaries separating segments are significant because they may be the sites of significant strain, may impede earthquake-rupture propagation, and may influence earthquake locations (e.g., Schwartz and Coppersmith, 1984;

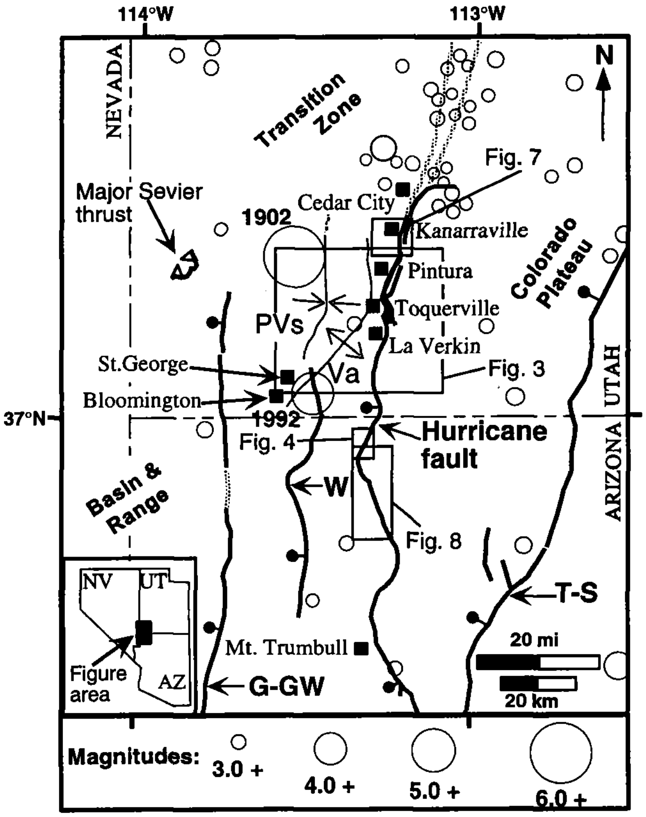


Figure 1. Locations of major faults in southwestern Utah and northwestern Arizona (ball and bar on downthrown side of normal faults; teeth on upper plate of thrust faults; stippled where concealed): G-GW = Gunlock-Grand Wash fault, W = Washington fault, and T-S = Toroweap-Sevier fault. Historical earthquakes are indicated with open circles, major earthquakes of 1902 and 1992 are labeled (modified from Bausch and Brumbaugh, 1994). The major folds are: PVs = Pine Valley syncline, Va = Virgin anticline. Major thrust is the Sevier-age Square Top Mountain thrust. Locations of Figures 3, 4, 7, and 8 along the Hurricane fault are outlined. Structural data compiled from Hintze (1980) and Reynolds (1988).

King, 1986; Bruhn et al., 1987; Bruhn et al., 1990; Susong et al., 1990; Crone and Haller, 1991; dePolo et al., 1991; Machette et al., 1991; Zhang et al., 1991; Janecke, 1993; Evans and Langrock, 1994). Segment boundaries may be defined based on a variety of data or concepts. In this paper a geometric segment boundary is defined as a zone across which a fault markedly changes strike and, in the case of a normal fault, forms a bend that is convex toward the hanging wall. An earthquake rupture segment boundary is defined as a location or zone where earthquakes repeatedly initiate or terminate, and thus, also restricts the locations of fault scarps. A segment boundary may be a geometric boundary, an earthquake rupture boundary or both. Identification of geometric segments and boundaries is critical for seismic-hazard analysis because segment length provides an estimate of the maximum rupture length during an earthquake and can be used to estimate paleoearthquake magnitudes. We examine two geometric segment boundaries of the Hurricane fault (Stewart and Taylor, 1996; Taylor and Stewart, in review), but fault geometry (Hintze, 1980) indicates that additional geometric segment boundaries probably exist (cf., Taylor and Stewart, in review).

Typical of the Basin and Range province, evaluation of seismic hazards in southwestern Utah and northwestern Arizona is complicated by the apparent contradiction between the moderate level of historical seismicity and the existence of long fault zones with Quaternary scarps. Although the region has experienced earthquakes ranging up to M 6.3 (fig. 1), geologic evidence, such as fault scarps and amount of Quaternary displacement, indicates that the potential exists for much larger (magnitude 7+) earthquakes. The Hurricane fault and other major late Cenozoic normal faults that cut the western margin of the Colorado Plateau in this region have substantial Quaternary displacement. Documented fault scarps on the Hurricane fault point to the recency of movement (Menges and Pearthree, 1983; Anderson and Christenson, 1989; Stewart and Taylor, 1996). It is difficult to effectively integrate this geologic evidence into seismic-hazard analyses, however, because very little is known about the size and timing of Holocene and late Pleistocene surface ruptures or the length of geometric fault segments that might rupture in individual large earthquakes.

Seismic and other geological hazards in southwestern Utah and northwestern Arizona are important because of their potential impact on the significant and rapidly growing population. The region includes one of the fastest growing areas in Utah, the St. George Basin (see Lund, this volume). Significant seismic hazards posed to the region by the Hurricane fault are discussed here. In the following paper Lund (this volume) discusses other geological hazards including problem soil and rock, landslides, shallow ground water, and flooding.

The field trip associated with this paper will follow the Hurricane fault for approximately 60 km along strike (see Stewart et al., field trip log, this volume). The paper and field trip proceed from south to north discussing and observing structures and kinematics associated with the fault. Two geometric segment boundaries and their associated seismic-hazard implications will be observed and discussed. Evidence for these geometric segment boundaries includes fault geometry, slip direction or kinematic considerations, scarp morphology, changes in amount of offset around the fault bend, and fault zone complexity. These boundaries may be earthquake rupture boundaries. Documented fault scarps on the Hurricane fault are not common, especially in Utah; this trip will visit known scarps in three locations. We will also examine the landslide in Springdale, Utah, triggered by the September 2, 1992, St. George earthquake, probably generated by movement on the Hurricane fault. Shortening structures predating the Hurricane fault and a synextensional basin will be discussed and observed at the New Harmony and Kanarraville Basins. The Toquerville fold, a synextensional footwall flexure will be discussed.

GEOLOGIC BACKGROUND

The Hurricane fault represents the youngest period of deformation in southwestern Utah and northwestern Arizona (Dobbin, 1939; Cook, 1957; Anderson and Christenson, 1989). It is a 250-km-long, north-south striking, high-angle, down-to-the-west normal fault that, in exposures, cuts Paleozoic, Mesozoic and Cenozoic rocks. The Paleozoic and Mesozoic rocks (fig. 2) predate all exposed deformation in the region (Armstrong, 1968). Thrust faults of the Sevier orogenic belt cut the area west and northwest of the Hurricane fault and Pine Valley Mountains during the Cretaceous, moderately folding older rocks in front of the thrust belt to form the Virgin anticline and the Pine Valley syncline (fig. 1) (Armstrong, 1968; Cowan and Bruhn, 1992).

Southwestern Utah and northwestern Arizona underwent a period of tectonic quiescence during the early and middle Tertiary (Cook, 1957) followed by magmatism and extension. Volcanism began about 33 million years ago just north of the Pine Valley Mountains and migrated southward through time (e.g., Rowley et al., 1979; Best and Grant, 1987; Best et al., 1989). Between ~20 and 22 million years ago the Pine Valley laccolith and other intrusions were emplaced (Armstrong, 1963; Nelson et al., 1992). Extension began in the Oligocene north of the Pine Valley Mountains and continued through the Miocene into the Quaternary near the Pine Valley Mountains and the Hurricane fault (Gardner, 1941; Cook, 1952, 1957; Mackin, 1960; Taylor and Bartley, 1992; Axen et al., 1993).

Volcanism accompanied extension on normal faulting in the transition zone. Small-volume basalt flows and cinder cones exist throughout southwestern Utah (fig. 3). Best et al., (1980) dated flow rocks near Hurricane, Utah, between 0.289 and 1.7 Ma using the K-Ar method. Sanchez (1995) used $^{40}Ar/^{39}Ar$ to date flows near Hurricane, Utah, at between 353 ± 45 ka and 258 ± 24 ka (a period of at least 100,000 years.)

Chronology of faulting

Long normal faults in this region, including the Hurricane, Toroweap-Sevier, Grand Wash, and Washington fault zones (fig. 1), have varying amounts of Quaternary displacement. The late Quaternary behavior of these faults has been investigated on a reconnaissance basis (Menges and Pearthree, 1983; Pearthree et al., 1983; Anderson and Christenson,

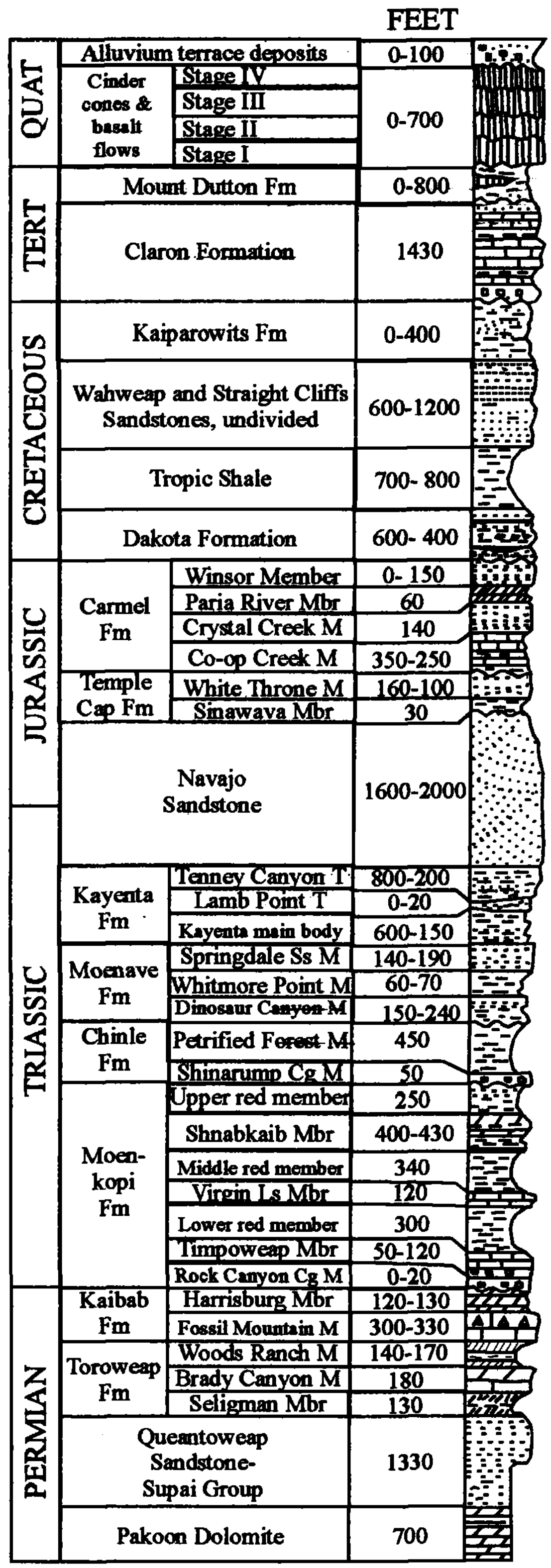


Figure 2. Stratigraphic column from the Zion Park—Cedar Breaks area in Utah; modified from Hintze (1980) and (1988) and Stokes (1986).

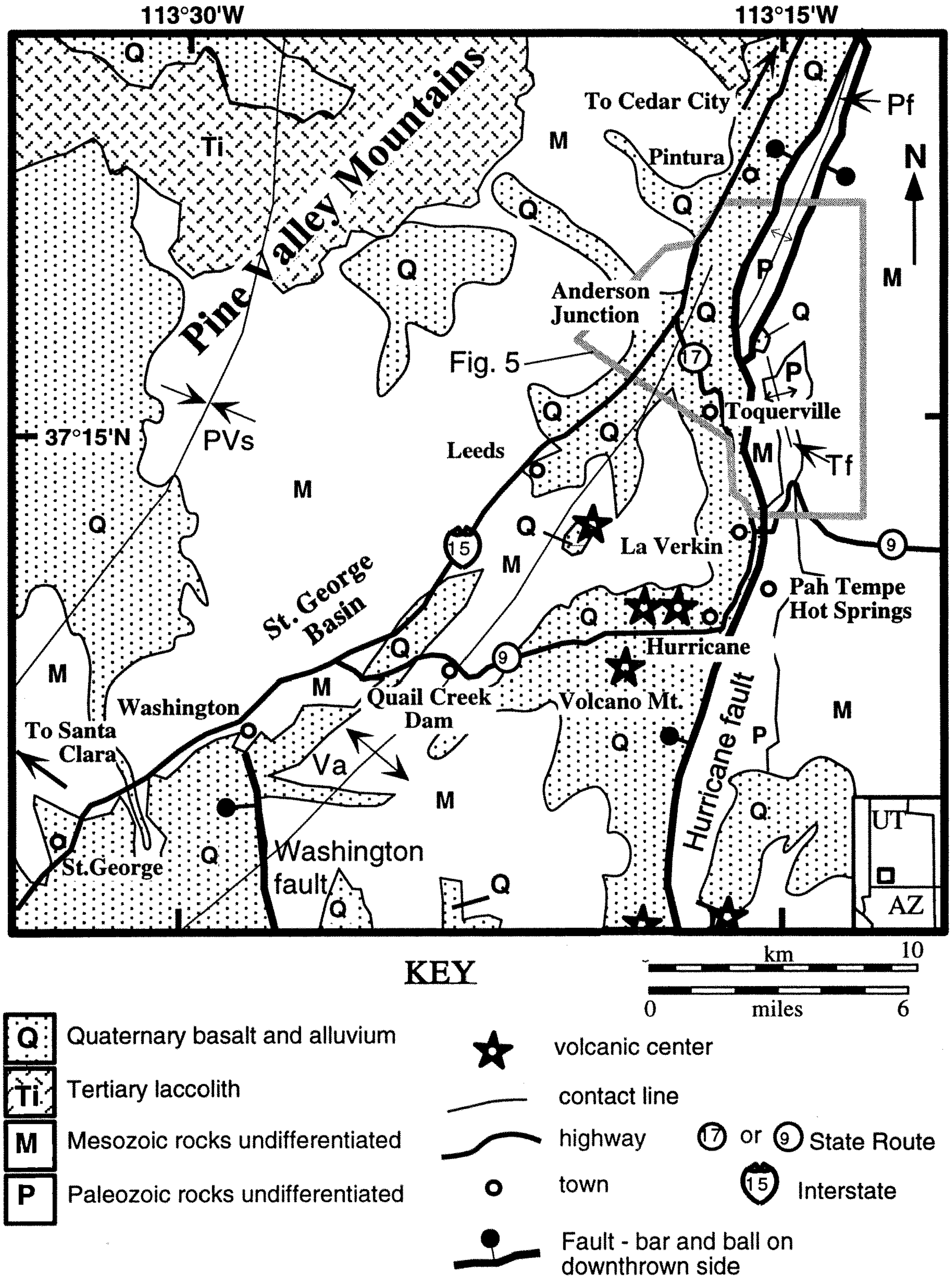


Figure 3. Location map of St. George Basin, surrounding communities, and highways. Folds discussed in text: PVs = Pine Valley syncline, Va = Virgin anticline, Pf = Pintura fold, Tf = Toquerville fold. Area of Figure 5 is outlined by dark stipple. Geology modified from Hintze (1963) and (1980).

1989; W.J. Taylor, unpublished mapping; H.A. Hurlow, unpublished mapping). Portions of the Hurricane fault (Stewart and Taylor, 1996) and Toroweap fault (Jackson, 1990) have also been studied in more detail. However, the age of youngest surface rupture, the frequency of ruptures, the amount of displacement per rupture, and the length of recent ruptures on most of these faults are poorly constrained at this time. Here we discuss the faulting history for that portion of the Hurricane fault that we will visit on the field trip.

It is unclear when movement first began along the Hurricane fault. Based on structural and stratigraphic relations some geologists suggest an initiation age of Miocene (Gardner, 1941; Averitt, 1964; Hamblin, 1970; Stewart and Taylor, 1996), or contemporaneously with laccolith emplacement (Cook, 1957). Others suggest Pliocene or Pleistocene initial movement for some sections of the fault (Anderson and Mehnert, 1979; Anderson and Christenson, 1989).

Fault scarps are evident in several places along the Hurricane fault in Arizona. Near the Utah-Arizona border Menges and Pearthree (1983) documented fault scarps up to 20 m high cutting steep alluvial fans at the base of the Hurricane Cliffs (fig. 4). Many of the scarps are large enough to be the result of several surface-faulting events. Holocene rupture may have occurred along part of the Hurricane fault, based on smaller scarps found on Holocene (?) deposits at one location just south of the Arizona-Utah border (Menges and Pearthree, 1983; Pearthree et al., 1983), but this age has not been demonstrated definitively. Fault scarps exist at a number of localities along the fault zone north of Mt. Trumbull, Arizona. These scarps range in height from about 4 to 25 m, with estimated vertical displacements of 1 to 10 m (Pearthree, unpublished data). In Whitmore Canyon near the Colorado River, the Hurricane fault probably ruptured in the early Holocene to latest Pleistocene based on analyses of fault scarps found there (Pearthree et al., 1983).

Near Toquerville, Utah, unconsolidated Quaternary alluvium is offset at three places along the Hurricane fault. Two scarps are exposed along the northern Ash Creek geometric fault segment (fig. 5) where they displace an alluvial deposit, but the precise age of the deposit is unknown. The largest fault scarp is 6 m high and the other is 3 m high. Bucknam and Anderson's (1979) maximum scarp height-slope angle technique provides a crude age approximation for the scarps of between 1,000 and 15,000 yr old (Stewart and Taylor, 1996). The third exposure of offset Quaternary sediment is along the Anderson Junction segment (fig. 5), where a gravel of unknown age in a stream channel is cut by two fault strands that crop out 3 m apart, but no scarps are present. As much as 3 m of stratigraphic separation was measured along the strand that dips 60°W; 1.2 m of stratigraphic separation was measured along the other strand, which is oriented N12°W, 73°W. The displaced deposits are older than the most recent sedimentation in the area. The age of faulting is unknown and may represent a single or multiple events.

Quaternary displacement on the Hurricane fault near Toquerville, Utah, is shown by 450 m of stratigraphic separation of the top of undated Quaternary basalt (fig. 6; Stewart and Taylor, 1996). This basalt is geochemically similar to the 353 ± 45 ka basalt of Sanchez (1995). Prior to basalt extrusion, stratigraphic separation across the Hurricane fault ranges from 1740 to 2070 m in this area based on the location of Permian to Jurassic units in the footwall and their inferred locations in the hanging wall. Assuming a relatively constant strain rate, it is possible to back-calculate an estimated time of initial fault movement on this section of the Hurricane fault as Late Miocene to early Pleistocene.

Near the New Harmony and Kanarraville basins (fig. 7), stratigraphic and structural relations indicate that the Hurricane Cliffs and the presently observable slip on the Hurricane fault developed after about 1 million years ago (Anderson and Mehnert, 1979). The Kanarraville basin began forming in Late Pliocene or Quaternary time due to normal displacement on the Hurricane fault (H.A. Hurlow, unpublished mapping).

STRUCTURAL GEOLOGY

Total stratigraphic separation along the Hurricane fault (measured on Permian to Jurassic units directly along the fault) generally increases from south to north (Gardner, 1941). Near the southern tip line, south of the Grand Canyon, less than 61 m of stratigraphic separation is documented (Hamblin, 1970). Total stratigraphic separation is 450 m at the Grand Canyon (Hamblin, 1970), about 900 m in Arizona 30 km south of the Utah border, and 2070 m near Toquerville, Utah (Stewart and Taylor, 1996).

Stewart and Taylor (1996) identified a geometic segment boundary along the Hurricane fault near Toquerville, Utah, at an abrupt change in fault strike. Taylor and Stewart (in review) identified another geometric segment boundary in northwestern Arizona, marked by a large change in strike. The nature and history of these geometric fault segments and segment boundaries are important to understand because they have significant implications for seismic-hazard evaluation.

Hurricane fault near the Utah-Arizona state line

A prominent geometric fault bend exposed near the Utah-Arizona state line (Taylor and Stewart, in review) is interpreted as a geometric segment boundary based on fault geometry, changes in the amount of offset around the bend, changes in Quaternary fault scarps around the bend, and the presence of a small mafic intrusion at the bend. The strike of the fault changes about 40° from approximately

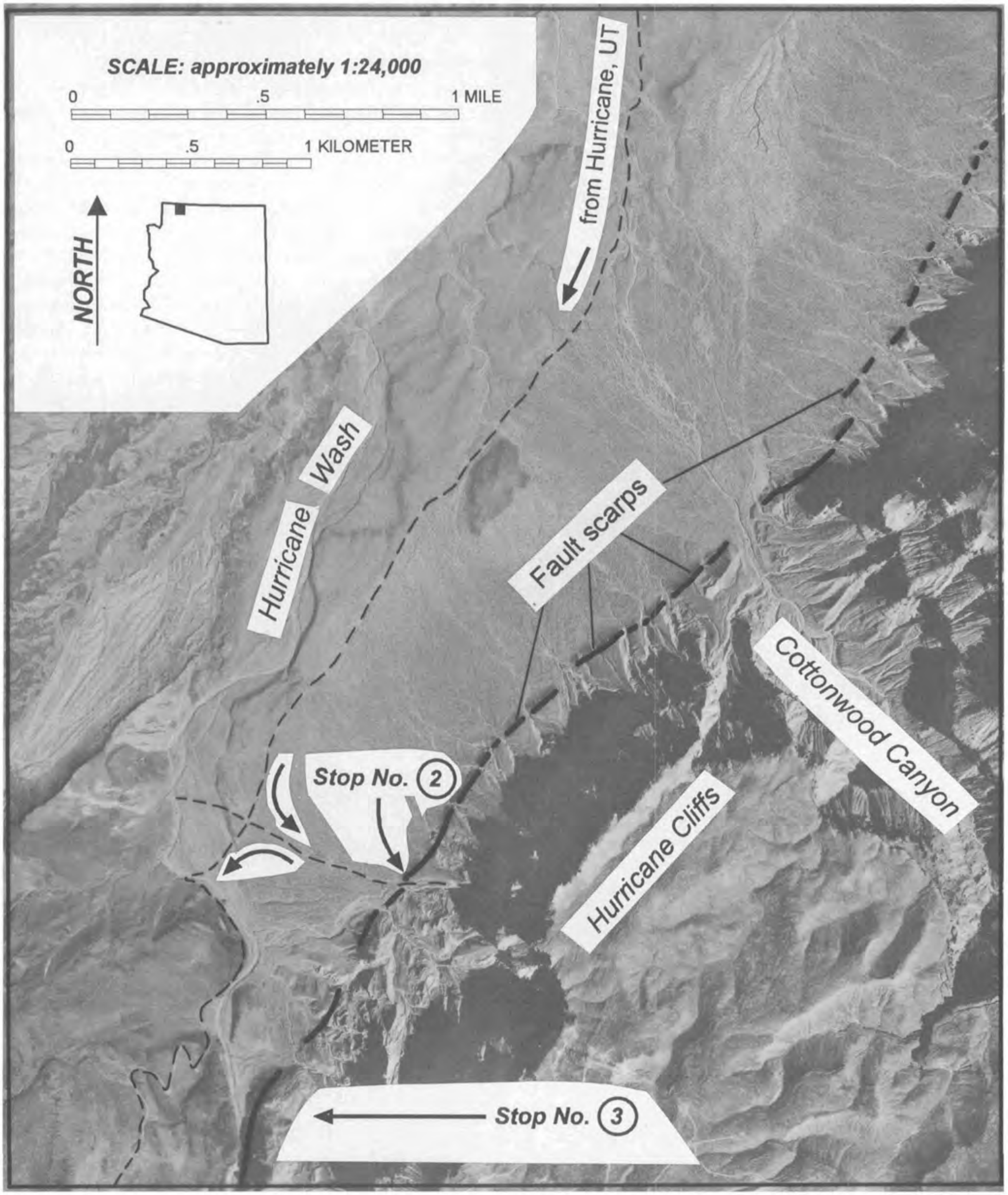


Figure 4. Annotated aerial photograph (scale 1:24,000) of a portion of the Hurricane fault south of the Utah-Arizona border (see Figure 1 for approximate location). Fault scarps are highlighted with bold lines on the footwall block. Gravel roads are shown with dashed lines, and the field trip route is shown with arrows.

N20°E north of the bend to N15-20°W south of it (fig. 8). This prominent bend also has strongly curved and asymmetric reentrant segments on either side of it. The southern segment is longer than the northern segment.

Stratigraphic separation, throw and heave measured on Permian and Mesozoic units decrease markedly from north to south across the fault bend (for definitions of these terms see figure 9). In addition, north of the fault bend the hanging wall basin is areally small, but south of the bend an areally much larger basin is present.

Footwall structures also change at the fault bend. Gentle to open folds and a few normal faults crop out south of the bend. The folds tend to continue for only 1 to 4 km along trend and generally parallel the Hurricane fault, thus they appear to be related to movement along the Hurricane fault. North of the bend only small stratigraphic separation normal faults are present. This change in footwall structures suggests that the change in fault geometry influenced the type of footwall deformation near the Hurricane fault.

Fault scarps in Quaternary deposits of approximately the same age (Billingsley, 1992b) crop out both north and south of the bend, but appear to be lacking in the area of maximum curvature. The fault scarps north of the bend are distinctly higher than those south of the bend. We interpret these data to suggest that the fault bend may be an earthquake rupture barrier.

Basalt. The Quaternary (?) igneous rocks near the apex of the large, sharp bend just south of the Utah-Arizona state line include mafic flow rocks and a small pluton that intrudes them (fig. 8). The presence of these rocks suggest that the Hurricane fault was active and that the segments north and south of the segment boundary were linked prior to emplacement of the igneous. The outcrop pattern of the flows shows that they thin away from the fault, but lie near the fault in the area of maximum fault curvature. This pattern suggests that the flows may have ponded in a topographic low created by the fault. For a topographic low or basin to exist at the bend apex, the two segments must have overlapped or been linked so that the fault(s) was able to down drop the hanging wall at the segment boundary. No evidence for along strike overlap of faults or fault segments exists in this area, so it appears that the two segments linked and the throughgoing fault downdropped the basin in which the basalt ponded.

The composition and mineralogy of the flows and pluton suggest that they may be related. The flows are fine grained and contain plagioclase and olivine phenocrysts. The pluton or plug also has plagioclase and olivine phenocrysts, but is granular and medium to coarse grained. Maureen Stuart (unpublished data from UNLV XRF laboratory, 1995) analyzed samples from four flows and the small intrusion that crops out just west of the bend for major and trace element contents. They are all subalkaline tholeiitic basalt (cf., Irvine and Baragar, 1971; Le Bas et al., 1986). Stuart also found that (1) the samples have an Ocean Island Basalt (OIB) pattern on a Spider diagram, but have slightly lower elemental abundances which is consistent with Pliocene and younger basalts in the transition zone, and (2) the incompatible element ratios (Nb/Ba vs. Rb/Sr and Nb/Ba vs. Zr/Y) show narrow ranges. These similarities between the flows and pluton suggest a possible genetic relationship between the flows and the intrusion. However, the small number of samples analyzed requires the hypothesis to be tested further.

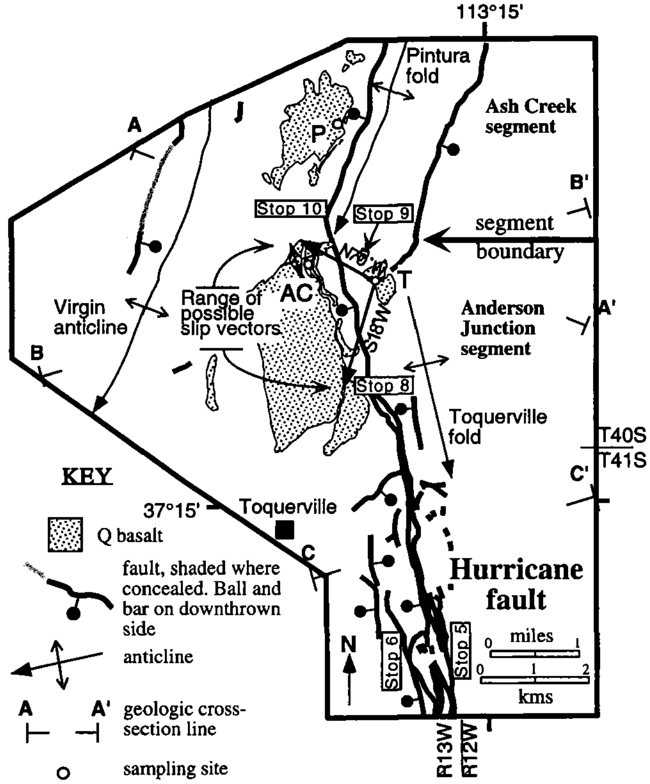
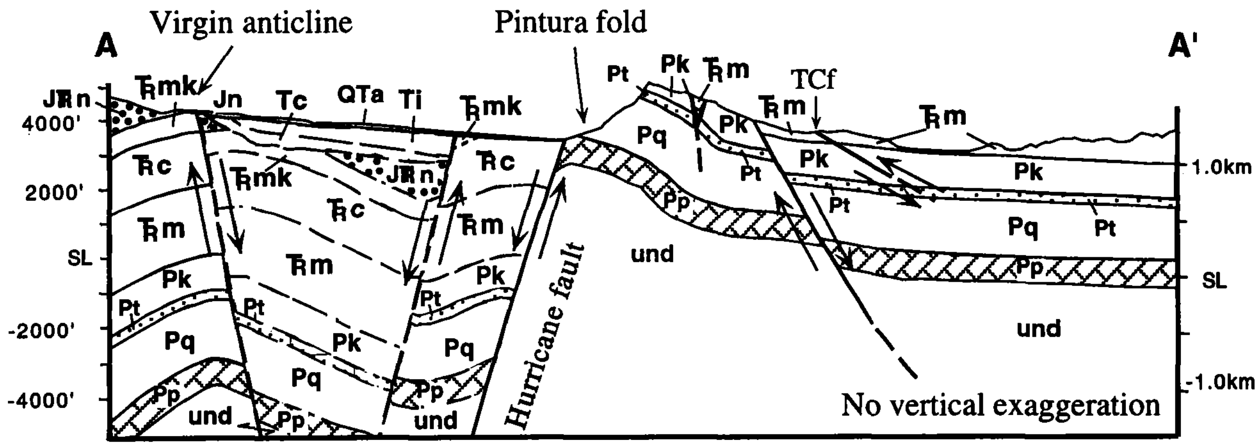


Figure 5. Simplified structure map of area near Toquerville, Utah. Basalt fields are stippled. Cross-section locations A-A′ to C-C′ are shown constructed on Figure 6. Open circles with letters adjacent (T = Toquerville, P = Pintura, or AC = Ash Creek) indicate where basalt sections were sampled. A range of possible slip vectors is shown between 73°, N70°W and 75°, S18°W, determined from correlating geochemically identical basalt in the hanging wall and footwall (sites T and AC) and assuming the basalt field is laterally homogeneous. Field trip stops 5, 6, 8, 9, and 10 are labeled.

The intrusion and flows were emplaced after initiation of movement along the Hurricane fault because they lie on Triassic rocks which were eroded off the footwall prior to the emplacement of different, but similar-aged basalt on the footwall. The basalt has not been dated. The assumption of a similar age for all the basalts is based on the fact that they are all surficial deposits, and chemically and miner-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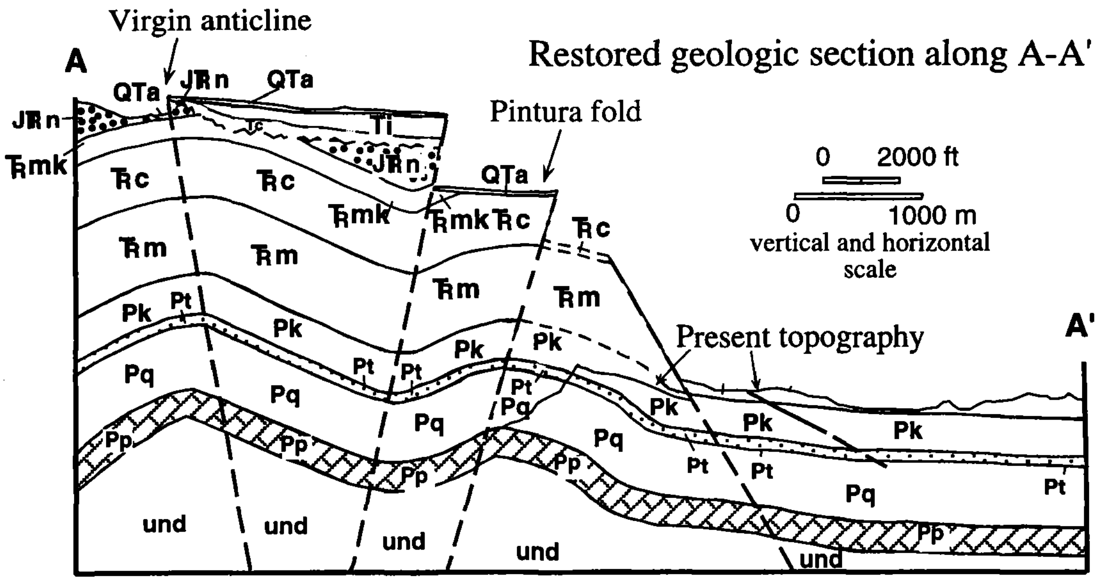
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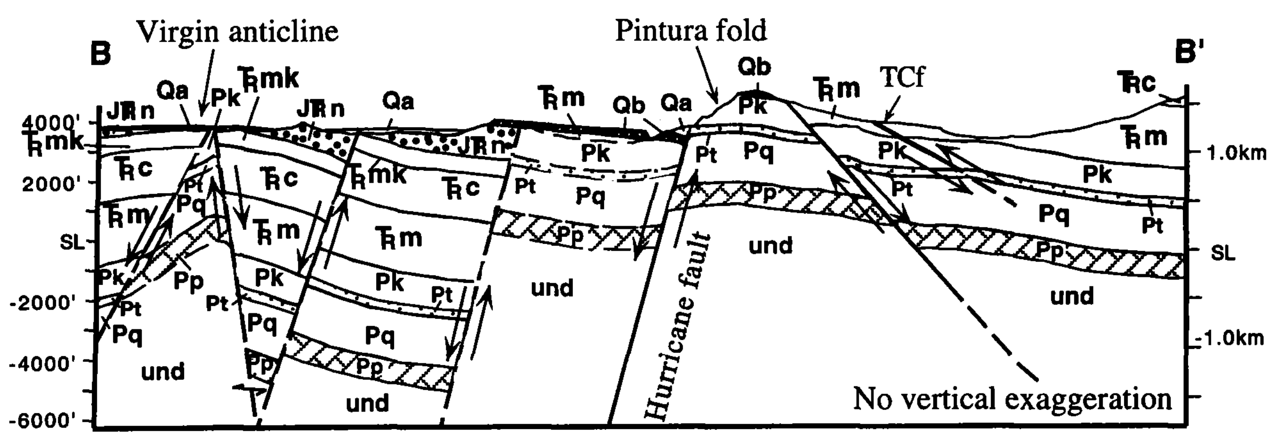
Virgin anticline
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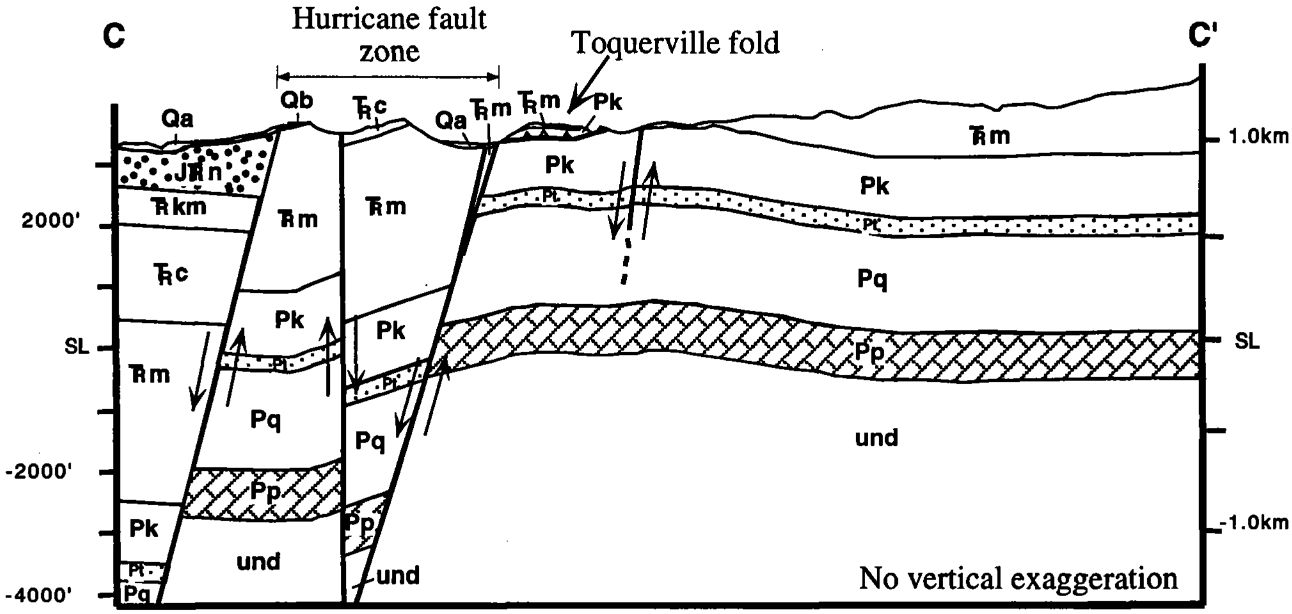


Figure 6. Geological cross sections along A-A' to C-C' from Figure 5. Cross-section A-A' is also drawn restored. Faults shown are drawn with relative motion arrows; dashed faults indicate geometrically required assumed faults. TCf = Taylor Creek thrust fault. Unit explanation: Qa = Quaternary alluvium and colluvium, QTa = Quaternary-Tertiary alluvium, weakly consolidated, Qb = Quaternary basalt, Ti = Tertiary monzodiorite, Tc = Tertiary Claron Fm., JTRn = Jurassic-Triassic Navajo Sandstone, TRmk = Triassic Kayenta Fm. and Moenave Fm., TRc = Triassic Chinle Fm., TRm = Triassic Moenkopi Fm. undifferentiated, Pk = Permian Kaibab Fm., Pt = Permian Toroweap Fm., Pq = Permian Queatoweap Fm., Pp = Permian Pakoon Dolomite, und = undifferentiated Paleozoic rocks and basement. These units are shown on Figure 2, however, relative thicknesses of units in cross-sections are derived from detailed mapping of area in Figure 5 (Schramm, 1994).

alogically similar basalt flows in the region are all Pliocene or younger (eg., Best et al., 1980; Sanchez, 1995). However, whether the intrusion has been cut by the Hurricane fault remains equivocal.

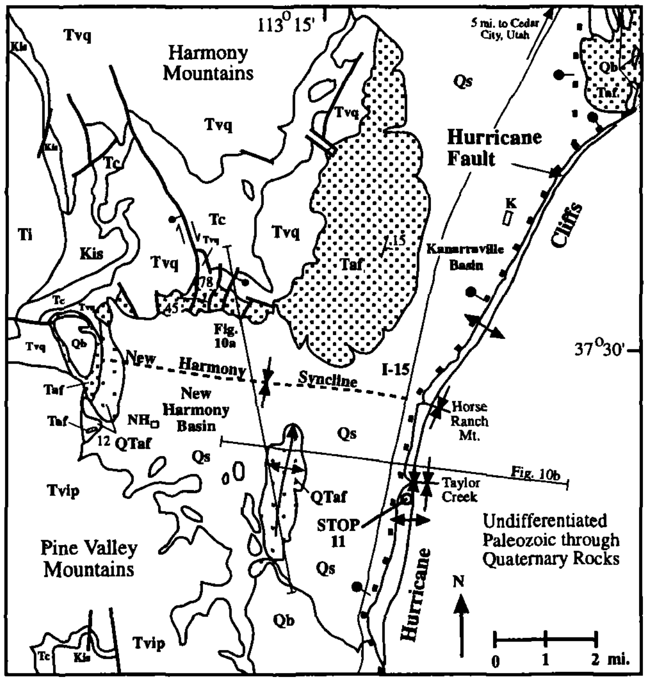
The intrusion suggests the possiblity, at this location, of a non-conservative segment boundary (a boundary along which the slip vector and line the formed where the segments intersect are not parallel, and thus, space is generated or destroyed). In the situation where fault slip on different geometric segments is of different ages or magnitudes, space may be generated in the hanging wall. Space may be persistently created, resulting in extension or space-filling intrusions, or destroyed, resulting in folds or reverse faults as rocks are moved across a non-planar surface. The mismatch in the shapes of the hanging wall and footwall results in local strain near the geometric boundary which is then also a kinematic boundary that may impede rupture propagation, forming an earthquake rupture segment boundary.

Stratigraphic Separation. Variations in the amount of offset across a fault bend suggest that different numbers or sizes of earthquakes or slip events occurred on opposite sides of it. Therefore, where significant differences in total throw or stratigraphic separation along the fault occur across a bend, the geometric bend is likely to be an earthquake rupture boundary.

Detailed geologic mapping allows calculation of the stratigraphic separation, throw and heave across the Hurricane fault (fig. 9; Billingsley, 1992a, 1992b, 1993; W.J. Taylor, unpublished data). The calculated stratigraphic separations, throws and heaves are shown in figure 9 for the locations shown on figure 8. The stratigraphic separation, throw and heave, as measured from cross sections directly along the fault, markedly increase from south to north across this geometric bend suggesting that it has been an earthquake rupture barrier for some of the earthquakes and related slip along the fault.

Hurricane fault near Toquerville, Utah

Near Toquerville, Utah, a large change in fault strike (~34° from N13°W to N21°E) marks the boundary between two geometric fault segments (Stewart and Taylor, 1996) (fig. 5). Based strictly on map view (Hintze, 1980) the segment north of the boundary (Ash Creek segment) is at least 24 km long and the segment south of the boundary (Anderson Junction segment) is between 19 and 45 km long (Stewart and Taylor, 1996). These estimates are straight line distance



(a)

Normal fault (dotted where concealed)

Dextral-normal fault

Line of cross section in Figure 10

Anticline axial trace showing plunge of hinge

Syncline axial trace showing plunge of hinge (dotted where concealed)

45 Strike and dip of bedding

Age	Formation		Symbol	Thickness (ft)	Lithology
Quaternary	Quaternary sediments		Qs	0-1500	
	Quaternary basalt		Qb	0-500	
	Alluvial-fan deposits		QTaf	25-150	
Pliocene	Alluvial-fan deposits	Upper Member	Taf	0-700	
Miocene		Middle Member	Taf	0-450	
		Lower Member	Taf	350	
19 Ma	Racer Canyon Tuff		not shown	0-30	
21 Ma	Pine Valley monzonite & latite		Tvip	1000	
22 Ma	Stoddard Mt. intrusion		Tis		
23 Ma 24 Ma	Quichapa Group		Tvq	1000	
Eocene-Oligocene	Claron Formation		Tc	700-1000	
Cretaceous	Iron Springs Formation		Kis	3800	

(b)

Figure 7. Simplified geologic map and lithologic column for the New Harmony and Kanarraville basins and adjacent areas. (a) Geologic map, based on Cook (1960), Grant (1995), and Hurlow (in press). NH is town of New Harmony, K is town of Kanarraville. Field trip stop 11 is labeled near Taylor Creek. (b) Lithologic column, based on same sources as geologic map.

measurements and may need to be refined with detailed mapping to the north and south of the segment boundary and Toquerville study area. The Ash Creek segment is characterized by a single surface trace and a few fault scarps in alluvium, whereas the Anderson Junction segment has multiple fault strands and no clear fault scarps, although offset of unconsolidated sediments of unknown age is observed. Apparent differences in Quaternary fault scarp patterns suggest that the two segments may have different slip histories to the north and south of the geometric bend and may be an earthquake rupture boundary. A small-scale, hanging wall anticline mapped in Quaternary basalt near the large change in fault strike on the Hurricane fault and normal to the fault is further evidence for the existence of a geometric segment boundary (Scott et al., 1994; Schlische, 1993) (fig. 5).

Basalt correlation. Undated Quaternary basalt is present in the hanging wall and footwall of the Hurricane fault (fig. 5). Stewart and Taylor (1996) conducted whole-rock trace element analysis to correlate flow rocks across the fault. Samples were collected from stratigraphic intervals from each of the three sites: one location in a paleochannel in the footwall (site T) , and two locations in the hanging wall (sites AC and P; fig. 5). Trace-element data reveal striking positive correlations between flows at different stratigraphic intervals. However, the lowest flow at T and AC exhibit clear grouping in trace element plots suggesting that they relate genetically. From these data, Stewart and Taylor (1996) inferred a range of slip vectors for the fault, from 73°, N70° W to 75°, S18°W.

Stratigraphic separation. Near Toquerville, Utah, total normal stratigraphic separation measured directly along the Hurricane fault on Permian to Jurassic units ranges from 2070 m along A-A′ to 1740 m along C-C′ (fig. 6). A local northward increase in stratigraphic separation across the geometric segment boundary is observed.

Sense of slip. Movement on the Hurricane fault in the Quaternary is dominantly dip slip. Evidence for dip slip includes: (1) stratigraphic separation of geochemically identical Quaternary basalt flows in the footwall and hanging wall and the suggested slip vector (fig. 5); (2) rakes of slickenlines between vertical and 74° (Kurie, 1966; Schramm, 1994); (3) earthquake rake (–89° ± 14°) from the 1992 St. George earthquake (Lay et al., 1994); and (4) slip direction

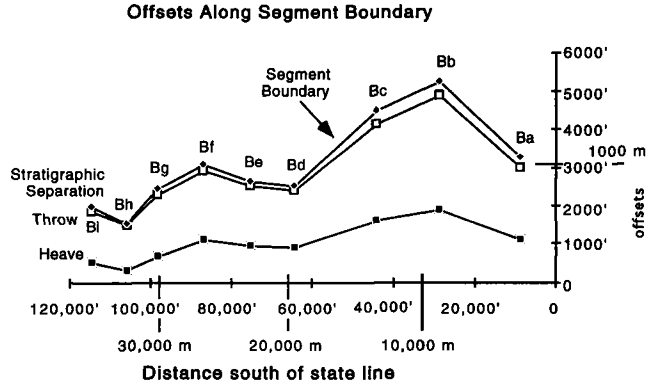


Figure 9. This graph shows the total stratigraphic separation, throw, and heave across the Hurricane fault in the vicinity of the geometric segment boundary (Fig. 8). Stratigraphic separation is the distance measured along the fault between a unit boundary in the hanging wall and the same unit boundary in the footwall. The throw is the vertical component of offset. The heave is the horizontal component of offset. All stratigraphic separations, throws and heaves shown here were measured on Permian to Jurassic units. Little to no variation in these measures was found among Permian to Jurassic units. The marked change in these parameters along the south side of the geometric bend supports the interpretation that this location is a behavioral or earthquake rupture segment boundary and that equal numbers or sizes of earthquakes did not occur to the north (right) and south (left) of the bend.

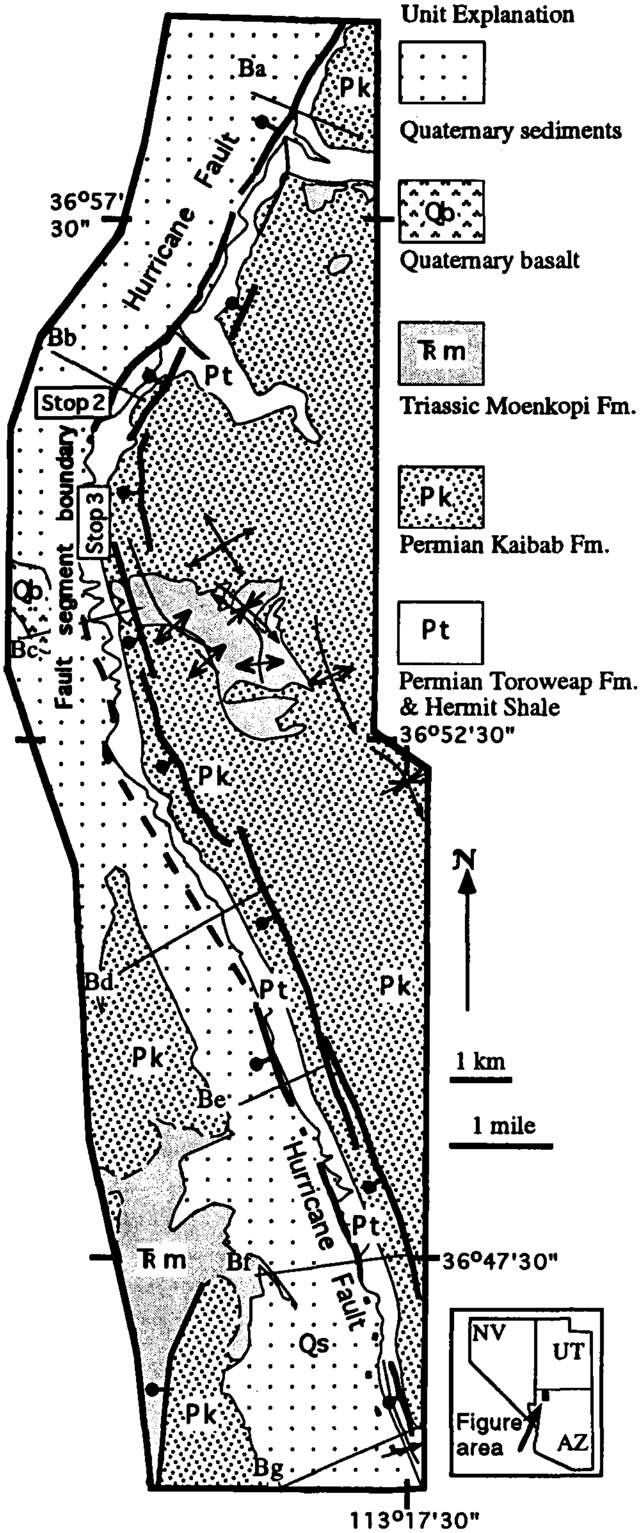


Figure 8. Simplified geologic map of area surrounding the fault segment boundary in Arizona based on geologic mapping of the Gyp Pocket and Rock Canyon 7.5′ quadrangles by Billingsley (1992a, 1992b, 1993) and W. J. Taylor (unpublished mapping). Lines labeled Ba through Bg show locations where the stratigraphic separation, heave and throw were calculated as shown on Figure 9. Line Bh lies 2332 m south along the fault from line Bg. Line Bi lies 4952 m south of line Bg. Stop 2 of the field trip is located near line Bb and Stop 3 is near line Bc. Conventional symbols are used for faults and folds.

of N75–85°W from dip analysis on syndeformational basalt using the technique of Scott et al., (1994) (Stewart and Taylor, 1996). This slip direction agrees with the calculated stress field data for the transition zone of S78°E–N78°W ± 21° (Zoback and Zoback, 1980; Arabasz and Julander, 1986). Relative motion on the Ash Creek segment is purely dip-slip, and on the Anderson Junction segment is dominantly dip-slip with a small dextral slip component (fig. 5).

The pre-Quaternary normal sense of movement on the Hurricane fault near Toquerville, Utah, is inferred from downdropped Jurassic-Triassic Navajo Sandstone in the hanging wall of the fault relative to Permian Kaibab Formation in the footwall (fig. 2). Our evidence neither supports nor refutes strike-slip or reverse motion along the Hurricane fault prior to the Quaternary (cf., Moody and Hill, 1956; Lovejoy, 1964; Anderson and Barnhard, 1993a).

Hurricane fault—New Harmony and Kanarraville Basins

The structural evolution of the New Harmony and Kanarraville basins, two relatively small Tertiary-Quaternary depositional centers in southwestern Utah (fig. 7), illustrates aspects of Neogene-Quaternary deformation in the Colorado Plateau—Basin and Range transition zone and aspects of the early history of the Hurricane fault. The New Harmony basin is underlain by a late Tertiary syncline formed by north-northeast to south-southwest shortening that was coeval with regional east-west crustal extension (Anderson and Barnhard, 1993a, 1993b; Hurlow, 1996). The Kanarraville basin is interpreted to have formed during Quaternary normal slip on the Hurricane fault.

Geologic setting. The New Harmony and Kanarraville basins lie between Miocene volcanic deposits to the west and the Hurricane Cliffs, which comprise the footwall of the Hurricane fault, to the east (fig. 7). The 40-km^2 New Harmony basin trends west-northwest, perpendicular to the Hurricane fault and Kanarraville basin. The Kanarraville basin is north and east of the New Harmony basin and has approximately the same surface area, but has a long, narrow form that trends north-northeast.

The New Harmony basin is filled with Quaternary alluvial-fan sediments deposited on a folded and faulted sequence of Miocene to Pliocene (?) volcaniclastic alluvial-fan deposits (Taf; fig. 7). These fan deposits were derived from volcanic rocks to the west and were deposited over an area larger than the New Harmony basin (fig. 7; Anderson and Mehnert, 1979).

This alluvial-fan unit (Taf) is divided into three informal members based on reconnaissance field work and local detailed mapping (H.A. Hurlow, unpublished mapping). The lower member is tan to gray, planar-bedded, cemented diamictite, breccia, tuffaceous sandstone, and siltstone. Clasts are derived chiefly from the Miocene Quichapa Group, and the Stoddard Mountain and Pine Valley intrusions. This member is 107 m thick and is interbedded at its base with a white crystal tuff that P.D. Rowley of the U.S. Geological Survey (personal communication, 1996) correlates with the Racer Canyon tuff, which yielded a K-Ar date of 19 Ma (Rowley et al., 1979).

The middle member is ~135 m of predominantly poorly to laminar-bedded orange-tan tuffaceous siltstone with local conglomerate beds containing clasts of white biotite-feldspar crystal tuff. This member strongly resembles units northwest and west of the Pine Valley Mountains mapped as Muddy Creek Formation (Cook, 1960; Hintze et al., 1994).

The upper member is unconsolidated boulder gravel that is about 210 m thick. Clasts include Miocene volcanic and plutonic rocks and late Paleozoic through Tertiary sedimentary rocks exposed to the northwest and west. This unit is the "clastic debris" described by Anderson and Mehnert (1979) in both the hanging wall and footwall of the Hurricane fault.

A sequence of alluvial-fan deposits (QTaf), derived entirely from the Pine Valley laccolith and related volcanic rocks to the west, overlies unit Taf. Units Taf and QTaf were not distinguished by previous geologists (Cook, 1960; Grant, 1995), but their differentiation is crucial to deciphering the structural evolution of the New Harmony and Kanarraville basins. The pediment surface over which unit QTaf debris flows were transported and deposited slopes toward the southeast away from the Pine Valley Mountains. The pediment surface is now incised by modern drainages in the foothills of the Pine Valley Mountains, suggesting a Pleistocene age for unit QTaf deposits.

Structural geometry and evolution. The New Harmony syncline is defined by opposing dips of unit Taf on the north and southwest margins of the New Harmony basin (figs. 7 and 10a). In the southern Harmony Mountains, unit Taf dips moderately to steeply south and is overturned adjacent to a north-striking dextral-normal fault (fig. 7). In the same area the stratigraphically lower Quichapa Group and Claron Formation are also steeply dipping to overturned, but a tight anticline north of the syncline returns these units to moderate southward dips (fig. 10a). The Quichapa Group and Claron Formation are cut by numerous minor north- and east-striking normal, dextral-normal, and reverse faults, the majority of which are not shown in figures 7 and 10. The New Harmony syncline is interpreted to reflect north-northeast–south-southwest horizontal crustal shortening. Units QTaf and Qs are not deformed by the New Harmony syncline, nor are they cut by local faults that cut the fold.

The New Harmony syncline is exposed in the lower Hurricane Cliffs where it is expressed in cliff-forming exposures of Permian Kaibab Formation below Horse Ranch

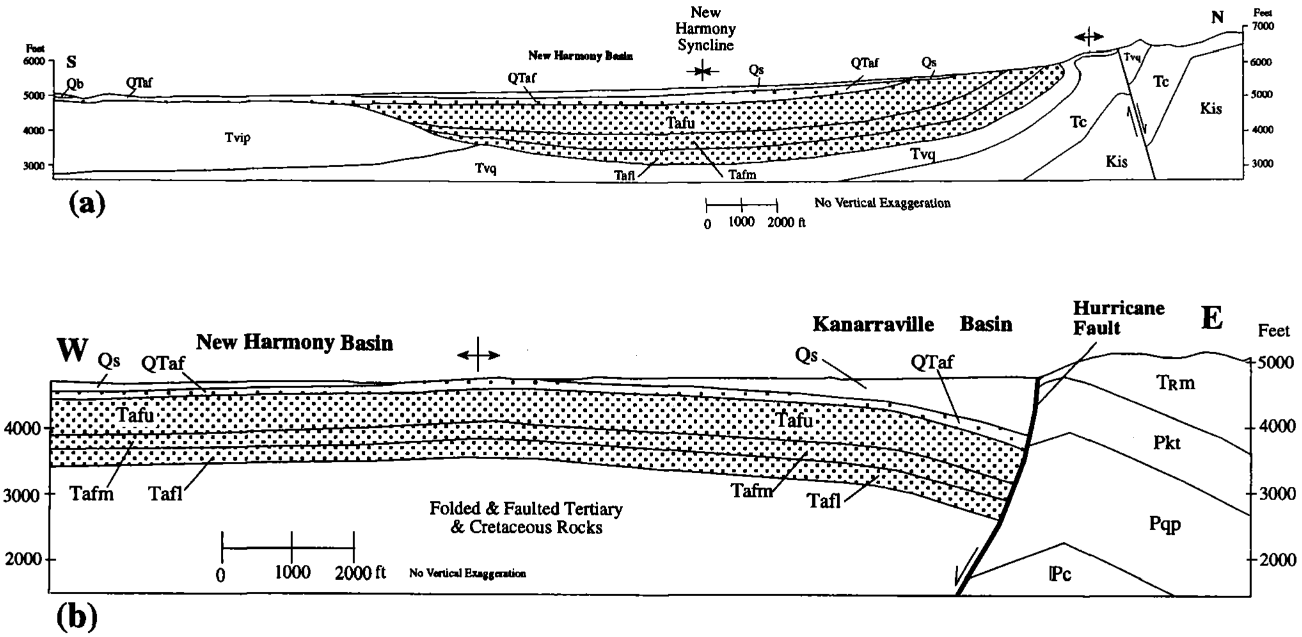


Figure 10. Geologic cross sections; locations shown in Figure 7. Scale is larger than in Figure 7. Units east of Hurricane fault not shown in Figure 7: TRm = Moenkopi Formation; Pkt = Kaibab Limestone and Toroweap Formation; Pqp = Queantoweap Sandstone and Pakoon Formation; and lPc = Callville Limestone.

Mountain. Another east-trending syncline is exposed along Taylor Creek at the entrance to the Kolob Canyons section of Zion National Park. These east-trending synclines re-fold a north-trending Sevier-age anticline, the Pintura fold (see below), exposed in the Hurricane footwall (fig. 7).

Unit QTaf is exposed along a north-trending ridge that divides the New Harmony and Kanarraville basins (fig. 7). This ridge is interpreted as an anticline related to reverse drag in the hanging wall of the Hurricane fault (fig. 10b).

The Kanarraville basin is adjacent and parallel to the Hurricane fault and is interpreted as a synextensional basin. Quaternary sediments are interpreted to have a wedge-shaped geometry reflecting infilling of the structural depression that formed in response to reverse drag in the hanging wall of the Hurricane fault (fig. 10b).

Discussion. Deformation of late Tertiary and Quaternary units in the New Harmony and Kanarraville basins suggests the following structural chronology:

1. North-south horizontal crustal shortening during Neogene time, manifested by the New Harmony syncline and east-west folds in the Hurricane Cliffs. The age of folding is not tightly constrained because the age of the upper member of unit Taf and its timing relative to the folding are unclear. The most likely time of folding is Late Miocene to Pliocene. The New Harmony syncline did not likely form in relation to a segment boundary or along-strike displacement gradient (Schlische, 1995) on the Hurricane fault because: (a) the Hurricane fault lacks apparent geometric segment boundaries at either end of the New Harmony basin; (b) the New Harmony basin is larger, has a different shape, and extends farther away from the Hurricane fault than examples cited by Schlische (1995); and (c) the displacement-gradient model does not explain the extreme tightness and overturning of the synclinal and adjacent anticlinal hinges (fig. 10a). Instead, the New Harmony syncline is interpreted to reflect north-south crustal shortening associated with major, regional east-west crustal extension in the Basin and Range Province, as outlined by Anderson and Barnhard (1993a, 1993b). This extension was accommodated in the New Harmony basin area by normal faults west of the trace of the present Hurricane fault (Hurlow, in press).
2. Faulting on a complex system of north- and east-striking normal and reverse faults deformed the New Harmony syncline but may also have been partly coeval with it.
3. The Kanarraville basin is a synextensional basin that began forming in Late Pliocene or Quaternary time due to normal displacement on the Hurricane fault based on stratigraphic and structural relationships.

Major regional folds

The Virgin anticline and the Pintura fold are large regional structures that have been documented for decades (Dobbin, 1939; Gardner, 1941; Gregory and Williams, 1947; Neighbor, 1952; Cook, 1957; Cook and Hardman, 1967; Anderson and Mehnert, 1979; Hintze, 1986; Blank and Kucks, 1989). Parts of these two anticlines and the Toquerville fold were mapped at a scale of 1:12,000 near Toquerville, Utah (Schramm, 1994). A discussion of the anticlines is critical for the understanding of the Hurricane fault. The folds are identified in cross sections and in outcrop and help to constrain the timing of motion on the Hurricane fault to post-Sevier folding.

Virgin anticline. The Virgin anticline (figs. 1 and 3) extends 45 km along strike (Hintze, 1980) in the hanging wall of the Hurricane fault. The anticline involves the Triassic Chinle and the Moenkopi Formations near Quail Creek Reservoir and the Jurassic-Triassic Navajo Sandstone (fig. 2) at the northern limit of the fold near Toquerville, Utah (Dobbin, 1939). Regionally, the Virgin anticline has double plunges, both exposed near Hurricane, Utah.

The anticline is upright, gently plunging, and open. The fold axis orientation locally near Toquerville, Utah, is 5°, S21°W (figs. 6 and 11). Beds in the western limb of the Virgin anticline strike from N-S to N50°E and dip from 10° to 30°W. Beds in the eastern limb of the anticline strike from N12°E to N35°E and dip from 10°E near the hinge to 41°E on the limb.

Pintura fold. Another anticline extends about 23 km along strike in the Hurricane fault footwall (fig. 5; Anderson and Mehnert, 1979). This anticline is referred to by some geologists as the Kanarra fold (i.e., Gregory and Williams, 1947; Anderson and Mehnert, 1979) and by others (i.e., Gardner, 1941; Neighbor, 1952) as the Pintura fold. The latter term is used here because of the fold's proximity to the town of Pintura, Utah.

The Pintura fold is an upright, gently plunging to horizontal, open anticline. The fold axis is oriented 8°, S24°W (fig. 11). Permian rocks of the Pakoon, Queantoweap, Toroweap and Kaibab Formations are exposed in the fold near Toquerville, Utah (fig. 2). The eastern limb of the fold contains beds that dip from 10° to 41°E and strike between N12°E and N35°E. The western limb of the fold contains beds that strike from N10°E to N42°E and dip from 14°W near the hinge to 75°W close to the Hurricane fault (fig. 11). Beds in the western limb of the Pintura fold may dip more steeply because of drag along the Hurricane fault (Schramm, 1994).

Toquerville fold. The Toquerville fold (Lovejoy, 1964) is a gently-plunging upright anticline that roughly parallels the strike, and lies within the footwall of the Hurricane fault (figs. 5 and 6, cross section C-C′). The fold, about 4-km long, is exposed in the Permian Kaibab Formation and the Triassic Moenkopi Formation. The attitude of the fold axis is 8°, S13°E (fig. 11). Beds in the western limb of the fold dip from 11°W to 35°W and strike from N10°W to N34°W. Beds in the eastern limb strike between N18°W and N52°E and dip from 10°E near the axis to 36°E away from the axis.

Discussion. The Virgin anticline, the Pintura fold, and the Toquerville fold involve Paleozoic and Mesozoic rocks. Both the Virgin anticline and the Pintura fold generally parallel regional structures related to Sevier compression (cf., Armstrong, 1968), and thus, are intrepreted to be Sevier-age structures (Stewart and Taylor, 1996). The term Sevier is used here to indicate Mesozoic to Paleogene deformation that pre-dates Neogene extension and movement on the Hurricane fault. The Virgin anticline and Pintura fold are connected by a syncline (fig. 6, restored A-A′ cross section) that is evident in Bouger gravity anomaly data (Cook and Hardman, 1967) and was mapped by Hamblin (1965) along strike to the south. These two anticlines and the syncline have similar wavelengths of about 10 km. The Virgin anticline and the syncline apparently parallel each other for at least 65 km along trend (Cook and Hardman, 1967).

Near Toquerville the Hurricane fault truncates the Pintura fold (fig. 5). Further to the south the Virgin anticline is cut by the Washington fault (fig. 1), a regionally-related normal fault (Dobbin, 1939; Hamblin, 1970) that parallels the Hurricane fault. These cross-cutting relationships indicate that these folds are older than the regional normal faults, consistent with a Sevier age.

The Toquerville fold, like the Pintura fold, is within the footwall of the Hurricane fault. The axial trends of the Toquerville fold and the Pintura fold are not parallel to each other, and thus, the anticlines appear to be unrelated genetically (fig. 11). The trend of the Toquerville fold axis does not parallel regional Sevier structures (cf., Armstrong, 1968), suggesting it is not a Sevier-age fold. The Toquerville and Pintura folds occur near fault sections with different strikes and have fold axes that parallel the strike of the fault, criteria required for extension-related footwall flexure. One or both of these folds could be footwall folding caused by isostatic rebound of the footwall or lithospheric flexure (Buck, 1988; Wernicke and Axen, 1988). However, as has already been interpreted, the Pintura fold is an older, pre-extensional structure. The Toquerville fold could be related to flexure of the footwall due to the initial break of, and movement along, the Hurricane fault. With footwall flexure due to isostatic rebound, rotation can occur by motion of vertical footwall shear zones (Wernicke and Axen, 1988). In lithospheric flexure, normal faults are affected by anelastic behavior of the upper crust and the footwall bends in response (Buck, 1988). The Pintura fold, existing prior to faulting,

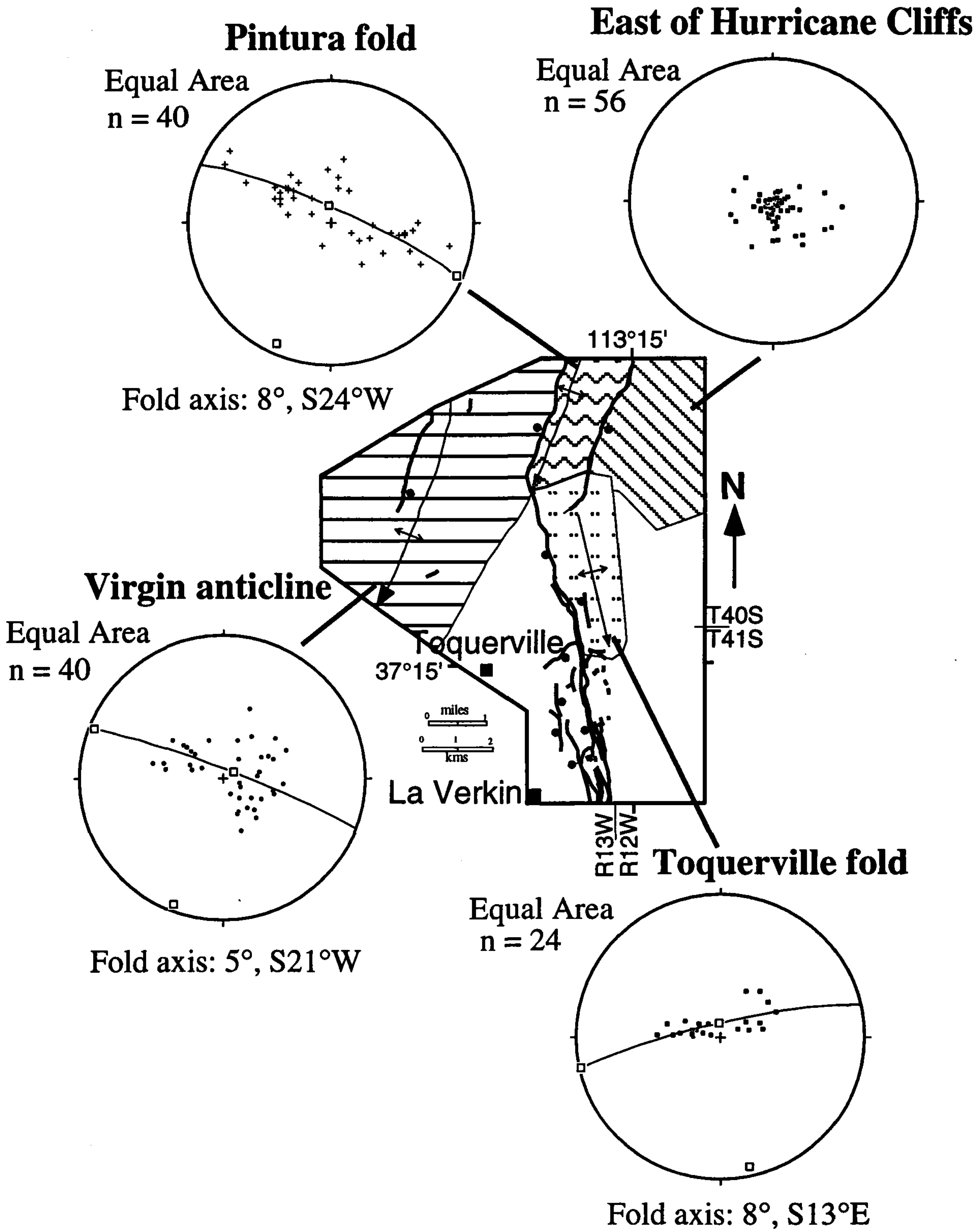


Figure 11. Map showing domains within the area of Figure 5 (marked with differing patterns) where attitudes were collected, and the equal area stereoplots of poles to bedding for domains. Great circles through the poles picked by the Bingham axial distribution analysis using Stereonet *by R.W. Allmendinger.*

may have been modified by footwall flexure but it is difficult if not impossible to determine if this is the case with the available data.

HISTORICAL SEISMICITY AND SEISMIC HAZARDS IN SOUTHWESTERN UTAH AND NORTHWESTERN ARIZONA

Historical seismic activity has been sufficient in southwestern Utah and northwestern Arizona to suggest a seismic hazard, but there have been no large, surface-rupturing earthquakes. Historical seismicity in the area generally has been diffuse, with several concentrations of activity and a few moderately large earthquakes (fig. 1). At least 20 earthquakes greater than M 4.0 occurred during this century in southwestern Utah and northwestern Arizona (Christenson and Nava, 1992).

The Hurricane fault lies near the southern end of the Intermountain Seismic Belt (ISB), a zone of relatively high seismic activity that extends from Montana to southern Utah and Nevada, and northern Arizona (Smith and Sbar, 1974; Smith and Arabasz, 1991). In southern Utah, the ISB coincides with the transition zone. The ISB is broad and poorly defined in southern Utah, and seismic activity diminishes substantially from northwestern to central and southern Arizona. Thus, the transition between the relatively active northern Basin and Range and the relatively inactive southern Basin and Range occurs in northwestern Arizona.

The historical record of seismic activity includes older earthquakes located primarily by felt reports (Arabasz and McKee, 1979; Dubois et al., 1982) and younger, instrumentally located events. Prior to establishment of a statewide seismic network by the University of Utah in 1962, epicentral locations and magnitude estimates were approximate. The detection threshold for earthquakes in southern Utah subsequently decreased to about M 2.5 around 1980 (Nava et al., 1990). The Arizona Earthquake Information Center (AEIC) at Northern Arizona University maintains a regional seismic network in northern Arizona, but AEIC coverage is limited in northwestern Arizona.

The epicenters of the two largest historical earthquakes in this region are located west of the west-dipping Hurricane fault (fig. 1). The largest event was a M 6.3 earthquake near Pine Valley, Utah, in 1902. This earthquake caused moderately severe damage in the epicentral region. The second largest earthquake was M 5.8 and occurred southeast of St. George, Utah, on September 2, 1992 (Arabasz et al., 1992b; Pechmann et al., 1992). The St. George earthquake had no foreshocks and only two aftershocks of M ≥ 2.0. Hypocenters of 40 microaftershocks, constrained by data from portable seismographs operated by the University of Utah Seismograph Stations, define the fault plane of the St. George earthquake. The epicenter was located ~15 km west of the Hurricane fault (Pechmann et al., 1992; Lay et al., 1994), the hypocenter depth is ~15 km, and the preferred fault plane dips west at about 45°; thus, it projects to the surface approximately at the trace of the Hurricane fault. The locations of these earthquakes raises the intriguing possibility that the 1992 event, and possibly the 1902 event, actually involved limited rupture on the Hurricane fault (Pechmann et al., 1992). No surface rupture has been documented for either the Pine Valley or St. George earthquakes (Black, et al., 1995).

Earthquake swarms are relatively common in southwestern Utah. Two moderate events (M ~5) occurred within a swarm near Cedar City in 1942. Other swarms occurred in 1971 in the Cedar City-Parowan Valley and in 1980–81, when two separate clusters of seismicity were recorded on each side of the Hurricane fault near Kanarraville (Arabasz and Smith, 1981; Richins et al., 1981). A swarm of more than 60 earthquakes occurred on the Hurricane fault near Cedar City, Utah, on June 28–29, 1992; the largest registered M 4.1 (Arabasz et al., 1992a). This swarm occured within an hour of the Landers, California, M 7.3 earthquake, 490 km southwest of Cedar City (Hill et al., 1993).

The largest historical earthquake in northwestern Arizona was the 1959 Fredonia earthquake (M~5.7; Dubois et al., 1982). Since 1987, the northwestern quarter of Arizona has been quite seismically active. More than 40 events with M>2.5 occurred, including the 1993 M 5.4 Cataract Creek earthquake located between Flagstaff and the Grand Canyon (Bausch and Brumbaugh, 1994).

Regional seismic hazards

Assessing seismic hazards is particularly important in southwestern Utah and northwestern Arizona because of the current population and construction boom. Zion National Park and the western part of Grand Canyon National Park also could experience damage from large earthquakes. Interstate 15, one of the major north-south transportation corridors of the Intermountain region, crosses southwestern Utah and northwestern Arizona and closely parallels the northern 40 km of the Hurricane fault.

A variety of potential earthquake-related hazards are recognized in southwestern Utah and northwestern Arizona (Christenson and Nava, 1992). Damage to structures as a result of strong ground shaking is likely the greatest hazard posed by large earthquakes in this region. The largest historical earthquakes have caused moderate to substantial damage to structures, and the potential exists for much larger earthquakes. A number of ancillary hazardous processes could occur as well, including surface displacement along the fault rupture, liquefaction along perennial streams like the Virgin River, rock falls, landslides, and flooding from dam failure (Christenson and Nava, 1992).

The potential for damage resulting from earthquakes in a region may be considered on a probabilistic basis. Probabilistic assessments typically depend on analysis of the historical seismic record, sometimes utilizing available information on late Quaternary fault behavior as well, to estimate the frequency of earthquakes of various magnitudes. Key data for such analyses are the frequency-magnitude relationship for the region, and if fault data are included, the locations of faults that are likely sources for large earthquakes. As was noted earlier, the frequency and size of large earthquakes in southwestern Utah and northwestern Arizona are poorly constrained. Probabilistic assessments of seismic hazard in this region suggest that it is moderate, with peak ground accelerations of <0.2 g that have a ten percent chance of exceedence in 50 years (Algermissen et al., 1990). The area lies within seismic zone 2B of the Uniform Building Code. Incorporation of the Hurricane and Toroweap-Sevier faults as discrete seismic sources in probabilistic analyses increases acceleration values, especially if longer intervals are considered (Euge et al., 1992; Bausch and Brumbaugh, 1994).

Seismic hazards caused by the 1992 St. George, Utah, earthquake

Ground shaking and slope failures were the dominant geologic effects of the 1992 St. George earthquake (Black et al., 1995). Ground shaking caused damage to buildings in Hurricane, La Verkin, Washington, St. George, and other communities (fig. 1). A destructive landslide in the town of Springdale destroyed three homes 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, changes to the springs at Dixie Hot Springs, and water-level fluctuations at the Quail Creek Main Dam (fig. 3). Carey (1995) estimated total earthquake losses from direct damage, response costs, and lost property values at about $1 million.

Ground shaking. Ground shaking is typically the most widespread and damaging earthquake hazard, but the region experienced relatively little damage from ground shaking during the 1992 earthquake. The maximum Modified Mercalli intensity (MMI) of the St. George earthquake was a weak VII in the Hurricane-Toquerville-Virgin area with a strong VI MMI for the epicentral region near St. George (Olig, 1995) (fig. 12). Many older, unreinforced masonry buildings showed minor structural damage in the area of maximum intensity, but cracked chimneys and fallen plaster were the predominant damage in St. George. Pechmann et al., (1995) estimated a moderate to high stress drop associated with the main shock, with a minimum value of 25 bars. Neither this stress drop nor the radiation pattern predicted from the earthquake location and mechanism provided them with any simple explanation for the relative lack of damage in St. George. Only one strong-motion record of the earthquake was obtained, but it was from Cedar City, 72 km north of the epicenter. Susan Olig (verbal communication reported in Black et al., 1995) used the empirical relation of Campbell (1987) to estimate a peak horizontal acceleration of about 0.2 g for St. George.

Slope failures. The most dramatic geologic effect of the St. George earthquake was the triggering of the 14 million m^3 Springdale landslide (Black et al., 1995) (fig. 13). This landslide, the largest of two landslides in Springdale resulting from the earthquake, is a complex block slide that likely involves both rotational and translational elements. The slide measures roughly 490 m from the main scarp to the toe, with a width of about 1,100 m and a surface area of about 40 hectares. The landslide has a clearly defined main scarp dipping 57 to 77° that is 8–15 m high along most of its length, as well as numerous fissures and minor scarps that form a broken 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. The basal slide plane is in the Petrified Forest Member of the upper Triassic Chinle Formation. The landslide involved this unit, the overlying Dinosaur Canyon Member of the lower Jurassic Moenave Formation (fig. 2), and a surficial cap of colluvium.

Detailed geologic mapping of the Springdale area (Solomon, 1996a), part of a comprehensive study of geologic hazards conducted in response to the Springdale landslide, shows that ancient landslide deposits are common in the area. The Springdale landslide is only one of 69 mapped slope failures in the 41 km^2 Springdale area (Solomon, 1996b). The largest of these landslides is the Pleistocene Eagle Crags landslide which, with a volume of about 140 million m^3 (Shroder, 1971), is an order of magnitude larger than the Springdale landslide. However, the Springdale landslide is particularly significant because its distance from the earthquake epicenter, 44 km, far exceeds the farthest distance, 18 km, at which similar landslides have been triggered in earthquakes of the same magnitude worldwide (Jibson and Harp, 1996).

At least part of the hillside that moved as a result of the St. George earthquake had been moving within the past few decades. Hamilton (1984) monitored a portion of the slope from August 1974 to June 1975 and documented 3.3 cm of movement over 9 months. Dynamic analysis of the landslide by Jibson and Harp (1996) using Newmark's (1965) method yielded maximum predicted coseismic displacements of about 1–8 cm, which is supported by eyewitness accounts of small coseismic displacement followed, after several minutes, by catastrophic failure over a 10-hour period. Jibson and Harp (1996) attribute movement of the Spring-

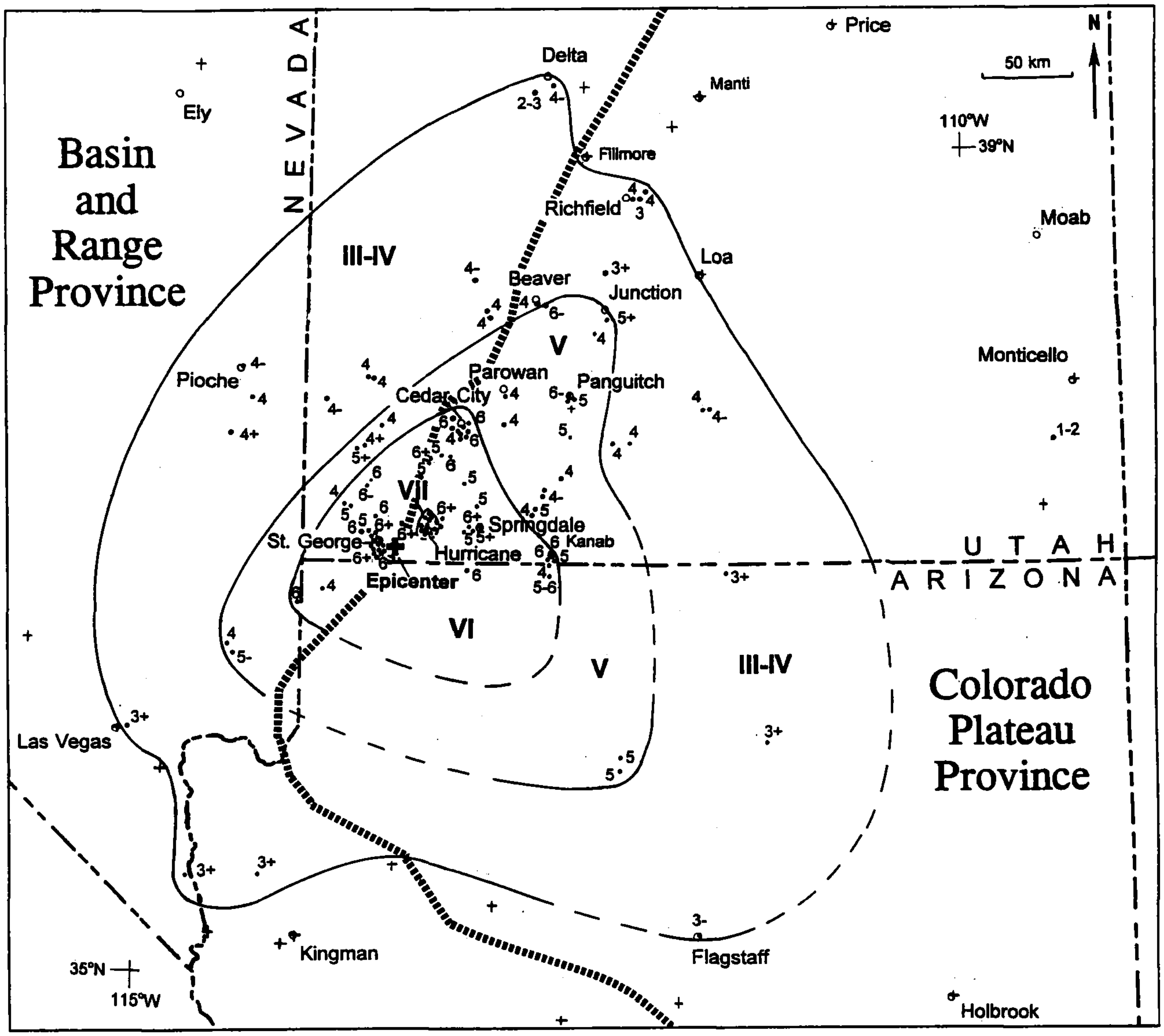


Figure 12. Preliminary isoseismal map for the M_L 5.8 September 2, 1992, St. George earthquake (from Olig, 1995). The map was developed from observations at 242 sites (not all are shown). Preliminary intensities from 85 sites were provided by the National Earthquake Information Center. Sites where shaking 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 obscures 5 sites of intensity VI). Isoseismal lines are dashed where poorly constrained.

dale landslide to a less stable geometry of the failed slope in an area of headward broadening of the Virgin River Canyon. The unstable slope configuration was susceptible to seismically triggered movement, and the catastrophic failure following small coseismic displacement was most likely the result of the time-dependent deformation behavior of plastic clays in the Petrified Forest Member (fig. 2). According to Jibson and Harp (1996), such behavior retards the deformation response of such clay to the brief, high-frequency stresses induced by seismic shaking. Stress relief is achieved through post-seismic deformation analogous to viscous creep, and the resultant reduction in shear strength along the pre-existing slip surface rendered the slide statically unstable.

Rock falls. Black et al., (1995) report numerous rock falls resulting from the St. George earthquake. Rock falls occurred along the steep cliffs above the Virgin River west of Springdale, in the Hurricane Cliffs along the Hurricane fault, and in St. George along the Red Hills and West Black Ridge. In

Figure 13. Aerial view of the Springdale landslide (from Black et al., 1995). Utah Highway 9 is at the bottom; short arrows show the main scarp of the landslide, long arrows indicate three houses damaged, medium arrow locates an abandoned water tank, and dashed line outlines landslide toe.

most cases, the rock falls either occurred in uninhabited areas without resultant damage, or fell onto roads and were quickly cleared away. Rock falls damaged a truck, a car, a wall, footpaths, and irrigation lines in southwestern Utah. Numerous fresh rock-fall scars, probably from rock falls caused by the earthquake, occur in cliffs of the Triassic Moenkopi Formation near the Arizona border.

Liquefaction. Liquefaction features observed by Black et al., (1995) were lateral spreads, sand blows, and caved stream banks in alluvium along the Virgin River from 2 km south of Bloomington to 6 km west of Hurricane (fig. 3). Involved sediment was poorly graded channel sands, commonly covered by thin overbank deposits of silt and clay. The largest lateral spread extended along the river for 60 m and perpendicular to the river for 20 m. The largest sand blow was 50 cm in diameter. Black et al., (1995) compared measurements from 17 lateral-spread features to calculated liquefaction severity index (LSI) values in the area affected by the earthquake. The LSI expresses the potential maximum magnitude of differential deformation resulting from liquefaction of susceptible soils (Youd and Perkins, 1987). Probabilistic values of LSI in Utah are related to earthquake magnitude and distance from the earthquake source by an equation developed by Mabey and Youd (1989). Measured deformation at sites nearest the earthquake epicenter was generally less than corresponding LSI values, but calculated LSI values more closely predicted measured displacements at greater distances.

Hydrologic effects. Everitt (1992) described changes in the hydrology of Dixie Hot Springs at Pah Tempe Resort, 3 km north of Hurricane along the Hurricane fault (fig. 3). The spring water is probably heated by a high geothermal gradient resulting from Quaternary volcanic activity, flows through joints and faults of small displacement, and issues from cavities in the Kaibab Formation near the Virgin River (Mundorf, 1970). Combined spring flow in 1966 was 328.4 m^3/sec, with a temperature ranging from 37.8–42.2°C (Mundorf, 1970). Following the St. George earthquake, flow from the springs decreased dramatically, water emerged from new sources at a lower elevation and closer to the river, and flow ceased at springs more than 0.3 m above the river. Everitt (1992) credits these changes to fracturing of barriers between the aquifer and river bed, creating new outlets at lower elevations and causing water levels to drop below the elevation of the resort.

Borgione (1995) documented earthquake-induced changes in pore-pressure in the emankment and foundation measured in piezometers at the Quail Creek Main Dam, 8 km west of Hurricane (fig. 3). The dam is a zoned earthfill embankment, with the dam axis roughly parallel to the strike of beds in the Triassic Moenkopi Formation which dip downstream along the southeast flank of the Virgin anticline. Water-level fluctuations along the dam's embankment and abutments ranged from a rise of nearly 1.5 m to a drop of nearly 5.2 m immediately after the earthquake. However, none of the design parameters of the dam were exceeded and the dam was considered safe for continued operation.

SUMMARY AND CONCLUSIONS

The 250-km long Hurricane fault in southwestern Utah and northwestern Arizona is segmented. Identification of earthquake rupture segment boundaries is critical for seismic-hazard analysis. Two geometric segment boundaries have been identified in the northern 60 km of the Hurricane fault, which may correspond to rupture segment boundaries. One geometric segment boundary, near the Utah-Arizona state line, was identified on the basis of fault geometry, changes in the amount of stratigraphic separation across the fault bend, fault scarp morphology, and a small mafic intrusion that crops out at the bend (Taylor and Stewart, in review). The other fault segment boundary, near Toquerville, Utah, was identified using fault geometry, fault scarp morphology, slip direction, and shortening structures near the bend (Stewart and Taylor, 1996).

Shortening structures are associated with extensional faulting on the Hurricane fault. Neogene north-south crustal shortening was interpreted from deformation of late Tertiary and Quaternary sediments in the New Harmony basin where a syncline formed adjacent to the Hurricane fault. The Toquerville fold, a footwall structure near Toquerville, Utah, is related to footwall flexure following initial faulting on the Hurricane fault. In addition, a small anticline that folds Quaternary basalt in the hanging wall of the fault and perpendicular to a fault bend was used to identify a geometric segment boundary (Stewart and Taylor, 1996).

A few short, isolated Quaternary fault scarps are present along the Hurricane fault. Scarps as high as 20 m near the Utah-Arizona border suggest multiple faulting events. Near the geometric segment boundary near Toquerville, two fault scarps, 6 and 3 m high, are formed in Quaternary (?) alluvium and bedrock north of the boundary. South of the boundary no scarps exist, but offset in a Quaternary (?) gravel deposit was observed in a stream channel. These fault scarps and the offset alluvium show that the Hurricane fault is active, although no historical surface ruptures have occurred.

Further suggestive evidence that the Hurricane fault is active is the 1992 St. George M 5.8 earthquake as well as other moderate earthquakes and earthquake swarms in the region. Moderate earthquakes occur with enough frequency to render a seismic risk in this rapidly growing portion of Utah. Seismic hazards such as ground shaking, slope failures, rock falls, liquefaction, and ground-water level changes resulted from the St. George earthquake and these hazards remain.

ACKNOWLEDGMENTS

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References for this paper are provided after the field trip log in the Combined References.

Geologic hazards in the region of the Hurricane fault

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ABSTRACT

Complex geology and variable topography along the 250-kilometer-long Hurricane fault in northwestern Arizona and southwestern Utah combine to create natural conditions that can present a potential danger to life and property. Geologic hazards are of particular concern in southwestern Utah, where the St. George Basin and Interstate-15 corridor north to Cedar City are one of Utah's fastest growing areas. Lying directly west of the Hurricane fault and within the Basin and Range–Colorado Plateau transition zone, this region exhibits geologic characteristics of both physiographic provinces. Long, potentially active, normal-slip faults displace a generally continuous stratigraphic section of mostly east-dipping late Paleozoic to Cretaceous sedimentary rocks unconformably overlain by Tertiary to Holocene sedimentary and igneous rocks and unconsolidated basin-fill deposits. Geologic hazards (exclusive of earthquake hazards) of principal concern in the region include problem soil and rock, landslides, shallow ground water, and flooding.

Geologic materials susceptible to volumetric change, collapse, and subsidence in southwestern Utah include: expansive soil and rock, collapse-prone soil, gypsum and gypsiferous soil, soluble carbonate rocks, and soil and rock subject to piping and other ground collapse. Expansive soil and rock are widespread throughout the region. The Petrified Forest Member of the Chinle Formation is especially prone to large volume changes with variations in moisture content. Collapse-prone soils are common in areas of Cedar City underlain by alluvial-fan material derived from the Moenkopi and Chinle Formations in the nearby Hurricane Cliffs. Gypsiferous soil and rock are subject to dissolution which can damage foundations and create sinkholes. The principal formations in the region affected by dissolution of carbonate are the Kaibab and Toroweap Formations; both formations have developed sinkholes where crossed by perennial streams. Soil piping is common in southwestern Utah where it has damaged roads, canal embankments, and water-retention structures. Several unexplained sinkholes near the town of Hurricane possibly are the result of collapse of subsurface volcanic features.

Geologic formations associated with slope failures along or near the Hurricane fault include rocks of both Mesozoic and Tertiary age. Numerous landslides are present in these materials along the Hurricane Cliffs, and the Petrified Forest Member of the Chinle Formation is commonly associated with slope failures where it crops out in the St. George Basin. Steep slopes and numerous areas of exposed bedrock make rock fall a hazard in the St. George Basin. Debris flows and debris floods in narrow canyons and on alluvial fans often accompany intense summer cloudburst thunderstorms.

Flooded basements and foundation problems associated with shallow ground water are common on benches north of the Santa Clara River in the city of Santa Clara. Stream flooding is the most frequently occurring and destructive geologic hazard in southwestern Utah. Since the 1850s, there have been three major riverine (regional) floods and more than 300 damaging flash floods. Although a variety of flood control measures have been implemented, continued rapid growth in the region is again increasing vulnerability to flood hazards.

Site-specific studies to evaluate geologic hazards and identify hazard-reduction measures are recommended prior to construction to reduce the need for costly repair, maintenance, or replacement of improperly placed or protected facilities.

INTRODUCTION

The geology along the nearly 250-km-long Hurricane fault is both complex and variable. Geologic units range from Paleozoic sedimentary rocks to late Quaternary basalt flows and unconsolidated Holocene basin-fill deposits. The topography along the fault is similarly variable, ranging from nearly flat valley bottoms and plateaus to steep cliffs and deep canyons. As expected in such diverse terrain, natural conditions commonly exist that present a risk or potential danger to life and property. However, only in southwestern Utah near the northern end of the Hurricane fault is the population sufficient to make geologic hazards a significant concern. As a companion paper to the preceding one (Stewart et al., this volume), this report provides an overview of geologic hazards, exclusive of seismic hazards, affecting communities near the Hurricane fault. A number of figures from Stewart et al., (this volume) are referred to in this paper; therefore, the figures in both papers are numbered consecutively. The principal geologic hazards present include: problem soil and rock, landslides, shallow ground water, and flooding.

The St. George Basin and the Interstate-15 (I-15) corridor north to Cedar City (fig. 1) lie immediately west of the Hurricane fault and are one of Utah's fastest growing areas. In 1970, Washington and Iron Counties, Utah's two southwestern most counties, had populations of 10,270 and 10,780, respectively (Utah Governor's Office of Planning and Budget, 1996). Bureau of Census population estimates for July 1, 1994 place the population of those counties at 66,125 and 24,426, respectively. About 55,000 people live in and around St. George, a popular resort and retirement community. Although growth in Cedar City has been less rapid (1996 estimated population 24,000), the arrival of several new industries, continued expansion as a center of local and state government, and conversion of Southern Utah University from college to university status has produced significant new development there as well.

SETTING AND GENERAL GEOLOGY

St. George and the surrounding communities of Washington and Santa Clara lie within the St. George Basin (fig. 3). The basin is a fault block within a broad system of faults that forms a transition zone between the Colorado Plateau and Basin and Range physiographic provinces in extreme southwestern Utah. The basin has been downdropped 1,800–2,400 m along the Hurricane fault to the east and is bounded on the west by the Grand Wash fault (fig. 1). I-15 enters the basin from the Virgin River Gorge to the southwest and departs along Ash Creek to the northeast through a narrow gap between the Hurricane Cliffs (footwall of the Hurricane fault) and the Pine Valley Mountains (fig. 3). The interstate parallels the Hurricane Cliffs for another approximately 40 km to Cedar City. At Cedar City, the Hurricane Cliffs form the boundary between the Colorado Plateau and the Basin and Range physiographic provinces.

Bedrock in the St. George Basin consists of Permian, Triassic, and Jurassic sedimentary rocks that include limestone, sandstone, siltstone, shale, conglomerate, and gypsum (fig. 2). Upper Jurassic, Cretaceous, and lower Tertiary rocks found to the north in the Pine Valley Mountains have been eroded from the basin, but upper Tertiary and Quaternary basalts and thin, discontinuous deposits of unconsolidated Quaternary clay, silt, sand, and gravel are present. The basalts flowed down paleostream channels. Subsequent erosion of the surrounding sedimentary rocks has inverted the topography, and the basalt flows now cap long, narrow, south-trending ridges. Sedimentary rocks in the St. George Basin dip gently (5–10°) to the northeast except in the vicinity of the Virgin anticline (see Stewart et al., this volume), which trends northeasterly through the basin east and south of St. George. The anticline is a broad, generally symmetrical fold with maximum flank dips of 25 to 30° to the southeast and northwest. Several north-south-striking normal faults are present north of St. George and in the Washington area. The most prominent of these is the Washington fault (fig. 1; Earth Science Associates, 1982; Anderson and Christenson, 1989).

The Hurricane Cliffs bound the St. George Basin on the east and continue northward past the towns of Hurricane, La Verkin, and Toquerville to where Ash Creek enters the basin from the north (fig. 3). Bedrock exposed along the cliffs consists of Permian, Triassic, and Jurassic sedimentary rocks including limestone, sandstone, gypsiferous mudstone, shale, and conglomerate capped locally by Quaternary basalt flows. The basalt flows are displaced down to the west across the Hurricane fault (Hamblin, 1963; Stewart and Taylor, 1996) and overlie the Jurassic Navajo Sandstone, which crops out over a broad area in the St. George Basin between the Hurricane Cliffs and the Virgin anticline. At Ash Creek, Permian and Triassic sedimentary rocks, locally capped by Quaternary basalt, form the Hurricane Cliffs east of I-15. Intrusive igneous rocks and basalt (the same flow found east of I-15 downdropped across the Hurricane fault) are west of the freeway along the flanks of the Pine Valley Mountains. At the top of the canyon of Ash Creek, I-15 enters the south end of Cedar Valley and follows the Hurricane Cliffs to Cedar City. Cedar Valley is a typical basin-and-range valley, downdropped along bordering faults (chiefly the Hurricane fault to the east) and filled with unconsolidated and semi-consolidated Quaternary basin-fill deposits.

Cedar City lies at the base of the Hurricane Cliffs, mostly on alluvial-fan material deposited by Coal Creek, which drains from the cliffs. More recent development has extended west of I-15 into the Cross Hollow Hills and north onto the Fiddlers Canyon alluvial fan. The Cross Hollow Hills are underlain chiefly by Miocene to Pliocene fanglomerate and Pleistocene basalt (Averitt and Threet, 1973). The Fiddlers Canyon fan consists of a coarse mixture of gravel, cobbles, and boulders deposited where Fiddlers Creek issues from the Hurricane Cliffs. Bedrock exposed in the Hurricane Cliffs east of Cedar City consists of a steeply east-dipping to locally overturned sequence of faulted and folded Lower Triassic to Upper Cretaceous sedimentary units including limestone, shale, mudstone, siltstone, sandstone, and minor conglomerate (Averitt and Threet, 1973; fig. 2).

GEOLOGIC HAZARDS

Geologic hazards (exclusive of earthquake hazards) of principal concern in the region include problem soil and rock, landslides, shallow ground water, and flooding.

Problem Soil and Rock

Geologic materials susceptible to volumetric changes, collapse, and subsidence are common in southwestern Utah. Particularly troublesome are (1) expansive soil and rock, (2) collapsible soil, (3) gypsum and gypsiferous soil, (4) limestone karst, and (5) soil piping and other ground collapse.

Expansive Soil and Rock. Expansive soil and rock is the most common problem deposit in southwestern Utah (Mulvey, 1992). The Triassic Chinle and Moenkopi Formations and the Cretaceous Dakota and Tropic Formations (fig. 2) are clay-rich and are the chief sources of expansive material in the region. The most common clay mineral associated with these deposits is montmorillonite, which expands and contracts with changes in moisture content.

Expansive deposits are extensive in the St. George Basin where the Petrified Forest Member of the Chinle Formation (locally known as the "blue clay") crops out. Cracking of walls and foundations has occurred in buildings in Santa Clara (fig. 14), and in Washington and the southern part of St. George. Expansive clays are also present in the Shnabkaib Member of the Moenkopi Formation. A housing development recently constructed on this unit in the Washington area will bear watching in the future for evidence of soil problems. The Chinle, Moenkopi, Tropic, and Dakota Formations all crop out in the Hurricane Cliffs east of Cedar City, but little development has taken place there, so expansive soils are not a widespread problem in the Cedar City area.

Collapsible Soil. Hydrocompaction, the phenomenon of subsidence in collapse-prone soil, occurs in loose, dry, low density materials that decrease in volume when saturated for the first time following deposition (Costa and Baker, 1981). Alluvial fans containing debris-flow deposits consisting of 10 to 15 percent clay are the most common environment for collapse-prone soils.

Figure 14. Cracks in the wall of a home on the Santa Clara Bench caused by expansion of the underlying Petrified Forest Member of the Chinle Formation.

Collapse-prone soils are widely distributed throughout those areas of Cedar City underlain by alluvial fans that have fine-grained sedimentary rocks in their drainage basins. Measured collapse strains of 5 to 15 percent are common in these fan deposits (Rollins et al., 1992). The Triassic Moenkopi and Chinle Formations, which crop out extensively along the Hurricane Cliffs east of town and in Coal Canyon, account for much of the collapsible soil material in Cedar City. Collapse-induced settlements have damaged many structures in Cedar City, and settlements became so great (up to 1.8 m) in 1977 on the northeast side of town that 14 homes had to be removed from their foundations and moved to new locations (Kaliser, 1978a). Collapsible soils have also been reported near the Hurricane airport, where Kaliser (1978b) documented as much as 1.6 m of subsidence.

Gypsiferous Soil and Rock. Gypsum is a primary component of some rocks and the soils derived from them. Gypsiferous deposits are subject to settlement caused by dissolution of the gypsum which creates a loss of internal structure and volume (Mulvey, 1992). Gypsiferous soils are common in southwestern Utah, particularly along the base of the Hurricane Cliffs and in parts of St. George. The Shnabkaib Member of the Moenkopi Formation and the Carmel Formation are the principal gypsum-bearing rock units in the area (fig. 2). Dissolution of gypsum can damage foundations, and create sinkholes. The January 1, 1989, catastrophic failure of the Quail Creek dike (fig. 15) located on the crest of the Virgin anticline about 22 km northeast of St. George was in part attributed to piping caused by dissolution of gypsum in the bedrock of the dike foundation. The unit involved was the Shnabkaib Member of the Moenkopi Formation, which post-failure investigation showed to be as much as 50 percent gypsum in some places beneath the dike (Gourley, 1992).

Figure 15. Quail Creek dike failure, January 1, 1989; dike was constructed across axial trace of the Virgin anticline on the gypsum-rich Shnabkaib Member of the Moenkopi Formation (photo credit, Ben Everitt, Utah Division of Water Resources). Location shown on Figure 3.

Figure 16. In 1985, a sinkhole in the Toroweap Formation opened suddenly in the bed of the Virgin River and swallowed the entire flow of the river for several months. The sinkhole is now behind an earthen dike on the south side of the river (shadow area at the base of the canyon wall).

Strongly cemented gypsum layers in unconsolidated deposits in the shallow subsurface commonly mark the water table and locally form a confining layer causing artesian conditions in the St. George area (Christenson, 1992). The layer, locally termed "water rock," may have been deposited as shallow ground water evaporated in soil voids. The extent of the "water rock" has not been determined, but this layer has been encountered at shallow depths in many places in the St. George area. Changes in ground-water conditions may result in local dissolution of the layer and eventual subsidence.

Gypsum is also an inherently weak material which can deform or fail when loaded with the weight of a structure. In addition, when dissolved in water, gypsum forms sulfuric acid and sulphate which react with certain types of cement and weaken foundations (Bell, 1983).

Limestone Karst. Karst features are caused by ground- and surface-water dissolution of carbonate rocks, chiefly limestone and dolomite. The Kaibab and Toroweap Formations (fig. 2), which crop out in several areas along and near the Hurricane fault, are the principal carbonate rock units affected by dissolution in southwestern Utah. Due to the area's dry climate, most of the karst features are probably relict and related to wetter climates during the Pleistocene, although dissolution may be presently occurring where limestone crops out along the Virgin River and its tributaries. In the spring of 1985, a large, open sinkhole appeared in the bed of the Virgin River just downstream from a new diversion dam in Timpoweap Canyon (fig. 16) and swallowed the entire flow of the river for several months. The water captured by the sinkhole recharged the fractured limestone aquifer and almost immediately caused changes in discharge, temperature, and chemistry at springs located at the mouth of the canyon nearly three miles downstream (Everitt and Einert, 1994). In July 1996, a small gravel- and cobble-filled sinkhole developed in the channel of La Verkin Creek where the stream crosses the Kaibab Formation. An estimated 85 L/sec of flow disappeared into the sinkhole (Lund, 1996). A small coffer dam and pipeline were constructed to divert the stream around the sink area.

Soil Piping and Other Ground Collapse. Soil piping, removal of material by subsurface flow of water, is a common phenomenon in southwestern Utah. Soil piping forms open voids and subsurface cavities into which overlying material may collapse. The three prerequisites for piping are: a susceptible deposit, usually fine-grained alluvium or poorly cemented sedimentary rock (claystone, siltstone); subsurface flow of water; and a free face for the exit of seepage water and entrained sediment. In arid areas such as southwestern Utah, piping is an important process in the headward extension of gullies, which may intersect and damage roads. Piping has also affected canal embankments and water-retention structures constructed of fine-grained material near St. George (Christenson and Deen, 1983).

Several sinkholes of undetermined origin have opened over time in the vicinity of the town of Hurricane (Solomon, 1993). Although never investigated in detail because they have not damaged or threatened structures or roads, all have been in unconsolidated alluvium near outcrops of Miocene to Quaternary basalt flows, suggesting that the sinkholes result from the collapse of buried volcanic structures (e.g., lava tubes, blowholes). The most recent sinkhole opened in January 1993, about four months after the September 1992, M_L 5.8, St. George earthquake (Christenson, 1995). The sinkhole, which was 6 m wide and 4 m deep, probably opened in response to the collapse at depth

Figure 17. Truman Drive landslide on the south side of the Santa Clara Bench; failure occurred in the Petrified Forest Member of the Chinle Formation.

Figure 18. Rock-fall hazard in Bloomington area in southern St. George.

of a volcanic feature affected by earthquake ground shaking (Solomon, 1993).

Landslides

Landslides, including rock falls, large slump-type failures, debris and earthflows, and debris slides are common in southwestern Utah (Harty, 1992). Along the Hurricane fault, the geologic formations most commonly associated with slope failures are the Triassic Moenkopi and Chinle Formations, the Cretaceous Tropic and Dakota Formations, and the Tertiary Claron Formation (fig. 2). In Iron County, numerous landslides in these formations are located along and just east of the Hurricane Cliffs. Two examples are the Green Hollow and Square Mountain landslides located about 3.2 and 6.4 km, respectively, south of Cedar City. These large, complex, prehistoric landslides are failures in the Dakota Formation and involve approximately 221 and 36 million m^3 of material, respectively (Harty, 1992). The landslides likely failed in the late Pleistocene under wetter climatic conditions, but the Green Hollow landslide has produced historical earth and debris flows. A housing development has been approved on this landslide and several large homes have been constructed there.

Landslides in the St. George area are predominantly in the Petrified Forest Member of the Chinle Formation (Harty, 1992). A high clay content and low shear strength make the Petrified Forest Member (blue clay) prone to failure. Slumps in this unit have damaged roads, canals, and utility lines. In 1992, a reactivation of a failure in the Petrified Forest Member where it crops out along the south edge of Santa Clara damaged a utility line and removed most of the backyard of a home at the top of the bench (Lowe, 1992; fig. 17).

Many steep slopes and areas of exposed bedrock make rock fall a prevalent hazard in the St. George Basin (fig. 18), as was demonstrated in 1984 when a large boulder rolled down the east side of West Black Ridge narrowly missing an office building. Studies by a geological consultant and the Utah Geological Survey (Christenson, 1985) identified numerous other unstable boulders on the slope and led to a modification of the slope and construction of a catch fence to better protect the building.

Debris flows may occur during the summer months in southwestern Utah canyons and on alluvial fans at their mouths. They typically develop in response to intense cloudburst thunder storms of short duration. For that reason, debris flows and associated flash floods are almost impossible to predict and present a significant hazard for backcountry travel.

Shallow Ground Water

Shallow ground water can flood basements, septic-tank soil-absorption systems, and other subsurface structures and may reduce foundation stability by decreasing soil bearing strength and increasing liquefaction susceptibility during earthquakes (Christenson, 1992). Shallow ground water at depths of less than 3 m is found in unconsolidated deposits along river flood plains and adjacent lowlands in the St. George Basin. Ground-water levels fluctuate seasonally and annually in response to precipitation and stream flow. A very irregular shallow water table is found beneath St. George resulting from suballuvial discharge from bedrock aquifers (Christenson and Deen, 1983). Development in Santa Clara has been especially troubled by shallow groundwater problems. There, on terraces above the Santa Clara River, flooded basements are common as are foundation problems associated with expansion of the Petrified Forest Member of the Chinle Formation in response to wetting by ground water. Paleotopography on the Chinle Formation, now buried by several feet of fluvial gravel and sandy

Figure 19. Damage caused by a flash flood in July 1989 in the Fiddlers Canyon area of Cedar City (photo credit, Kimm Harty, Utah Geological Survey).

eolian deposits, channels the ground water toward some areas and away from others. As a result, ground-water problems are irregularly distributed across the terrace. Except for a narrow zone along the flood plain of Coal Creek, shallow ground water is not a significant hazard in Cedar City.

Flooding

Stream flooding is the most frequently occurring and destructive geologic hazard in southwestern Utah (Lund, 1992). The high flood hazard results from the complex interaction of the area's rugged topography and seasonal weather patterns that bring moisture to the state. Two types of stream flooding typically occur in the region: riverine floods and flash floods. Riverine floods are usually regional in nature, last for several hours or days, and have return periods of 25 to more than 100 years. They commonly result from the rapid melt of the winter snowpack or from periods of prolonged heavy rainfall. Flash floods result from thunderstorm cloudbursts. They are localized, quickly reach a maximum flow, and then just as quickly diminish. Return periods for flash floods are erratic, ranging from a few hours to decades or longer for a particular drainage. Both types of flooding have caused extensive damage in the St. George and Cedar City areas.

Three major riverine floods have affected southwestern Utah since the area was settled in the 1850s. They occurred in 1966, 1983, and 1984. The 1966 flood resulted from an intense three-day rainstorm that produced record peak flows on the Virgin River (Butler and Mundorff, 1970). The flood caused $1.4 million (1966 dollars) damage to facilities and farm land, and remains the largest historical natural flood on the Virgin River. The 1983 and 1984 floods occurred in response to the rapid melting of maximum-of-record and greater-than-average snowpacks respectively. Both were statewide events that affected drainages throughout Utah. The occurrence of two major floods in successive years, each with an estimated return period of 25 to 100 years, demonstrates the unpredictable nature of riverine flooding.

Flash floods are by definition sudden, intense, and localized. The first recorded flash flood in southwestern Utah was on Coal Creek in Cedar City on September 3, 1853, when a "tremendous flood carried away bridges and dams, brought immense quantities of boulders and rocks into town, and did extensive damage to the iron works" (Woolley, 1946). Since then, over 300 damaging flash floods have been reported in southern Utah, and many towns such as Cedar City, St. George, and Santa Clara have experienced repeated flooding (Woolley, 1946; Butler and Marsell, 1972; Utah Division of Comprehensive Emergency Management, 1981).

In recent years, many communities have implemented various kinds of flood-control measures to eliminate or reduce the risk from flash floods. However, as rapid growth continues, development is outpacing these protective measures. Cedar City provides a good example; since 1853 extensive measures have been taken to control floods on Coal Creek. However, in the 1980s Cedar City expanded to the northeast onto alluvial-fan surfaces at the base of the Hurricane Cliffs. In July 1989, an afternoon thunderstorm over the cliffs produced approximately 2 cm of rain in 30 minutes (Harty, 1990). The resulting flood from canyons in the cliff advanced across the fan surface damaging residences and businesses, and burying parked cars (fig. 19).

SUMMARY AND RECOMMENDATIONS

Southwestern Utah, particularly in and around St. George and Cedar City, is one of the fastest growing regions of Utah. In addition to seismic hazards associated with the Hurricane and other potentially active Quaternary faults (see Stewart et al., this volume), development in the area may be adversely affected by problem soil and rock, landslides, shallow ground water, and flooding. Site-specific studies to evaluate hazards and identify hazard-reduction measures are recommended prior to construction in areas subject to geologic hazards (Christenson and Deen, 1983; Christenson, 1992). Initial planning and engineering to avoid or mitigate adverse geologic conditions can greatly reduce the need for costly repair, maintenance, or replacement of improperly placed or inadequately engineered structures.

References for this paper are provided after the field trip log in the Combined References.

Field Guide to Neotectonics, fault segmentation, and seismic hazards along the Hurricane fault in southwestern Utah and northwestern Arizona

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INTRODUCTION

This road log provides an overview of structures associated with the Hurricane fault from near the Arizona-Utah state line to Kanarraville, Utah. Stewart et al., (this volume) describe the general geologic background for this trip. Stops include Quaternary fault scarps, the landslide triggered by the 1992 St. George earthquake, and two fault segment boundaries. Shortening structures related to extension on the Hurricane fault will be visited. To conserve space, the figures and references for this road log are combined with Stewart et al., (this volume) and Lund (this volume). The field trip stops for this road log are shown in figure 20.

ROAD LOG

Day 0. Travel from Las Vegas to Hurricane, Utah

Log of Travel associated with the Hurricane fault GSA field trip

Incremental Mileage	Total Mileage	
0	0	Leave UNLV Geoscience Building and drive west on Harmon.
0.6	0.6	Continue straight (west) through the stop light at Harmon and Swenson.
0.1	0.7	At stop light at Paradise and Harmon turn right (north) onto Paradise.
0.4	1.1	At stop light at Flamingo and Paradise turn left (west) onto Flamingo. Continue straight (west) through lights along Flamingo past Las Vegas Boulevard ("The Strip").
1.5	2.6	Turn right (north) at ramp onto I-15 north.
8.2	10.8	The Cheyenne exit, a landmark only.
0.2	11.0	At 10:00 see the Las Vegas Range on the right (east) and Sheep Range on the left (west). The Sheep Range contains the Gass Peak thrust plate, a part of the Mesozoic Sevier orogenic belt (Longwell et al., 1965; Armstrong, 1968). The Las Vegas Range contains the Gass Peak thrust footwall. The Gass Peak thrust is exposed near the topographically low area that separates the two ranges (Longwell et al., 1965).
5.1	16.1	At ~2:00, are Frenchman and Sunrise Mountains. A Quaternary fault lies along the east side of Frenchman Mountain. These mountains contain Precambrian rocks on the east side, the Great Unconformity that separates Proterozoic and Paleozoic rocks and most of the Paleozoic stratigraphic section in this region. The

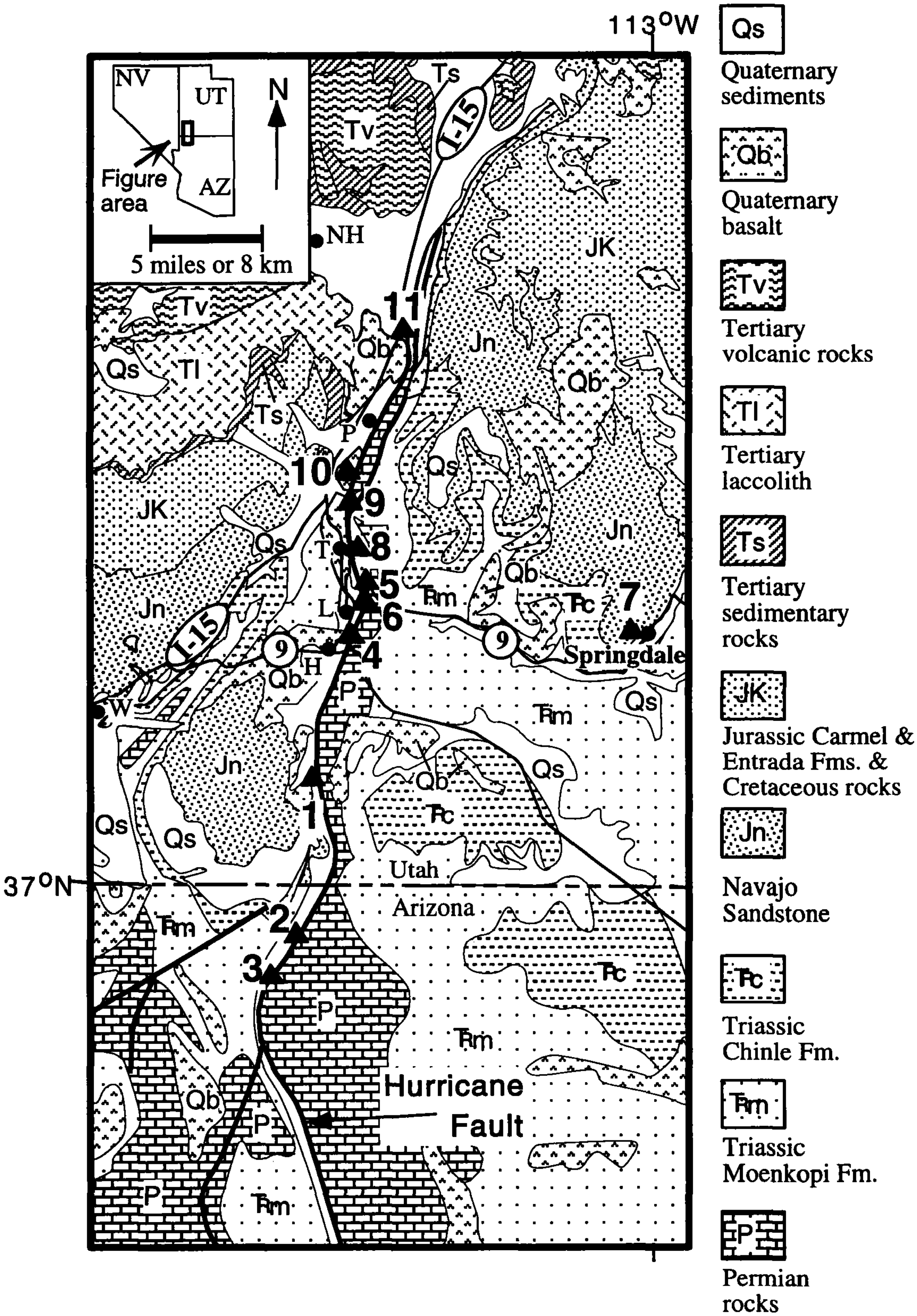

Figure 20. Field trip stop locations are shown on this map by triangles and labeled with stop numbers. Map is modified from Hintze (1980) and Reynolds (1988). Corrections of discrepancies between those two geological maps are generalized. Most faults are not shown. Towns, shown by a solid circle, are: H = Hurricane, L = La Verkin, NH = New Harmony, P = Pintura, T = Toquerville, and W = Washington.

rocks dip moderately to steeply to the east; the tilting is a result of Cenozoic extension. The rocks in Frenchman and Sunrise Mountains are thought to have been formerly continuous with rocks near the Nevada–Arizona state line and have been transported to their present position during Cenozoic extension and strike-slip faulting.

9.5 25.6 Straight ahead and on the right are the Dry Lake Mountains. These mountains consist dominantly of the Bird Spring Formation which may range from Mississippian to Permian in age, but is mostly Pennsylvanian.

1.1 26.7 On the left (north) side of I-15 is the Chemical Lime plant and open-pit mine. The nearly horizontal cylinders are the kilns in which the lime is produced. The process involves heating the limestone to a high temperature using crushed coal blown into the kilns. This procedure drives off volatiles such as water and other impurities from the limestone.

10.4 37.1 The mountains on the right at ~3:00 are the Muddy Mountains. The lower mountains to the left (north) are the North Muddy Mountains.

Along the west side of these ranges is a young fault, called the California Wash fault (Bohannon, 1983a, W.J. Taylor, unpublished data). In good light the scarp along the fault can be seen from I-15. The scarp is approximately west facing.

In the Muddy Mountains the Muddy Mountain thrust, another fault of the Sevier orogenic belt, is exposed (Longwell, 1922, 1928; Bohannon, 1983a, 1983b). The North Muddy Mountains expose large folds and small thrusts also related to the Mesozoic Sevier orogenic belt (Longwell et al., 1965; Armstrong, 1968; Bohannon 1983a, 1983b).

4.0 41.1 The Mormon Mountains lie at ~11:00. The high peak on the right (south) end of the range is called Moapa Peak.

The Mesozoic Mormon thrust and Tertiary Mormon Peak detachment are exposed in the Mormon Mountains (Axen et al., 1990). The north–south part of the dome or arch that is typical of detachment terranes is visible in the topography from this vantage point.

3.2 44.3 At 2:00 between the highway and the bedrock is a small bluff at the edge of the alluvial fans. The bluff is the scarp of the California Wash fault continuing to the south along the west side of the North Muddy and Muddy Mountains.

3.0 47.3 Looking toward the northeast and the Mormon Mountains at ~11:00 the alluvial fan is broken by bluffs along the west and southwest side. Above the bluff is an old alluvial surface called Mormon Mesa which is capped by a well-developed thick layer of caliche.

8.3 55.6 The red-brown sedimentary rocks surrounding the small towns of Glendale and Moapa are dominantly Tertiary basin-fill deposits, mostly conglomerate, sandstone and siltstone.

14.8 70.4 Here the highway crosses a surface that is equivalent in elevation to Mormon Mesa, and thus, possibly is similar in age.

5.2 75.6 Enter Mesquite basin or valley. This basin contains some of the thickest (~10 km) basin-fill deposits in Nevada. The mountains straight ahead and on the right (southeast) are the Virgin Mountains. The Frenchman Mountain block is thought to have lain near the south end of these mountains prior to Cenozoic extension. The alluvial fans are well developed and protrude westward from the range. Some of these fans are dissected. The ends of the fan are cut by the Virgin River which runs through the topographic low.

19.4 94.0 Cross Arizona state line.

6.7 100.7 The mountains straight ahead and to the north are the Beaver Dam Mountains. The obvious light colored, white and orange, sandstone exposed nearly straight ahead is the Permian Queantoweap Sandstone (Hintze, 1986).

The highway crossing the Beaver Dam Mountains at ~10:00 is a state highway that cuts through the Cenozoic Castle Cliffs detachment fault (Axen et al., 1990).

5.9 106.6 Near here the Interstate enters the Virgin River gorge. At the near (west) end of the gorge two strands of the range-bounding fault are exposed on the right (south). The rocks near one strand are brightly colored purple and yellow from alteration along the fault. The other strand lies further west.

		In the gorge most of the Paleozoic stratigraphic section is exposed (Hintze, 1986). A small fault block at the west end comprises middle to upper Paleozoic rocks (Hintze, 1986). A short distance into the gorge (0.5–0.75 miles) many small stratigraphic separation normal faults are visible in the road cut.
1.1	107.7	From here to the east, the highway passes by Cambrian through Permian rocks. The green shales exposed near here lie within the Cambrian section.
3.7	111.4	This orange sandstone is the Permian Queantoweap Sandstone. Many small stratigraphic separation faults are exposed in the road cut. This sandstone crops out in much of the upper part of the gorge and is overlain by the Permian Toroweap Formation. The Toroweap Formation forms the cliffs above the sandstone straight ahead.
8.6	120.0	The chert-rich carbonate exposed near the sign that says "Black Rock Road 1 mile" is the Permian Kaibab Limestone.
		From here to the Hurricane fault lies the transition zone between the Basin and Range Province to the west and the Colorado Plateau to the east. The Colorado Plateau can be seen straight ahead in the distance, on the skyline.
		The transition zone is marked by small ridges, most of which are fault bounded. The fault blocks are dominantly east-tilted Mesozoic rocks.
3.4	126.8	To the east-northeast at 10:00 lie the Pine Valley Mountains. The upper part of these mountains is underlain by the Tertiary Pine Valley laccolith (Cook, 1957). Between the vehicle and the Pine Valley Mountains is a black surface which is the top of a young basalt that flowed down a surface that slopes toward the vehicle.
0.7	127.5	Cross state line into Utah.
3.6	131.1	On top of the red-brown colored ridge straight ahead and to the north (left) the resistant cap rock is the Shinarump Conglomerate, the lowest member of the Triassic Chinle Formation. A short distance ahead is a road cut through the Shinarump Conglomerate.
9.9	141.0	At ~10:00 in the road cut, a basalt flow fills a paleochannel in the Mesozoic red beds.
1.3	142.3	Take exit 16 onto Utah Highway 9 to Hurricane, heading east. Turn right (east) at bottom of off-ramp.
0.7	143.0	In the road cut on the left (north) side of the road, a syncline is exposed in Mesozoic rocks.
0.7	143.7	Quaternary volcano at 1:00.
0.4	144.1	Straight ahead is the Virgin anticline. The beds on the right dip east; the beds on the left dip west. Follow these beds toward the dam on Quail Lake and they become more gently dipping. Continuing along, the fold hinge zone can be seen to the left over the top of the dam. Some small stratigraphic separation faults cut the fold hinge zone.
1.3	145.4	The hinge zone of the anticline is to the left. A former version of this dam failed in 1989 when foundation problems caused dam failure and a flood (Lund, this volume). The flood water from the failure caused a large amount of scouring which is visible in this area.
		The Shinarump Conglomerate crops out near the road in a short distance.
1.2	146.6	On the right (east) is a basalt flow filling a paleochannel cut in the Triassic Moenkopi Formation.
3.3	149.9	On the right (south) is the Quaternary volcano, Volcano Mountain. $^{40}Ar/^{39}Ar$ data from one flow erupted from this volcano are not of high quality; Sanchez (1995) was only able to conclude that flow had a maximum age of 270 +/−50 ka. To visit the volcano, turn right here and travel through this new subdivision.
		At ~10:00, north of the highway, is a polycyclic (multiple eruption) volcano.
0.3	150.2	The cliffs straight ahead as well as toward 2:00 and 10:00 are the Hurricane Cliffs which are the Hurricane fault line scarp.
1.9	152.1	Turn right (south) onto 700 W.
0.05	152.15	Turn left (east) into Super 8 Motel parking lot, Hurricane, Utah.
Day 1.		Examine a fault segment boundary in Arizona and the Anderson Junction fault segment.
0.0	0.0	Leaving Super 8. Turn left (south) on 700 W.
0.3	0.3	Stop at stop sign, then proceed ~straight across small bridge.

0.1 0.4 The Hurricane Cliffs are on the left (east) and straight ahead.

1.7 2.1 Stay on the same paved road and follow it to the right (west) around curve. Continue around curves and stay on this paved road.

4.3 6.4 Cross cattle guard. Road becomes dirt. Go straight, which is the left fork.

0.7 7.1 **Stop 1. Lava Cascade.** This stop is on The Divide, UT, 7.5′ quadrangle, Secs. 3 & 4, T.43S, R.13W. To the left (east) at ~10:00 is a lava cascade. A dark-colored lava flow is exposed where it flowed down the upper part of the Hurricane Cliffs. The flow ends part way down the cliff. The source of the basalt flow is a volcanic center exposed on the plateau east of the Hurricane Cliffs (Sanchez, 1995).

The rock is fine grained, black in color, and contains small olivine phenocrysts. It is a basanite with less than 46% silica (Sanchez, 1995).

This lava flow falls into the Stage IV flows of Hamblin (1970). According to this classification scheme, Stage IV flows are young and were deposited in the present drainage system, the surface features are only slightly modified and the associated cinder cones are well preserved. Older flows belonging to Stages I (oldest), II and III were erupted onto older, topographically higher surfaces.

The rock in the lava cascade has not been dated radiometrically, but the geomorphic-type stage dates can be used in combination with radiometric dates to estimate the age of the lava flow. Another Stage IV flow that was erupted from Volcano Mountain (seen along Utah Highway 9 west of Hurricane) was dated by Sanchez (1995) at 258 ± 24 ka using $^{40}Ar/^{39}Ar$. A Stage II flow in Hurricane Valley yielded a 353 ± 45 ka $^{40}Ar/^{39}Ar$ date (Sanchez, 1995). According to Sanchez, the dated flow has the same chemistry as the flow that is exposed in the Hurricane Cliffs, above other Stage II flows exposed in Hurricane Valley.

The Hurricane fault was active and the Hurricane Cliffs existed as essentially a fault escarpment, at least in part, prior to the eruption of the lava in the cascade because the flow conforms to the topography showing that it flowed down the cliff. The cliffs are about 300 m high here and the flow ends about 150 m down the cliff which suggests that at least one half of the total scarp height may have formed prior to eruption of the flow at about 200–300 ka ago.

The lava flows exposed in the hill west of the road are Stage III, and thus, older than the flow in the lava cascade. Also, the rock is an alkali basalt, not a basanite, and appears to have erupted from a volcanic center located to the west (Sanchez, 1995).

0.8 7.9 Cross cattle guard.

0.7 8.6 Continue straight south (left fork). The right fork goes to an exposure of dinosaur tracks and historic Fort Pearce.

2.0 10.6 Cross cattle guard.

0.7 11.3 On the right (east), the unconformity between Mesozoic and Quaternary deposits is exposed in the wash.

0.55 11.85 Cross cattle guard.

1.15 13.0 Quaternary (?) basalt is visible on the rounded hills and in the butte straight ahead.

0.1 13.1 Pass the trail head for the Honeymoon Trail on the left (east) where there is a nice fault exposure (Hamblin, 1970).

2.2 15.3 Cross wash and drive over outcrops of sandstone; continue to the left (east).

1.7 17.0 Continue on left fork. Straight ahead (southeast) are the Hurricane Cliffs. The cliffs contain mostly Permian formations such as the Kaibab Formation, Toroweap Formation, and Hermit Shale.

0.3 17.3 To the left (east), a high-angle fault cuts through the footwall of the Hurricane fault. It is most easily seen by the offset of one of the thick beds in the cliffs.

0.4 17.7 At ~11:00 is a large canyon called Cottonwood Canyon. Rocks exposed on the right are Moenkopi Formation overlain by Quaternary (?) basalt.

1.0 18.7 Continue straight (south) through the fence. Remember to leave the gate as you found it, either open or closed.

0.9 19.6 **Stop 2. Fault scarps along the Hurricane fault.** Turn left on steep road beneath powerline. Continue up the road about

500 m if it is passable. If not, hike up road toward the Hurricane Cliffs until you reach the prominent fault scarp on the north side of the road.

This stop is in the Rock Canyon 7.5′ quadrangle, Mohave County, Arizona, Sec. 27, T. 41 N., R. 10 W. It is located at the southern end of a 7-km-long portion of the Hurricane fault where relatively low fault scarps formed in Quaternary deposits and bedrock are common along the base of the Hurricane Cliffs. It is just north of the prominent bend in the Hurricane fault that is discussed at Stop 3 (fig. 4). Between the town of Hurricane, Utah, and the Arizona border, the Hurricane Cliffs are composed almost entirely of the resistant rocks of the Kaibab and Toroweap formations. Along this section south of the Arizona border, the lower slopes of the fault escarpment are formed in rocks of the Supai Group, which generally are less resistant to erosion than the rocks of the overlying formations. Because of the erodibility of the Supai Group rocks, the steeper upper portions of the Cliffs have retreated by varying amounts from the principal Hurricane fault zone.

The relatively low fault scarps evident at this stop apparently record late to latest Quaternary displacement on this section of the Hurricane fault system. The scarp at this locality is typical of the scarps along this section of the fault. The scarp is high (~25 m) and steep (maximum slope of 35°). The scarp is formed on a steeply sloping landform colluvial/alluvial surface that mantles the lower part of the cliffs. The colluvial/alluvial deposits are typically quite thin (a few meters thick or less) over a bedrock erosion surface on the upthrown side of the fault. The scarp is formed in these deposits and bedrock, so the bedrock may exert some influence on scarp morphology and degradation rates. Reasonably well-developed calcic soils are developed in the faulted colluvial /alluvial deposits, suggesting that they are of late(?) Pleistocene age. The alluvium exposed immediately downslope of this fault scarp may be correlative with the colluvium/ alluvium above the scarp, or it may be younger alluvium derived from the scarp and adjacent drainages. Based on the size of the scarps, they almost certainly record multiple late Quaternary fault ruptures. The age of the youngest rupture on this section of the fault is not well constrained, but young terrace and alluvial-fan deposits are unfaulted.

No alluvial fault scarps are obvious in the area of the major bend along the Hurricane fault immediately south of Stop 2 (discussed in Stop 3). Relatively low scarps exist at many places along the base of the Hurricane Cliffs on the Shivwitz Plateau south of this locality. None of these scarps are as high or as steep as the scarp observed at Stop 2.

Continue along same road (center fork) to next stop. In a short distance along the center fork is another sign that says Temple Trail.

0.3 19.9 At wash. If driving two-wheel drive or low-clearance vehicle stop here for Stop 3. Otherwise continue along this road another 1.8 miles.

Stop 3. Segment boundary on the Hurricane fault. This is the southernmost stop on the Hurricane fault on the field trip. At this stop in the Rock Canyon 7.5′ quadrangle (Secs. 26, 27, & 34, T.41S, R.10W), northern Mohave County, Arizona, a relatively abrupt bend in the trace of the Hurricane fault parallels the visible bend in the cliffs which lie to the east and south. We will walk along the Hurricane fault in the northern part of the bend and examine the fault geometry and Quaternary deposits which include older alluvium, talus, recent alluvium, mafic volcanic rocks, and a small mafic intrusion.

Taylor and Stewart (in review) suggest that the large bend, convex toward the hanging wall, bend in the Hurricane fault in this area is a geometric segment boundary (cf., Crone and Haller, 1991; dePolo et al., 1991). Several pieces of information support this interpretation. (1) The fault bends and changes strike from approximately N20°E north of the bend to N15–20°W south of the bend. We will walk along the NNE-striking fault section and view the area of maximum curvature (fig. 8). (2) The total stratigraphic separation decreases toward the bend both from the north and from the south (fig. 9). We will see an artifact of this change in the elevation of the Triassic Chinle Formation in the hanging wall relative to the Paleozoic units in the footwall (described below). The elevation of the Chinle Formation is higher near the inflection point of the bend than along the fault sections to the north and south which corresponds to a decrease in stratigraphic separation at the bend. (3) A Quaternary(?) basaltic intrusion and basalt field near the apex of the bend suggest the possibility of non-conservative slip in the hanging wall near the segment boundary zone. Nonconservation of space suggests that the slip direction, magnitude and/or timing of movement is not constant on the fault sections around or on either side of the bend. (4) The footwall structures near the bend change from dominantly gentle to open folds and a few normal faults south of the bend to small stratigraphic separation normal faults north of the bend (Billingsley, 1992; W.J. Taylor, unpublished mapping). These differences in structural style imply a kinematic change at the bend. (5) In addition, fault scarps in Quaternary deposits crop out both north and south of the bend, but appear to be lacking in the area of maximum curvature. We saw scarps north of the bend at stop 2 and will note the lack of scarps in this area. This change in the Quaternary fault scarps suggests the possibility that this geometric barrier may also be a behavioral or paleoseismic barrier as well, if the Quaternary deposits are of similar ages (King, 1986).

The Paleozoic units exposed in the cliff near here lie in the footwall of the Hurricane fault. Recognition and identification of these units is critical in determining the total stratigraphic separation on the fault segments north and south of this bend as well as at the bend. The units are, from lowest to highest, the Permian Esplanade Sandstone which is a red, white or tan sandstone near the base of the cliffs; the Permian Hermit Shale which is a red, brown and white siltstone to sandstone; the Permian Toroweap Formation that contains three members: a lower unit of interbedded gray, yellow and brown sandstone, siltstone and dolomite (Seligman Member); a middle gray limestone cliff (Brady Canyon Member); and an upper gypsiferous unit of gray siltstone and light-red siltstone to sandstone (Woods Ranch Member); and near the top of the cliffs, the Permian Kaibab Formation with a lower gray cherty limestone (Fossil Mountain Member) and an upper red and gray unit of interbedded limestone, sandstone and siltstone with white gypsum. More complete descriptions of these units are available with the quadrangle map for this area (Billingsley, 1992) and in Sorauf and Billingsley (1991).

Along the base of the Hurricane Cliffs and in the hanging wall a variety of Quaternary deposits are exposed. These deposits lack scarps near the apex of the bend, but they or similar deposits are faulted on the segments to the north and south of the bend. The sedimentary deposits include small alluvial fans, talus, alluvium, landslide deposits, colluvium, and gravel terraces. Many of these deposits are the debris slope and wash slope facies associated with the degradation of the escarpment associated with the Hurricane fault. The igneous deposits include mafic lava flow rocks and a small pluton that intrudes them. The hill to the west is composed of mafic extrusives and contains at least four distinct flows that are separated by agglomerate. The flows are fine grained and contain varying amounts of plagioclase and olivine phenocrysts. The pluton or plug also has plagioclase and olivine phenocrysts, but is granular and medium to coarse grained. Maureen Stuart (unpublished data from UNLV XRF laboratory, 1995) analyzed samples from the four flows and the plug for major and trace element contents and they are all subalkaline tholeiitic basalt (cf., Irvine and Baragar, 1971; Le Bas et al., 1986).

		Turn around and follow same route to Utah Highway 9.
3.9	23.8	Cross under the power lines.
0.9	24.7	Pass through fence.

2.4	27.1	On the hill at ~10:00 are purple, red-brown, and tan layers. The tan unit is the Shinarump Conglomerate. The unit below it is the Moenkopi Formation.
4.35	31.45	Cross cattle guard. The lava cascade is visible from here.
1.45	32.9	Cross cattle guard.
1.9	34.8	Turn to **Optional Stop** at dinosaur tracks. To go to dinosaur tracks and Fort Pearce use the following directions.
		At 2.0 miles Cross cattle guard.
		At 3.4 miles Cross cattle guard and continue straight.
		At 0.7 miles Straight ahead (north) the purple outcrops are the Chinle Formation. In the topographically low area toward the vehicle from those exposures, is a yellow-tan exposure of the Shinarump Conglomerate.
		At 0.5 miles Turn right and follow small dirt road to dinosaur tracks at this intersection. Park in parking area at the end of the road and then hike along the trail to the dinosaur tracks.
		At 1.6 miles Cross cattle guard
		At 0.4 miles Dirt road to the left here leads to Fort Pearce. Return along same route to field trip route.
0.7	35.5	Cross cattle guard.
0.8	36.3	To the left (east) at ~10:00 is the lava cascade.
0.7	37.0	Cross cattle guard. Road becomes paved. Go straight.
4.3	41.3	Follow this same paved road to left (north) around curve and continue along it.
1.7	43.0	The Hurricane Cliffs are on the right (east).
0.1	43.1	Cross small bridge and stop at stop sign, then proceed straight.
0.3	43.4	Pass Super 8 Motel on 700 W and turn right (east) onto Utah Highway 9 at stop sign.
0.15	43.55	Follow road around curve to left (north).
0.95	44.5	Turn right onto Enchanted Way, the lane into Pah Tempe Resort.
0.3	44.8	**Optional Stop 4. The Hurricane fault at Pah Tempe Resort near Dixie Hot Springs.** This stop is on the Hurricane, UT, 7.5′ quadrangle, SW1/4, Sec. 25, T.41S, R.13W. At this stop the Anderson Junction segment of the Hurricane fault consists of at least two fault strands. Both strands offset the young basalt at the top of the section, much of which contains well-developed columnar joints. On the south side of the canyon, the block between the two fault strands has been steeply tilted(~60–80°W), causing a large angle across the unconformity between the Cenozoic basalt and the Mesozoic rocks in the block. Note that in the footwall the angle across the unconformity at the base of the basalt is small (i.e., the unconformity is only slightly angular), but that all of the Mesozoic units are missing, probably due to erosion of the uplifted footwall prior to basalt emplacement. A group of springs, Dixie Hot Spring, flows into the Virgin River just upstream from the parking lot. The spring temperatures are about 100–120°F. The combined flow from these springs decreased after the 1992 St. George earthquake (Stewart et al., this volume). Everitt (1992) suggests that flow from springs was diverted following the earthquake and attributes these new discharge points to the fracturing of hydrologic barriers between the aquifer and the river bed which resulted in a drop in water levels. Turn around and return to Utah Highway 9.
0.3	45.1	Turn right (north) back onto the highway and cross the Virgin River.
1.0	46.1	The town of La Verkin.
0.6	46.7	Turn right (east) staying on Utah Highway 9 and head toward Springdale.
1.4	48.1	Slickenlines and slickensides on a fault surface that is a strand of the Hurricane fault are exposed to the right (east). Rounding the curve in the road to the right, the Hurricane fault can be seen toward the left (north).
0.4	48.5	Turn left (north) onto a dirt road that passes a shooting range in a short distance on the right.
0.5	49.0	**Stop 5. The Hurricane fault zone, Anderson Junction segment.** Drive along dirt road toward the northwest. This road is

rather rugged and not maintained. Once parked, walk toward the west to the eastern margin of the Hurricane fault zone. The stop is on the Hurricane, UT, 7.5′ quadrangle, SE1/4, SE1/4, Sec. 12, T.41S, R.13W.

The vans are parked on the footwall of the Hurricane fault. Here the fault is a zone 1.5 km wide and multiple normal fault strands can be seen (fig. 6, cross section C-C′). These multiple normal fault strands are one line of evidence that this section of the fault is a distinct fault segment and differs from the fault segment north of a segment boundary to be discussed in Stop 10. Permian Kaibab Formation crops out in the footwall. Different members of the Triassic Moenkopi Formation lie within the hanging wall and are displaced along synthetic and antithetic faults. The yellow to tan-colored unit is the Timpoweap Member which is a fine-grained limestone and shale that breaks in platy fragments. The red unit is the Lower Red Member which is composed of finely-laminated mudstone to thin beds of sandstone.

The close hill to the west at ~11:00 is capped with the Virgin Limestone Member of the Moenkopi Formation. This member comprises interbedded limestone, sandstone, and siltstone and is typically yellow-tan to light gray.

0.5	49.5	Return to Utah Highway 9. Turn right and head west.
2.0	51.5	Turn right at Utah Highway 17 in La Verkin.
0.4	51.9	Turn right at road with a white office trailer (unnamed street). This is an entrance to a gravel pit and is private property; permission to drive through should be obtained prior to entry.
0.25	52.15	**Stop 6. Gravel/conglomerate offset by the Hurricane fault along the Anderson Junction segment.** Follow road around and park near a part of the road that is constructed on a large ~9 ft diameter metal tunnel. Walk down from road towards the east and then follow a dry stream bed ~0.25 miles. This stop is on the Hurricane, UT, 7.5′ quadrangle, NE1/4, SW1/4, Sec. 13, T.41S, R.13W.

In a small, scoured canyon is an exposure of Quaternary gravel with a small amount of stratigraphic separation along two fault strands about 3 m apart. The gravel can be correlated across the fault. This reddish gravel is a basin deposit that accumulated in the depression adjacent to and formed by the Hurricane fault. The red color is likely derived from weathered red members of the Moenkopi Formation. The age of this gravel is unknown, but it is older than the most recent sedimentation in the area. About 3 m of stratigraphic separation is observed on the 60°W dipping fault strand and 1.2 m of offset is measured on the 73°W strand. No fault scarp exists. Lack of an escarpment may be related to two reasons: (1) the age of the offset is so old that the scarp was eroded away or (2) the bedrock unit is the nonresistant Moenkopi Formation which may be less likely to form scarps than other less erodible formations. Either way, exposures such as this are uncommon along the Hurricane fault, but that should change as more geologists continue detailed mapping along the fault.

This stratigraphic separation of Quaternary gravel is another piece of evidence that this is a unique fault segment. As is typical of adjacent fault segments on normal faults, faulting history varies between the Anderson Junction segment and the Ash Creek segment in that no fault scarps are present on the Anderson Junction segment, although the Quaternary gravel is offset. Stop 10 will discuss two fault scarps on the Ash Creek segment.

Walk back to vans.

0.25	52.4	Return to Utah Highway 17. Turn left (south) and continue going south on Utah Highway 9.
2.1	54.5	Cross Virgin River.
1.9	56.4	Turn left (south) onto 700 W near the Chevron station in Hurricane.
0.05	56.45	Turn left (east) into Super 8 Motel parking lot.
Day 2.		Examination of the Springdale landslide, the Anderson Junction and Ash Creek fault segments and folds in the New Harmony and Kanarraville basins.

Incremental Mileage	Total Mileage	
0.0	0.0	Leave Super 8 Motel on 700 W, Hurricane, Utah.
0.15	0.15	Follow road around curve to the left (north).
0.95	1.1	Pass Enchanted Way, the lane into Pah Tempe Resort.
1.0	2.1	The town of La Verkin.
0.6	2.7	Turn right (east) staying on Utah Highway 9 at this intersection between Highway 9 (right) and Highway 17 (straight). Continue toward Springdale.
4.2	6.9	Hurricane Mesa on the left (north), site of U.S. Air Force supersonic research facility. Almost complete section of Triassic Moenkopi Formation is exposed in cliff face, capped by resistant ledge of Shinarump Member, Triassic Chinle Formation.
2.1	9.0	The town of Virgin.
1.6	10.6	Westernmost exposure of the Pleistocene Crater Hill basalt, capping mesas to the left (north) of the road for the next 5.1 miles. The Crater Hill cinder cone is 3 miles to the northeast.
5.1	15.7	Cross Coalpits Wash. Easternmost exposure of the Crater Hill basalt unconformably overlies the Pleistocene Parunuweap Formation on west side of wash. The town of Grafton is to the right (south) of the road.
0.5	16.2	Parunuweap Formation, with basalt boulders, unconformably overlying Moenkopi Formation in roadcut on the left (north).
1.0	17.2	Sand and gravel pit in Holocene Orderville gravel, across Virgin River flood plain to the right (south).
0.6	17.8	The town of Rockville, named for rockfall debris derived from the Shinarump Member capping the Rockville Bench to the left (north) of the road.
1.7	19.5	As the road curves left (northeast) into lower Zion Canyon, erosional remnants of the Jurassic-Triassic Navajo Sandstone are visible to the right (south). The remnants, known as Eagle Crags, stand at the head of a Pleistocene to Holocene landslide, one of the largest in Utah. Failure was due to downcutting of the East Fork of the Virgin River into the Chinle Formation, Petrified Forest Member.
0.6	20.1	To the right (east) is the Johnson Mountain landslide, another large Pleistocene slope failure in the Petrified Forest Member.
1.4	21.5	The road up lower Zion Canyon lies between the massive cliffs of Navajo Sandstone in Zion National Park. Mt. Kinesava is to the left (west) and The Watchman is to the right (east).
1.2	22.7	**Stop 7. Springdale landslide.** This stop is on the St. George, UT, 30 x 60′ quadrangle, at Secs. 26 & 27, T.41S, R.10W. Park at the landslide toe on the dirt road to the left (west) of the highway. The Springdale landslide lies at the juncture between the wide, lower Zion Canyon and narrow, upper Zion Canyon. The catastrophic failure of the landslide, although seismically induced by the 1992 St. George earthquake, is related to the normal process of headward broadening of the canyon as the river entrenches and encounters the Petrified Forest Member. Older landslide debris is found on the Pleistocene alluvial terrace overlooking the Springdale landslide (fig. 13). The Springdale landslide is a complex block slide with its basal slide plane in the Petrified Forest Member and its main scarp in the overlying Dinosaur Canyon Member of the Jurassic Moenave Formation (fig. 2). Note the numerous fissures and minor scarps that form a broken topography within the slide mass. Return along the same route to Utah Highway 17.
20.0	42.7	At intersection between Utah Highways 9 and 17 (near RV park) turn right (north) and continue along Highway 17.
1.1	43.8	On the left is basalt unconformably overlying Tertiary (?) alluvial or fluvial deposits. The town of Toquerville. At ~2:00 a large convex-toward-the-hanging-wall bend in the Hurricane fault is visible as the fault curves west around a footwall block.
2.3	46.1	Turn right (east) onto a small road, Spring Drive, just before (south of) the bridge over Ash Creek.
0.8	46.9	Continue straight across cattle guard. At 10:00, the contact between the carbonate cliffs on the east and the dark colored basalt on the west is the Hurricane fault.

		The basalt lies in the hangingwall. High on the cliff, in the Hurricane fault footwall, is a paleochannel filled with basalt.
0.25	47.15	Take the right fork on the dirt road.
0.1	47.25	**Optional Stop 8. Hurricane fault, Anderson Junction segment, near a gravel quarry.** The Hurricane fault is exposed both to the north and south of here. To the north is the fault segment boundary. Along this dirt road are slickenline exposures on Permian Kaibab Formation. This is the Pintura, UT, quadrangle, SW1/4, NW1/4, Sec. 36, T.40S, R.13W. Continue uphill along this road and road curves and heads south along the fault strand.
0.7	47.95	The view to the south from here is along the Hurricane Cliffs.
0.65	48.6	Straight ahead is basalt unconformably overlying Mesozoic rocks.
0.1	48.7	Small dirt road to right leads to a former oil or gas well site which is at ~2:00. The flat lying rocks in the distance are part of the Colorado Plateau and are in the footwall of the Hurricane fault.
0.8	49.5	The hills to the right (east) contain the red-white-red stripes of the Moenkopi Formation which is capped by the resistant tan-colored Shinarump Conglomerate Member which is overlain by the upper part of the Triassic Chinle Formation.
0.025	49.52	Down the hill among the light-colored rocks, a small stratigraphic separation thrust fault is visible, which is the southern exposure of the Taylor Creek fault (Lovejoy, 1964; fig. 6, cross sections A-A′ and B-B′). There is 15 m of stratigraphic separation of the Virgin Limestone Member of the Triassic Moenkopi Formation and the average orientation is N15°E, 30°E. Farther north near Zion National Park, the Taylor Creek thrust fault has more than 600 m of vertical and 760 m of horizontal displacement (Kurie, 1966).
0.225	49.75	To continue to the top of the ridge, take the left (west) fork.
0.05	49.8	To the right (~north) a high-angle fault is exposed. Kaibab Formation is in the footwall and Moenkopi Formation is in the hanging wall.
0.2	50.0	The red mudstone unit that we are driving through is the Upper Red Member of the Moenkopi Formation.
0.4	50.4	Look down to the right (southeast), and see the small thrust fault again.
1.0	51.4	**Stop 9. Top of the Hurricane Cliffs.** Drive up to the radio tower, shown as 'radio facility' on the Pintura, UT, 7.5′ quadrangle, SE1/4, SE1/4, Sec. 23, T.40S, R.13W.
		We are essentially at a fault segment boundary marked by a large bend in the Hurricane fault. The strike of the fault is N13°W to the south (right) along the Ash Creek fault segment and N21°E to the north (left) along the Anderson Junction segment. The local southward decrease in stratigraphic separation is marked across this segment boundary (fig. 6) and is indicative of a boundary that has been a persistent barrier to slip (King, 1986).
		The Quaternary basalt in the footwall of the fault is undated but is assumed to be between 0.3 and 1.1 million years old from dated geochemically similar nearby rocks (Best et al., 1980, Sanchez, 1995). The fault has 450 m of stratigraphic separation on the basalt (fig. 6). In the footwall basalt flowed onto Permian Kaibab Formation and in the hanging wall the basalt overlies Jurassic-Triassic Navajo Sandstone (fig. 2). Thus, it is apparent that the Hurricane fault existed as a normal fault prior to basalt flows. Based on observed relatively similar basalt thicknesses in the hanging wall and footwall, it appears that at the time of the basalt flows, there was very little to no fault escarpment.
		Geochemically identical basalt lies directly below this outcrop and a slip vector was determined to range from 73°, N70°W to 75°, S18°W (fig. 5; Stewart and Taylor, 1996).
		To the west are the Pine Valley Mountains. The Virgin anticline (fig. 11) is exposed in the valley (although this fold is not visible from this vantage).
		Turn around and return along same route to Utah Highway 17.
0.1	51.5	Pass fork on left (east) and continue along dirt road.
0.8	52.3	Pass road on east or left (T intersection).
0.95	53.25	The hill straight ahead (west) contains Moenkopi Formation capped by Shinarump Conglomerate in the tilted block.

1.05 54.3 Cross cattle guard and continue southwest.

0.6 54.9 Turn right (north) off Spring Drive back onto Utah Highway 17 and immediately cross bridge over Ash Creek.

1.5 56.4 The hill on the left (west) is Jurassic-Triassic Navajo Sandstone. On the right (east), Quaternary (?) basalt is exposed. Both of these units lie in the hanging wall of the Hurricane fault.

0.8 57.2 The small, somewhat conical hill at ~10:00 is intrusive rocks, probably related to the Pine Valley laccolith exposed in the Pine Valley Mountains to the west.

0.4 57.6 Take right fork and shortly thereafter take right turn. Just after taking the corner, the Pintura fold is visible in the footwall of the Hurricane fault folding the Permian Pakoon Dolomite, Queantoweap Sandstone, Toroweap Formation, and Kaibab Formation. The Pintura fold is a Mesozoic Sevier Orogeny-related fold and is truncated by the Hurricane fault (fig. 11).

0.45 58.05 Turn right (~east) toward Hurricane fault.

1.0 59.05 **Stop 10. Fault scarps along Ash Creek segment.** The road turns into dirt and then into sand. Park in sandy dune deposit. Note: the road is private property and permission to drive through must be obtained prior to entry.

Walk ~ 0.25 mile to the northeast to two fault scarps in Quaternary-Tertiary alluvium that are next to each other. This stop is on the Pintura, UT, quadrangle, middle of Sec. 23, T.40S, R.13W. The two fault scarps are formed in Quaternary-Tertiary deposits and bedrock. The larger fault scarp has a scarp slope of 30° and a scarp height of 6 m; the smaller scarp has a slope of 15° and is 3 m high; both are down-to-the-west. Scarp slopes were measured from the angle made by the horizontal surface in the footwall of the scarp to the middle of the steep face of the scarp slope using the technique of Bucknam and Anderson (1979). A thin layer of the Quaternary-Tertiary gravel is in the upthrown side of the fault and in the downthrown side the gravel is thicker and overlain by colluvium derived from the Hurricane Cliffs to the east. The Quaternary-Tertiary gravel is an unconsolidated alluvial deposit containing well-rounded boulders shed from west-to-east from the Pine Valley laccolith to the west, as well as cobbles of well-rounded light gray fossiliferous limestone, chert, bedded yellow and brown quartzite, sandstone (Navajo), and clasts of Claron Formation. This unit is of unknown age but is older than the most recent alluvium in the area. The offset Quaternary-Tertiary gravel here is a different composition than the offset sediment at Stop 6 and the morphology of the two sites is noticeably distinct. At this stop scarps have formed in alluvium and bedrock because the bedrock comprises the resistant Pakoon Dolomite and Queantoweap Formation.

To the north along the Ash Creek fault segment, the Hurricane fault is a single surface trace (fig. 6, cross section A-A′). Compare this to the section of the fault at Stop 5, where the fault is a complex zone of multiple fault strands.

Return along same route to stop sign.

1.85 60.9 Turn right (west) at stop sign and in a very short distance turn right onto the on ramp for I-15 N.

9.5 70.4 On the west side of I-15 north of Exit 36 is Ash Creek Reservoir, which was completed in 1960 in conjunction with construction of the Interstate. The natural abutments are highly fractured Quaternary basalt, and consequently the reservoir is permeable and loses water. Poor dam construction caused collapse of the road above the dam in 1969, the first time the reservoir approached its capacity. As a result, the State Engineer imposed water-level restrictions on the reservoir and the spillway was subsequently lowered.

12.6 83.0 Take Exit 40 (east) to the Kolob Canyons section of Zion National Park. Continue past the Visitor's Center into the park.

13.7 97.1 **Stop 11. New Harmony and Kanarraville Basins**. Park on the wide paved shoulder of the road just past a 90° curve (road bends from north to east). Walk west back to the curve and cross the guard rail to a flat, relatively open area west of the road. This stop is on the St. George, UT, 30 x 60′ quadrangle, Sec. 26, T.38S, R.12W.

View west is of the New Harmony basin, flanked by the Pine Valley Mountains on the south and west, and by the Harmony Mountains on the north. The Pine Valley Mountains are underlain by the 21 Ma Pine Valley laccolith and associated volcanic rocks. The steep, rounded peak visible due west is another Miocene intrusion. The Harmony Mountains are underlain by Miocene Quichapa Group volcanic rocks above Tertiary Claron Formation.

Miocene-Pliocene (?) volcaniclastic debris-flow deposits (unit Taf, fig. 7), are exposed on the south flank of the Harmony Mountains. The lower member of unit Taf dips moderately to steeply south towards the basin and is locally overturned. Highly faulted and locally overturned strata of the Quichapa Group and Claron Formation are exposed north of unit Taf. This faulting and tilting is in the hinge area of a tight, east-west trending anticline that is paired with the New Harmony syncline, whose axis lies to the south below unfolded Quaternary deposits (fig. 7). The folding is attributed to Neogene extension-normal shortening in the Basin and Range-Colorado Plateau transition zone and predated the modern expression of the Hurricane fault.

The wooded, north-trending, low ridge west of I-15 is composed of debris-flow deposits derived from the Pine Valley Mountains (unit QTaf, fig. 7). This ridge is interpreted as a gentle anticline related to rollover in the hanging wall of the Hurricane fault. We are standing on the footwall of the Hurricane fault, and the fault trace lies along the sharp break in topography at the base of the Hurricane Cliffs.

View to the north and northeast is of the Kanarraville basin, which trends northeast parallel to the Hurricane fault and is bounded on the west by the Harmony Mountains. Unit Taf forms two subtle, east-dipping hogbacks (lower and upper members) in the eastern foothills of the Harmony Mountains.

Return to vans. Just east of the parking area on the south side of the road, a steeply dipping normal fault juxtaposes Quaternary (?) colluvium, probably derived from the Lower red member of the Triassic Moenkopi Formation, with the Timpoweap Member of the Moenkopi. Farther east, another normal fault juxtaposes the Timpoweap and Lower red member of the Moenkopi. These normal faults are interpreted as subsidiary faults to the Hurricane fault. Normal faults are also exposed along Taylor Creek just east of the Hurricane fault trace and are accessible by hiking down the steep ravine from the overview site.

Return to I-15 and proceed north.

Continue along I-15 to Salt Lake City, Utah.

End of trip

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