Paleoseismologic Investigations of the Hurricane Fault in Southwestern Utah and Northwestern Arizona

Final Project Report

Philip A. Pearthree[1], William R. Lund[2], Heidi D. Stenner[1,3], Benjamin L. Everitt[4]

[1]Principal Investigator, Arizona Geological Survey
416 W. Congress St. Tucson, AZ 85701
(520) 770-3500, e-mail Pearthree_Phil@pop.state.az.us

[2]Co-Principal Investigator, Utah Geological Survey
Southern Utah Regional Office
Southern Utah University, Box 9053, Cedar City, UT 84720
(801) 865-8126, e-mail lund@suu.edu

[3]Department of Geology
Arizona State University, Tempe, AZ 85287
e-mail heidi.stenner@asu.edu

Utah Department of Water Resources
1636 W N Temple, Suite 310, Salt Lake City, Utah 84116
e-mail nrwres.beveritt@state.ut.us

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NON-TECHNICAL PROJECT SUMMARY

The Arizona Geological Survey and the Utah Geological Survey have begun a cooperative research effort to evaluate seismic hazard in southwestern Utah and northwestern Arizona. We have conducted studies that allow us to begin to understand the potential for large, damaging earthquakes on the long, active Hurricane fault zone that cuts through this region. These investigations will significantly improve our understanding of seismic hazard in this rapidly growing region at a time when this information can be incorporated into design standards and building practices.

In Utah, we have visited many sites along the fault and identified several places that are most promising for future, more detailed mapping and trenching investigations. Based on our preliminary work, we believe that most or all of the Hurricane fault in Utah has ruptured in large earthquakes during the past few tens of thousands of years. The youngest large earthquake probably occurred on the northern part of the fault about 10,000 years ago. We also dated a basalt that flowed across the Hurricane fault and has subsequently been displaced by faulting. The part of this flow that is east of the Hurricane fault is now about 330 to 400 meters higher than the part of the flow that is west of the fault. Thus, the flow has been displaced by about 350 meters since it was erupted 850,000 years ago. Using these numbers, we estimate that the long-term slip rate on the fault is about 0.3 to 0.4 mm/year. Preliminary estimates of the slip rate over the past 100,000 years or so are quite a bit less, indicating that the fault may have been less active recently.

We have conducted a more detailed investigation of the Hurricane fault in the area of the Utah-Arizona border, where lots of relatively young geologic deposits have been faulted. We have estimated the ages of some of these deposits and measured their displacement. Using this information, we estimate the slip rate on the fault in this area is about 0.15 to 0.3 mm/year over the past 100,000 years or so. We also excavated several trenches across the fault zone to get a better understanding of the age and the size of the youngest paleoearthquake on this part of the fault. We believe that the youngest paleoearthquake occurred between 5,000 and 10,000 years ago. Displacement in this event was less than 1 meter, and the rupture length may have been 10 to 15 kilometers, so the magnitude was probably around 6.6. We suspect that sometimes this part of the fault is involved in larger displacement, larger magnitude earthquakes that rupture 30 to 40 kilometers of the fault zone at one time.

TECHNICAL ABSTRACT

We have completed initial paleoseismologic investigations to evaluate the recency and size of paleoearthquakes and long-term slip rates on the Hurricane fault in southern Utah and northern Arizona (SUNA). Assessing seismic hazard on the Hurricane fault is important because southwestern Utah is experiencing a more than decades-long construction and population boom. The Hurricane fault is a long, west-dipping normal fault with substantial late Cenozoic displacement within the structural and seismic transition between the Colorado Plateau and the Basin and Range province. Previous reconnaissance studies of the fault in northern Arizona and southern Utah had documented evidence of late Quaternary activity. Because of its great length, the Hurricane fault almost certainly ruptures in segments, and abundant geometric and structural characteristics suggestive of fault segmentation exist along its trace. We have focused our initial efforts to explore the behavior of the Hurricane fault on a systematic, detailed reconnaissance of the fault from the Utah-Arizona border north to Cedar City and a detailed investigation of 20 km of the fault from the border southward into Arizona.

Approximately the northern 80 km of the 250-km-long Hurricane fault trends northward through southwestern Utah to Cedar City. Previously, only one site on the Utah portion of the Hurricane fault was recognized with scarps on unconsolidated deposits and only a few locations were known with late Quaternary bedrock scarps. This study identified five additional sites with scarps on unconsolidated deposits and several more bedrock scarps. The youngest deposits displaced are latest Pleistocene or early Holocene across what may be a single-event scarp at one locality, but large, multiple-event scarps are the rule. The number, type, and preservation of scarps along the fault provide insight into possible seismogenic segmentation. The greatest number and best preserved scarps are at the north end of the fault. A previously undocumented graben parallels the Hurricane fault for at least 17 km along Ash Creek Canyon and displaces geologic units in the hanging wall down-to-the-east, increasing apparent tectonic displacement across the Hurricane fault. Displaced alluvial surfaces at Shurtz Creek, tentatively dated on the basis of soil-profile development, provide a minimum slip rate of 0.11 mm/yr for approximately the past 100,000 years. New $^{40}Ar/^{39}Ar$ age estimates for displaced basalt flows erupted from a volcanic center west of the Hurricane fault near Pintura provide slip rate of 0.39 mm/yr over the past 900,000 years. The most recent surface faulting on the Hurricane fault in Utah occurred in the latest Pleistocene or early Holocene, at the north end of the fault. Multiple surface-faulting earthquakes have occurred in the late Quaternary along most, if not all, of the Utah portion of the fault. The potential for developing information about the size and timing of prehistoric surface-faulting earthquakes is good, and the distribution of potential trench sites is such that it should be possible to determine if several prominent bends in the fault are seismogenic boundaries.

In Arizona just south of the Utah border, we conducted the first detailed study involving trenching of the Hurricane fault to estimate paleoseismic parameters. Recurrent vertical slip in the late Quaternary is indicated by numerous unconsolidated alluvial surfaces containing fault scarps of increasing height with increasing surface age. No evidence for significant Quaternary horizontal offset was observed. Cosmogenic isotope dating and soil development analyses provide age estimates of faulted surfaces. Displacements were measured using trench-exposed stratigraphic relationships and topographic scarp profiles. One-dimensional geomorphic profile modeling of fault scarps provides mass diffusivity values useful for future studies of the region to estimate scarp age. The youngest paleoearthquake along the studied 30 km portion of the Hurricane fault likely occurred 5-10 ka. A 0.60 m vertical displacement during the MRE measured at the trench site at Cottonwood Canyon is likely representative of a 10 km length of fault north of the site, where scarps of similar size and age exist. Another 18 km of fault farther north may have ruptured during this earthquake, but if it did evidence is obscure at the base of the steep Hurricane Cliffs. Statistical relationships between a rupture displacement and the moment magnitude suggest a moment magnitude of 6.6 (6.1-7.0) for the youngest event. At the Cottonwood Canyon site a large fault scarp developed in a 70-125 ka alluvial fan records about 20 m of displacement, yielding a slip rate of 0.15-0.3 mm/yr. The large scarp suggests that the 0.60 m-displacement event is not likely to be typical of previous late Quaternary faulting events recorded at Cottonwood Canyon, because an unlikely number of about 30 such events occurring every 2-4 ka would be required to produce the large scarp. Evidence exists for only one Holocene paleoearthquake, so some previous ruptures on this part of the fault likely were larger than the last and recur at intervals longer than 2-4 ka. The small displacement of the MRE at Cottonwood Canyon may be due to that site's proximity to a potential rupture boundary. Future research on the Hurricane fault in Arizona will be focused the late Quaternary rupture history of the next section of the fault to the south. This should aid in understanding the context of the recent small displacement rupture, and will permit comparison of longer-term slip rates on either side of a potential segment boundary.

CHAPTER 1. INTRODUCTION AND OVERVIEW

Seismic hazard in southwestern Utah and northwestern Arizona is poorly understood because of a lack of information about the size and frequency of occurrence of large, surface-rupturing earthquakes. This rapidly growing area currently has a population of over 50,000 and is crossed by a major north-south transportation route (Interstate Highway 15). Based on historical seismicity, seismic hazard in this region is considered moderate (seismic zone 2B, Uniform Building Code, 1994), and probabilistic estimates of 50-year, 10 percent probability of exceedance accelerations are fairly low (<0.2g; U.S. Geological Survey Seismic Hazard Mapping Program, 1996). Major late Cenozoic normal faults that break the western margin of the Colorado Plateau in this region, however, have substantial Quaternary displacement and likely represent a significant seismic hazard to northwestern Arizona and southwestern Utah. Efforts to characterize the potential for large earthquakes in this region have been fraught with uncertainty, however, because very little is known about the size and timing of Holocene and late Pleistocene surface ruptures or the length of fault segments that might rupture in individual surface ruptures. In this report, we summarize the results of our initial paleoseismologic investigations of the Hurricane fault, which is the most active normal fault in this region.

Extending from Cedar City, Utah, to south of the Grand Canyon at Peach Springs, Arizona, the 250-km-long Hurricane normal fault has produced hundreds to thousands of meters of vertical displacement during the late Cenozoic. It is located within the ~150-km-wide structural and seismic transition between the Colorado Plateau and the Basin and Range province (Figure 1.1). In this transition zone, the generally subhorizontal Paleozoic and Mesozoic strata of the Colorado Plateau are displaced hundreds to thousands of meters down-to-the-west by a series of north-trending normal faults. Displacement across the Hurricane fault is recorded by the impressively steep and linear the Hurricane Cliffs, which closely follow the fault trace. Previous reconnaissance studies of the Hurricane fault documented offset Quaternary basalt flows and alluvium (Anderson and Mehnert, 1979; Pearthree and others, 1983; Menges and Pearthree, 1983; Anderson and Christenson, 1989; Hecker, 1993; Stewart and Taylor, 1996). The Hurricane fault almost certainly ruptures in segments, as has been observed historically for long normal faults (Schwartz and Coppersmith, 1984; Schwartz and Crone, 1985; Machette *et al.*, 1991). Compilations of historic earthquake ruptures show that rupture lengths of 30-40 km are the most common for earthquake magnitudes of 6.75-7.5 (Schwartz and Coppersmith, 1984), although longer ruptures are possible. Although no detailed paleoseismologic investigations have been conducted on the Hurricane fault prior to the work summarized in this report, previous workers have suggested that major convex fault bends and zones of structural complexity are likely candidates for boundaries between seismogenic fault segments (Stewart and Taylor, 1996; Stewart and others, 1997).

Historical seismicity in SUNA has generally been diffuse, with several concentrations of activity and a few moderately large earthquakes. The CP-BR transition is coincident with the Intermountain Seismic Belt (Smith and Sbar, 1974), although this belt of epicenters becomes

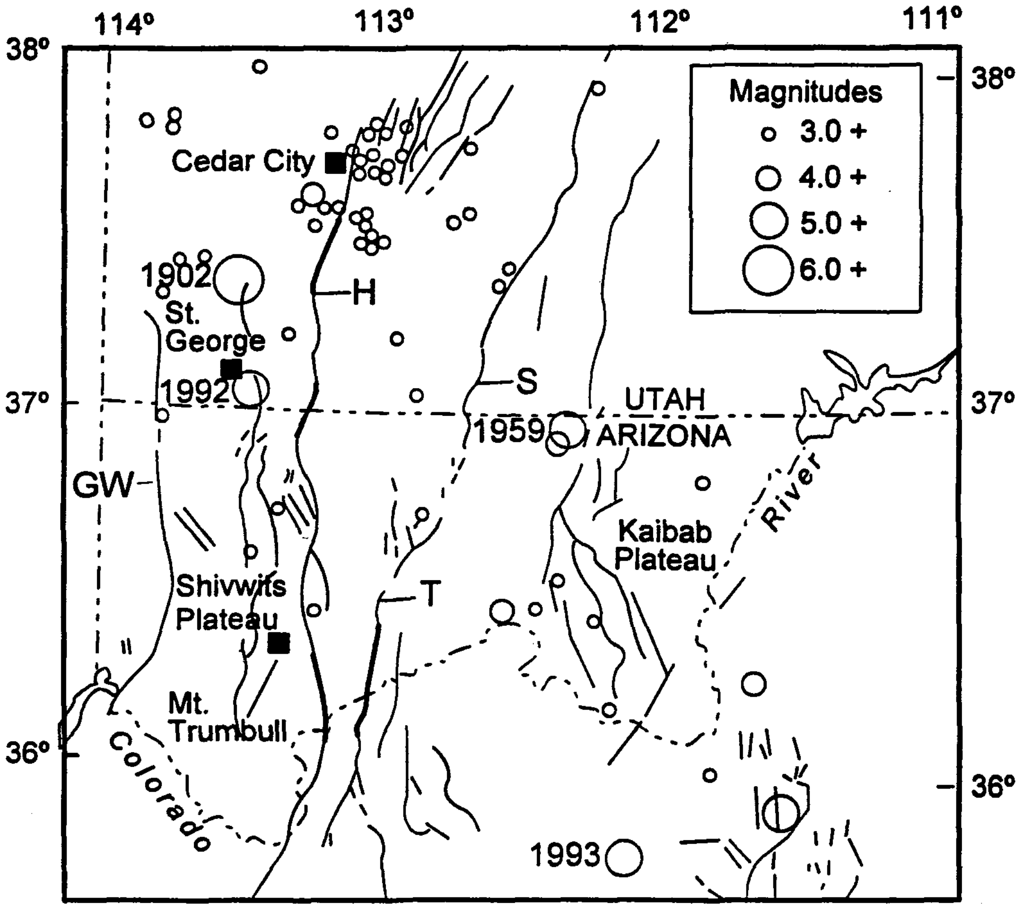

Figure 1.1. Quaternary faults and historical earthquakes in southwestern Utah and northwestern Arizona. Portions of faults with suspected Holocene ruptures are shown with bold lines.

much broader and more poorly defined from north to south. Although surface rupture has not occurred along the Hurricane fault historically, the area has moderate recorded seismicity. Most notable of past seismic events are the 1902 M ~6 Pine Valley, Utah, earthquake and the 1992 M 5.8 St. George, Utah, earthquake (Smith and Arabasz, 1991; Pechmann *et al.*, 1995). Both of these earthquakes are thought to have occurred on or near the Hurricane fault. Based on the hypocentral location, aftershock distribution, nodal plane orientation, and other data, Pechmann *et al.* (1995) concluded that the St. George earthquake occurred from buried slip on the Hurricane fault. Two moderate events (M ~ 5) occurred within a swarm near Cedar City in 1942. Other swarms of activity 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, 1979; Richins et al, 1981). The largest historical earthquake in northwestern Arizona was the 1959 Fredonia, Arizona, earthquake (M~5.7; DuBois et al, 1982). Since 1987 the northwestern part of Arizona has been quite seismically active. There have been more than 40 events with M>2.5; including the 1993 M 5.4 Cataract Creek earthquake located between Flagstaff and the Grand Canyon.

Changing geometries of the Hurricane fault trace have prompted recent workers to divide the fault into geometric segments. These portions of the fault are called "sections" in this report as their status as seismogenic segments has yet to be demonstrated with evidence of different rupture histories across the boundaries (Figure 1.1; Menges and Pearthree, 1983; Stewart and Taylor, 1996; Stewart *et al.*, 1997; Pearthree, 1998). Fault trace complexity and geometry, shortening structures, and scarp morphology are used to define a boundary between the Ash Creek section and the Anderson Junction section (Figure 1.1; Stewart and Taylor, 1996). A potential boundary zone has been identified about 10 km south of the Utah - Arizona border, based on changing cumulative slip measurements and the presence of a large convex bend in the fault trace (Stewart *et al.*, 1997). South of this bend, the Hurricane fault defines the eastern margin of the Shivwitz Plateau; thus, this is named the Shivwitz section. Another boundary zone has been identified at the southern end of the Shivwitz Plateau in the Mt. Trumbull area, where a major discontinuity exists in the fault trace (Menges and Pearthree, 1983; Pearthree, 1998). South of Mt. Trumbull, the Hurricane fault clearly displaces late Quaternary alluvium and basalt flows in Whitmore Canyon. Finally, there is no documented evidence of late Quaternary activity on the section of the fault south of the Colorado River, so this is considered another segment (Pearthree, 1998). Similar, if smaller-scale, changes in fault zone geometry that exist at a number of other locations along the fault are used to delineate shorter fault subdivisions in Utah in this report. Using this nomenclature, the Hurricane fault is divided into five sections that are roughly 40 to 50 km in length.

The research summarized in this report has focused on the Ash Creek and Anderson Junction sections of the Hurricane fault in Utah and the Anderson Junction - Shivwitz boundary zone in northernmost Arizona. These are the portions of the fault that are closest to the growing population centers of southern Utah. The detailed reconnaissance investigations conducted along the fault zone in Utah conducted by the Utah Geological Survey are detailed in Chapter 2 of this report. A detailed investigation of the southernmost Anderson Junction section and the Anderson

Junction - Shivwitz boundary zone was conducted by the Arizona Geological Survey in cooperation with Arizona State University. This investigation is summarized in Chapter 3 of this report. A combined list of references cited is after Chapter 3, and 6 appendices containing soils and fault scarp data are at the end of the report.

CHAPTER 2. RECONNAISSANCE PALEOSEISMIC INVESTIGATION OF THE HURRICANE FAULT IN SOUTHWESTERN UTAH

Including the Ash Creek Section and most of the Anderson Junction Section

by

William R. Lund and Benjamin L. Everitt

Introduction

Approximately 80 kilometers of the 250-kilometer-long Hurricane fault trend in a north-south direction through southwestern Utah (Figure 2.1). A high rate of Quaternary activity on the Utah portion of the fault is indicated by the geomorphology of the high, steep Hurricane Cliffs, that follow the trace of the fault from the Utah/Arizona border to Cedar City, and by Quaternary basalt flows displaced hundreds of meters down-to-the-west across the fault at several locations. However, while recognized as a potential source of large earthquakes in southwestern Utah, the absence of evidence for latest Pleistocene or Holocene rupture has made assessing the seismic hazard presented by the Hurricane fault problematic. Assessing seismic hazard in southwestern Utah is important because Washington and Iron Counties are experiencing a decades-long population and construction boom. The population of Washington County has increased six fold since the 1970s and has doubled since 1985 (Five County Association of Governments, unpublished information, 1998). Iron County's population has more than doubled over the same time period. A proposed pipeline from Lake Powell to the St. George basin, which would cross the Hurricane fault, could provide water for an additional 300,000 residents in southwestern Utah by early in the next century.

Study Goals and Scope of Work

The goals of the Utah portion of the Hurricane fault study are: (1) to determine the relative recency of movement on the fault in Utah, (2) to estimate medium- and long-term slip rates on the fault, and (3) to identify sites suitable for future detailed paleoseismic trenching studies. The scope of work for this investigation included: (1) interpretation of aerial photography along the fault, (2) a field reconnaissance of the Hurricane fault from the Utah/Arizona border to Cedar City, Utah, (3) measuring scarp profiles at key locations along the fault to estimate the amount and age of surface faulting, (4) analysis of soil-profile development to establish relative ages of Quaternary deposits at selected locations along the fault, (5) dating a displaced Quaternary basalt flow and alluvial surfaces to estimate slip rates, (6) geologic mapping, using 1:6000-scale color aerial photographs at sites where detailed information on the age and relation of geologic units to

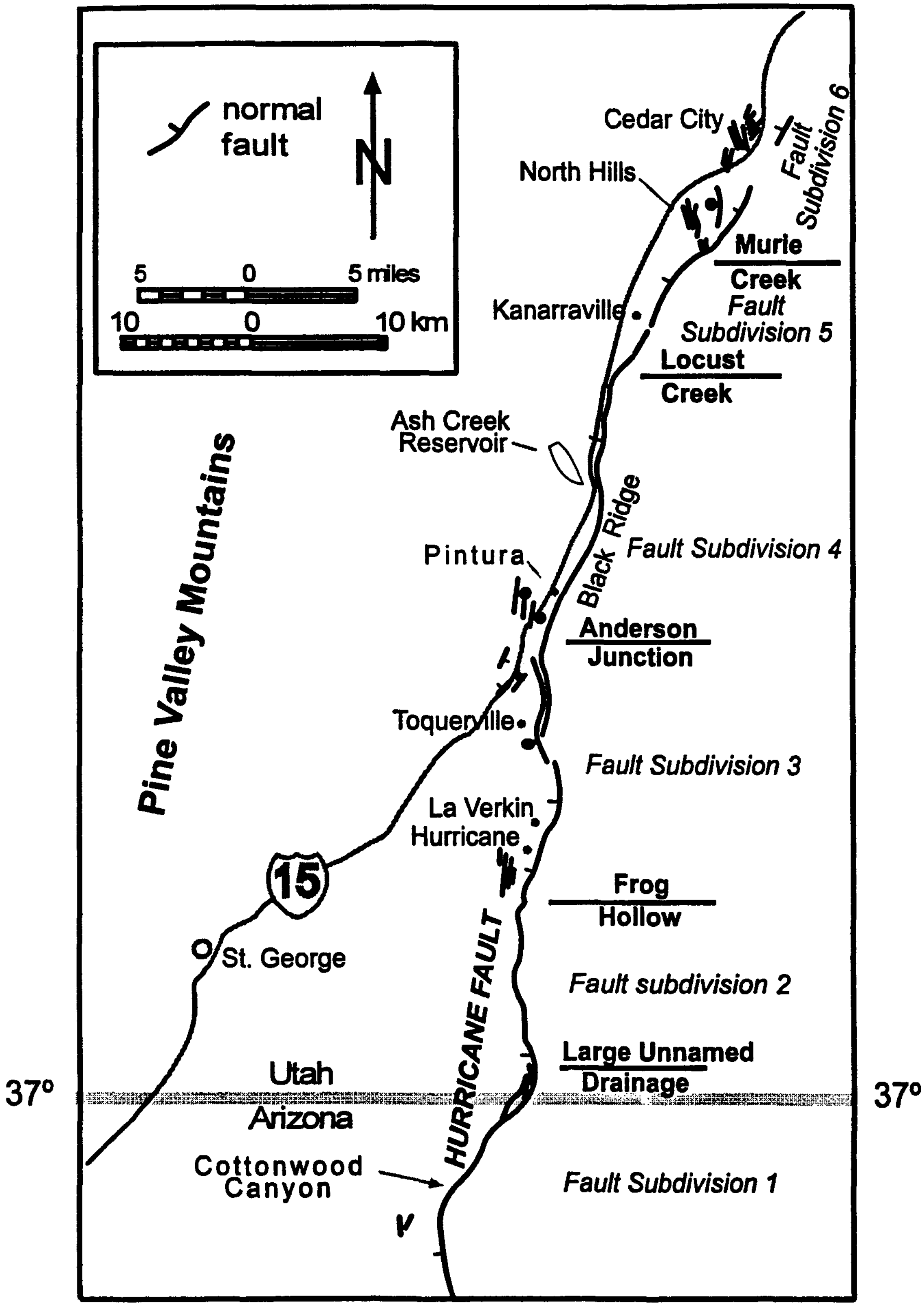

Figure 2.1. Hurricane fault and subsidiary structures in southwestern Utah. Fault section bounderies defined for this study delineated by arrows.

faulting provides insight into the fault's earthquake history, and (7) reconnaissance of displaced basalt flows and antithetic faulting associated with the fault.

Previous Investigations

Geologists have long been interested in the Hurricane fault. Huntington and Goldthwait (1904, 1905) first introduced several important ideas regarding the Hurricane fault including: (1) the fault partially follows an older fold and thrust belt, (2) displacement decreases from north to south, (3) much of the southern escarpment has retreated eastward from the trace of the fault, indicating a long period of quiescence or long recurrence interval, and (4) offset has been episodic through time. Gardner (1941, 1952) provides a general description of the fault in Utah. Averitt (1962, 1969) mapped the Hurricane fault in the Cedar Mountain and Kanarraville quadrangles, and Averitt and Threet (1973) mapped it in the Cedar City quadrangle. Averitt (1964) prepared a chronology of post-Cretaceous geologic events on the Hurricane fault. Kurie (1966) mapped the geology along 32 kilometers of the fault from Anderson Junction, near Toquerville, to Murie Creek, a few kilometers north of Kanarraville. Hamblin (1963, 1970a, 1987) studied late Cenozoic basalts along and near the fault in southwestern Utah and northwestern Arizona. His observations regarding displaced basalt flows resulted in several papers on the tectonics of the Hurricane fault (Hamblin, 1965a, 1965b, 1970b, 1984; Hamblin and Best, 1970; Hamblin and others, 1981). Anderson and Mehnert (1979) reinterpreted the history of the Hurricane fault, refuting several key elements of Averitt's (1964) fault chronology. They also provided a revised estimate of total net vertical displacement across the fault in Utah.

Several seismotectonic studies have been conducted along or near the Hurricane fault in Utah. Earth Science Associates (1982) mapped generalized surficial geology and photo lineaments along the fault and trenched scarps and sites of photo lineaments that cross U.S. Soil Conservation Service (now National Resource Conservation Service) flood-retention structures. Based on historical seismicity and existing geologic data they estimated the average return period for large, surface-faulting earthquakes (M 7.5) on the Hurricane fault as 1000-10,000 years. Anderson and Christenson (1989) compiled a 1:250,000-scale map of Quaternary faults, folds, and selected volcanic features in the Cedar City 1°x2° quadrangle based on existing data and reconnaissance field work. The apparent absence of young fault scarps in unconsolidated deposits along the fault in Utah led them to conclude that a surface-faulting earthquake probably had not occurred there in the Holocene. They noted that a lack of Holocene activity on the fault seems inconsistent with the high Quaternary slip rate derived from displaced Quaternary basalts (Anderson and Mehnert, 1979; Hamblin and others, 1981). Hecker (1993) included the Hurricane fault in her 1:500,000-scale compilation of Quaternary tectonic features in Utah and assigned a probable age of late Pleistocene (10 to 130 ka) to the time of most recent deformation. A structural analysis by Schramm (1994) of a complex portion of the Hurricane fault near Anderson Junction (Figure 2.1) showed that movement on the fault there is predominantly dip-slip with a slight right-lateral component. Stewart and Taylor (1996), and Stewart and others (1997) defined a structural and possibly a seismogenic (earthquake) boundary at the large geometric bend in the Hurricane fault near Anderson Junction.

Christenson and Deen (1983) and Christenson (1992) reported on the engineering geology of the St. George area and discussed seismic hazards associated with the Hurricane and other Quaternary faults in the area. Christenson and others (1987) and Christenson and Nava (1992) included the Hurricane fault and other potentially active faults in southwestern Utah in their reports on Quaternary faults and seismic hazards in western Utah, and earthquake hazards in southwestern Utah, respectively. Williams and Tapper (1953) discussed the earthquake history of Utah including the 1902, M 6.3 Pine Valley earthquake. Christenson (1995) provided a comprehensive review of the 1992, M_L 5.8 St. George earthquake, which likely occurred on the Hurricane fault. Stewart and others (1997) included a review of seismicity and seismic hazards in southwestern Utah and northwestern Arizona in their review of the neotectonics of the Hurricane fault.

Physiography and General Geology

Beginning at the Utah/Arizona border the Hurricane fault trends generally north and then northeast, giving the structure a distinct "dog-leg" trace in Utah (Figure 2.1). This irregular trace is likely related to underlying crustal structure (Best and Hamblin, 1970; Hamblin, 1970b). The Hurricane fault is typically expressed as a narrow (seldom exceeding 0.5 kilometers wide), complex zone of sub-parallel, en echelon, high-angle, west-dipping normal faults that displace Paleozoic, Mesozoic, and Cenozoic rocks including Quaternary basalt flows (Hamblin, 1970a; Hintze, 1988; Figure 2.2). South of Anderson Junction (Figure 2.1), the fault cuts relatively undeformed, gently east-dipping Permian, Triassic, and Jurassic sedimentary rocks and Quaternary basalt. At Anderson Junction, the north-trending Hurricane fault intersects a northeast-trending zone of Sevier-age folds and thrust faults, the Kanarra fold of Gregory and Williams (1947), that deform Paleozoic and Mesozoic rocks (Armstrong, 1968; Anderson and Mehnert, 1979; Cowan and Bruhn, 1992). At that intersection, the Hurricane fault veers to the northeast and follows the fold and thrust belt to Cedar City, displacing the deformed Paleozoic and Mesozoic rocks, the overlying undeformed Cenozoic sedimentary rocks, and Quaternary basalt flows across a narrow fault zone (Cook, 1960; Averitt, 1962, 1969; Averitt and Threet, 1973; Kurie, 1966; Hurlow, 1998).

Total stratigraphic separation increases along the Hurricane fault from south to north (Huntington and Goldthwait 1904, 1905; Gardner, 1941, 1952). Published estimates of normal separation on the fault in Utah range from 430 to 4000 meters (Anderson, 1980). Anderson and Christenson (1989) believe this large discrepancy arises from the failure of several investigators to subtract from the total apparent throw: (1) pre-fault folding of Sevier age along the northern 50 kilometers of the fault (Kurie, 1966), (2) reverse-drag flexing of the hanging wall (Hamblin, 1965a, 1970b), and (3) rise-to-the-fault flexing of the footwall (Kurie, 1966; Hamblin, 1970b). Using unpublished mapping, Anderson and Christenson (1989) constructed apparent dip components using 3-point solutions at sufficient distance from the fault to be representative of block interiors and projected those to the fault to measure throw. They obtained tectonic displacements (Swan and others, 1980) of 1100 and 1500 meters near St. George and

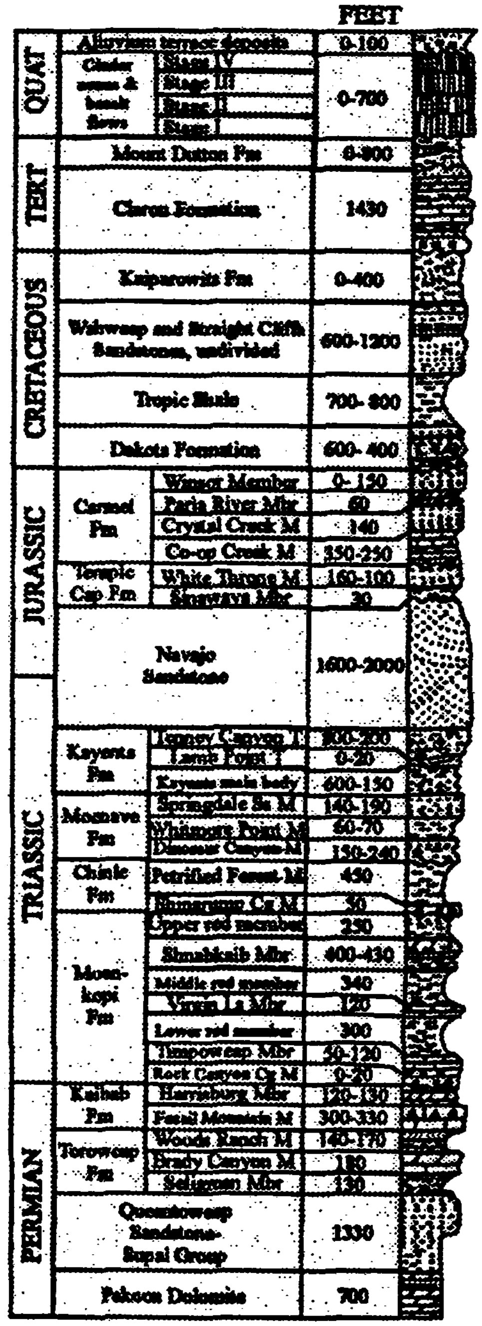

Figure 2.2. Stratitigraphic column from the Zion National Park - Cedar Breaks area, southwestern Utah (modified from Hintze [1988] and Stokes [1986])

Toquerville, respectively, and doubt that tectonic displacement or throw exceeds 2 kilometers anywhere on the Hurricane fault.

Following a detailed structural analysis of a portion of the Hurricane fault near Anderson Junction, Stewart and Taylor (1996) documented 450 meters of stratigraphic separation on Quaternary basalt and a total stratigraphic separation of up to 2520 meters across the fault. Because the basalt is displaced less than the older sedimentary rocks, they concluded that motion on the fault had to initiate prior to basalt volcanism and believe movement likely began as early as late Miocene or early Pliocene. Other workers assign the age of onset of motion on the Hurricane fault in Utah to the Miocene (Gardner, 1941; Averitt, 1964; Hamblin, 1970b), or contemporaneously with intrusion of the Pine Valley laccolith west of the fault (Cook, 1957). Others believe motion began in the late Pliocene or Pleistocene (Anderson and Mehnert, 1979; Anderson and Christenson, 1989).

Because of its great length, the Hurricane fault almost certainly ruptures in segments. Stewart and Taylor (1996) used hanging-wall and footwall shortening structures, fault geometry, increased complexity of faulting, and scarp morphology to define a fault segment boundary near Anderson Junction (Figure 2.3) where the fault bends to the northeast after intersecting the Sevier-age fold and thrust belt. They named the fault segment north of the boundary the Ash Creek segment, and believe it may be as much as 24 kilometers long (straight-line distance) based on map-view geometry and major changes in fault strike. South of the boundary, they named the Anderson Junction segment, which is at least 19 kilometers long or at most 45 kilometers long (straight-line distance) based on the same criteria. However, Stewart and Taylor (1996) note that a 45-kilometer fault segment length for the Anderson Junction segment is longer than general maximum segment lengths for normal-slip faults (Jackson and White, 1989; dePolo and others, 1991). As was noted earlier, we prefer to use the term "sections" for portions of the fault that may rupture in individual earthquakes, pending further paleoseismologic investigations to demonstrate such behavior.

Anderson and Christenson's (1989) reconnaissance of Quaternary tectonic features in the Cedar City 1°x2° quadrangle included the Utah portion of the Hurricane fault. They noted the conspicuous fault scarp first described by Averitt (1962) on a range-front strand of the Hurricane fault at Shurtz Creek about 8 kilometers south of Cedar City (Figure 2.3). The scarp is formed on coarse bouldery alluvium and is deeply incised by Shurtz Creek. They also noted three other kinds of geomorphic features that they interpreted as indicating late Pleistocene or younger surface displacement. Those features included: (1) several locations along the fault between Cedar City and Ash Creek Reservoir where short, steep sections at the base of the Hurricane Cliffs are formed on claystone and evaporite-bearing siltstone of the relatively nonresistant, Mesozoic Moenkopi and Chinle Formations, (2) several small areas at the base of the Hurricane Cliffs between Pintura and Anderson Junction where pediment-mantled bedrock is displaced across steep, bedrock-cored scarps (see also Stewart and Taylor, 1996), and (3) sharp nick points where small and intermediate transverse ephemeral drainages formed in resistant Paleozoic rocks cross the Hurricane Cliffs. Anderson and Christenson (1989) interpreted these three kinds of features along with the scarp at Shurtz Creek as evidence for a substantial rate of late Pleistocene

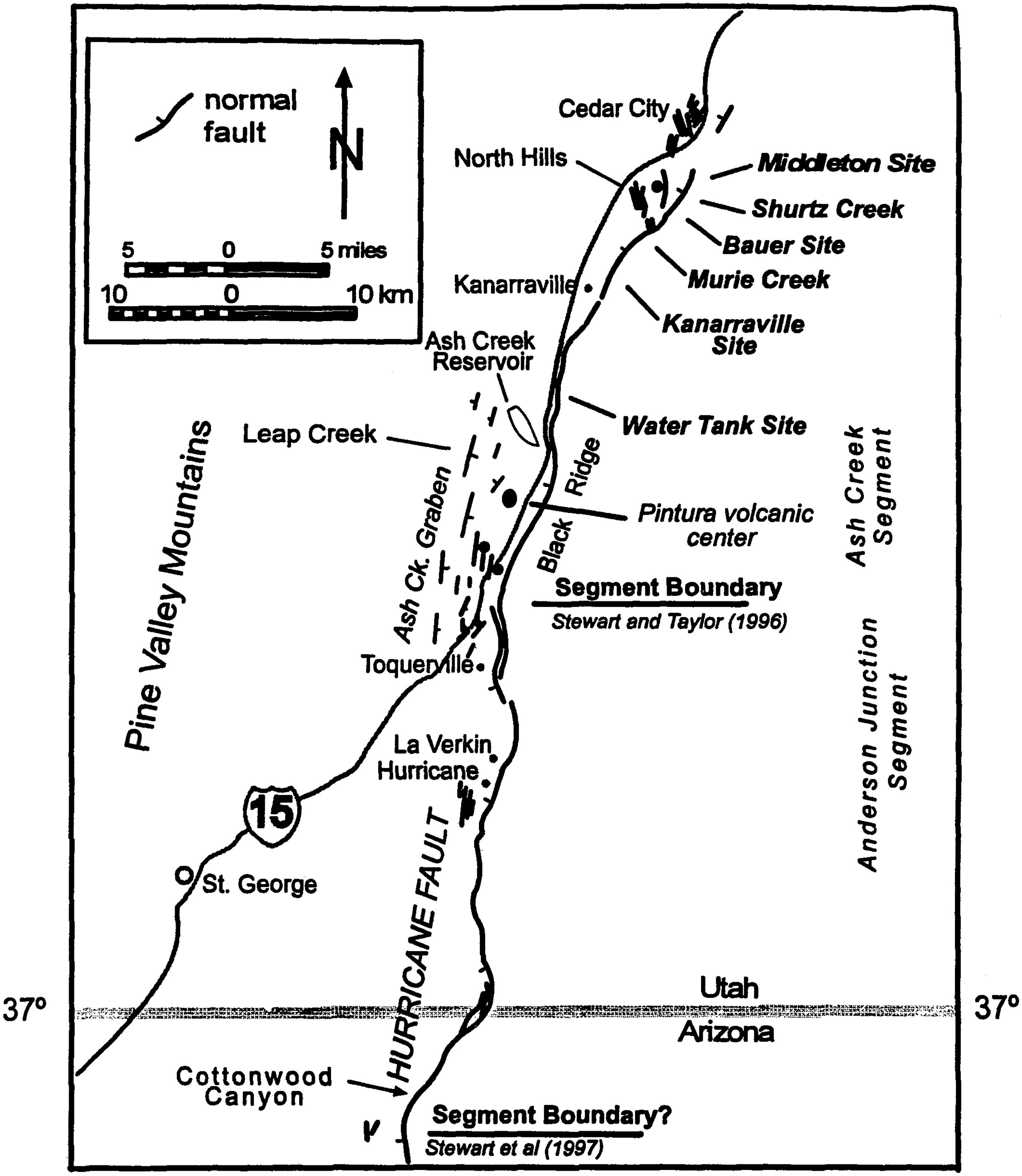

Figure 2.3. Hurricane fault in southwestern Utah showing sites with scarps on unconsolidated deposits; segment boundary of Stewart and Taylor (1996) shown with large arrow. Ash Creek graben and the Pintura volcanic center are also shown.

surface displacement on the Utah portion of the Hurricane fault, but were unable to document Holocene displacement. While not precluding the possibility of Holocene offset; they speculated that the time since the last surface-faulting earthquake on the Utah portion of the fault is probably greater than 10,000 years.

Field Reconnaissance

To document possible geologically recent faulting on the Utah portion of the Hurricane fault, we interpreted 1:24,000-scale, low-sun-angle (a.m.), black and white aerial photography to identify possible fault scarps, and made a systematic field reconnaissance along the fault from the Utah/Arizona border to Cedar City. Results of the reconnaissance are summarized below by "fault subdivision." Each fault subdivision represents a portion of the fault from 10 to 22.5 kilometers long that is constrained by changes in fault strike (bends) and generally similar geomorphic characteristics along its length (Figure 2.1). Thus, they represent shorter portions of the fault than the "segments" or "sections" described earlier. Two bends in the fault, one in Utah and the other in Arizona, have been identified as structural, and possibly seismogenic, fault segment boundaries (Stewart and Taylor, 1996; Stewart and others, 1997). Other bends may also be segment boundaries; however, additional detailed study is required to make that determination. Therefore, the term "fault subdivision" is used here in a purely descriptive manner for ease of discussion. Lengths of the fault subdivisions reported below are measured along strike. Details of the reconnaissance are presented in Appendix 1.

Fault Subdivision 1: Utah/Arizona Border to Large Unnamed Drainage

From the Utah/Arizona border, the Hurricane fault strikes N30°E for 1.5 kilometers to a large, unnamed, ephemeral drainage incised in the Hurricane Cliffs (sec. 26, T. 43 S., R. 13 W.). At the drainage, the fault changes strike abruptly to N5°W, creating a sharp bend in the fault trace (Figure 2.1). Southward into Arizona, the Hurricane fault continues on a trend of about N30°E for approximately 10 kilometers to another prominent bend in the fault just south of Cottonwood Canyon (see Stenner and Pearthree, this report). The 10 kilometers of the fault in Arizona and the contiguous 1.5 kilometers in Utah form a single fault subdivision as defined above. Along this fault subdivision, the Hurricane fault forms a narrow zone marked by a high, steep cliff with resistant, buff and yellow-tan Paleozoic limestone and sandstone in the footwall and less resistant, red Mesozoic claystone, siltstone, and sandstone in the hanging wall. The base of the Hurricane Cliffs is mantled by a nearly continuous colluvial apron, and alluvial fans have formed where ephemeral drainages issue from the Hurricane Cliffs.

Between the state border and the unnamed ephemeral drainage, short, likely colluvium-mantled bedrock scarps are present at isolated locations usually several tens of meters west of the base of the Hurricane Cliffs (FS1-1, FS1-2; Appendix 1). The colluvial apron between the cliffs and the trace of the fault (scarps) is mostly a thin mantle on a bedrock pediment indicating considerable retreat of the Hurricane Cliff escarpment since the onset of most recent displacement. The scarps are as much as 6 meters high, indicating recurrent surface-faulting earthquakes during the late Quaternary. However, at the mouth of the large unnamed ephemeral wash, young (likely middle to late Holocene) stream-terrace deposits extend across the projected trace of the Hurricane fault and are not displaced (FS1-3; Table 2.1), indicating an absence of geologically recent faulting.

Fault Subdivision 2: Large Unnamed Drainage to Frog Hollow

The Hurricane fault trends generally north-south for 12.5 kilometers from the large, unnamed drainage to Frog Hollow (sec. 15, T. 42 S., R. 13 W.) where the fault bends to the northeast. Along this fault subdivision, the Hurricane fault forms a narrow zone marked by a high, steep cliff with resistant, buff and yellow-tan Paleozoic rock in the footwall and less resistant, red Mesozoic rock in the hanging wall. The base of the Hurricane Cliffs is mantled by a nearly continuous colluvial apron, and alluvial fans have formed where ephemeral drainages issue from the Hurricane Cliffs.

Along this subdivision of the fault, evidence of geologically recent (late Quaternary) faulting is poorly preserved if present at all. A possible scarp about 5 meters high (FS2-2; Appendix 1) is present at the mouth of a small wash at the base of the Hurricane Cliffs about 5 kilometers north of the large unnamed ephemeral drainage that marks the southern end of this fault subdivision. The scarp is formed on very coarse, bouldery alluvium, and the ephemeral stream from the small wash has incised through it. Examination of the walls of the drainage showed no evidence of faulting or that the scarp is bedrock cored. Elsewhere, slight inflections in topography are present near the apices of some alluvial fans at the base of the Hurricane Cliffs. A deeply incised dry wash about 7.5 kilometers south of the Hurricane City airport exposes a steeply dipping fault contact between bedrock and older colluvium (FS2-3; Appendix 1). About 2 meters of unfaulted younger colluvium overlies the faulted deposits. The near absence of scarps on this subdivision of the fault, combined with stratigraphic relations in the fault zone indicative of no recent faulting, implies either a long period of quiescence since the last surface-faulting earthquake, or that the trace of the active fault is in bedrock high in the Hurricane Cliffs above the colluvium and alluvial fans.

Fault Subdivision 3: Frog Hollow to Anderson Junction

At Frog Hollow, the Hurricane fault begins a broad, 18-kilometer-long, Z-bend that extends to near Anderson Junction (SW1/4 sec. 23, T. 40 S., R. 13 W.). The strike of the fault changes through the bend and varies from about N35°E to N10°W. The communities of Hurricane, La Verkin, and Toquerville are on this fault subdivision, making it the most urbanized portion of the Hurricane fault. In many areas, development now extends onto the fault zone.

We could not positively identify any scarps along this fault subdivision; however, the fault is exposed in bedrock at several locations. Where exposed, the fault plane typically dips steeply to the west, and at one location (FS3-1; Appendix 1) slickenlines rake 86 degrees to the north, indicating a small component of right-lateral motion. An incised stream at La Verkin exposes bedrock in fault contact with older alluvium (FS3-6; Appendix 1; Stewart and Taylor, 1996). Unfaulted younger alluvium overlies the faulted units and no scarp is present. The north wall of a gravel pit in the town of Hurricane exposes a similar stratigraphic relation (FS3-3; Appendix 1). There, older colluvium is in fault contact with bedrock, but the faulted units are overlain by younger, unfaulted deposits with no scarp.

From near La Verkin to Anderson Junction, the Hurricane fault forms a wide zone (up to 1.5 kilometers) with several subparallel, west- and smaller east-dipping faults that displace the Mesozoic Moenkopi Formation incrementally down-to-the-west (Stewart and Taylor, 1996; Biek, in press). Unconsolidated deposits are generally absent along this part of the fault, but fault exposures in bedrock are common.

Fault Subdivision 4: Anderson Junction to Locust Creek

At Anderson Junction, the Hurricane fault bends to the east and trends generally N15°E for 22.5 kilometers to Locust Creek (sec. 16, T. 38 , R. 12 W.), about 6 kilometers south of Kanarraville (Figure 2.1). This subdivision of the fault follows the west limb of the Kanarra anticline (Gregory and Williams, 1947). From Anderson Junction to near Ash Creek Reservoir, the fault parallels Ash Creek Canyon at the base of Black Ridge (the Hurricane Cliffs). From Ash Creek Reservoir to Locust Creek, the Hurricane Cliffs (fault) form the east side of Cedar Valley.

Several short, isolated, colluvium-mantled bedrock scarps (FS4-3, FS4-11; Appendix 1) formed on resistant Paleozoic rock are present several tens of meters west of the base of Black Ridge from Anderson Junction to north of Pintura (Anderson and Christenson, 1989). The separation of the scarps from the base of the Hurricane Cliffs indicates considerable cliff retreat occurred prior to the onset of most recent surface faulting. Stewart and Taylor (1996) believed these scarps to be formed on "unconsolidated Quaternary gravel or alluvium," and cite them as evidence for geologically young displacement. However, the scarps are cored with bedrock and mantled with a thin layer of colluvium (Anderson and Christenson, 1989; this reconnaissance). The resistant bedrock core accounts for the steep slopes (~30 degrees) and considerable height (nearly 40 meters in some instances) of the scarps. Exposures in the walls of ephemeral drainages incised through the scarps show that the fault is overlain by unfaulted colluvium (FS4-4, Appendix 1), indicating an absence of geologically young (latest Pleistocene or Holocene) surface faulting.

Northward along the base of Black Ridge, large alluvial fans and talus slopes mantle the lower one-third of the ridge and show no evidence of fault displacement where they cross the inferred trace of the Hurricane fault (FS4-8; Appendix 1). Either the fans and talus post-date the most recent surface faulting, or the fault is higher on Black Ridge, concealed in the steep, rugged bedrock of the Hurricane Cliffs. Several large scarps are present in talus and suspected landslide deposits near the north end of Black Ridge (FS4-12, FS4-13; Appendix 1). The origin of these scarps is uncertain, but they do not appear to be caused by faulting and are likely related to slope failures in the underlying Moenkopi and Chinle Formations. A stream channel near Pintura exposes bedrock in fault contact with older alluvium (FS4-7). The fault dips 66 degrees to the northwest and the alluvium is tilted toward the west. A second exposure in the same drainage shows the fault dipping 52 degrees to the northwest and slickenlines raking 88 degrees to the north (FS4-7).

From Ash Creek Reservoir to Locust Creek, the fault is generally characterized by a steep, straight cliff with resistant, buff-colored Paleozoic limestone in the footwall and softer Mesozoic sedimentary rocks in the hanging wall. Several ephemeral streams cross this subdivision of the fault and have pronounced nick points at or near the fault trace. Scarps are mostly absent except for a pair of short, subparallel scarps about 1 kilometer south of the Kolob entrance to Zion National Park (FS4-16; Appendix 1). The eastern scarp is almost 13 meters high and appears similar to the large, colluvium-mantled bedrock scarps observed elsewhere on this subdivision of the fault. The smaller, western scarp is 4.5 meters high and is on alluvium. It is eroded in several places and buried or partially buried in others. This is the first scarp recognized north of the Arizona/Utah border that is unequivocally formed on unconsolidated deposits. The two scarps are located close to a large water tank near the base of the Hurricane Cliffs, so this location is hereafter referred to as the Water Tank site.

South of the Water Tank site, a bedrock fault is exposed where a small ephemeral drainage has incised the Hurricane Cliffs near Ash Creek Reservoir (FS4-15; Appendix 1). The fault brings yellow-tan Paleozoic limestone in the footwall into contact with red Mesozoic sedimentary rock in the hanging wall. Where observed in the north side of the drainage, several meters of apparently unfaulted colluvium overlie the faulted bedrock. This fault is likely subsidiary to the main Hurricane fault to the west, and may either no longer be active or may not be active during every surface-faulting earthquake on the main fault.

Fault Subdivision 5: Locust Creek to Murie Creek

At Locust Creek, the Hurricane fault bends farther east and trends N30°E for about 10 kilometers to Murie Creek (sec. 24, T. 37 S., R. 12 W.). The Hurricane Cliffs along this subdivision of the fault are straight and steep and are crossed by several ephemeral and three perennial streams. The ephemeral streams generally have pronounced nick points at the fault, whereas the perennial streams have incised through the cliffs and are graded to the floor of Cedar Valley. All of the streams have deposited alluvial fans where they issue from the cliffs. A number of possible scarps are formed on older colluvium along the base of the Hurricane Cliffs from Locust Creek to Kanarraville (FS5-1, FS5-2, FS5-4; Appendix 1). These features are short and generally much modified by erosion, and some may owe their origin to a process other than faulting. Some or all of these features may be bedrock cored, but bedrock does not crop out at the surface. Alluvial fans at the mouths of the perennial and ephemeral streams between Locust Creek and Kanarraville are geologically young (at least in part Holocene) and are not displaced.

About 1 kilometer north of Kanarraville, a short scarp about 5 meters high is formed on an older alluvial fan at the mouth of a small ephemeral drainage at the base of the Hurricane Cliffs (Figure 2.3; FS5-5, Appendix 1). The stream has incised through the scarp, and only about 10 meters of scarp are preserved along strike. A younger fan has formed where the ephemeral stream issues from the scarp. A little-used, two-wheel, dirt track at the base of the scarp has diverted the stream creating a gully that has eroded the toe of the scarp. The faulted alluvial fan sits as a remnant above the present drainage, and is probably late Pleistocene in age. Because of its proximity to the town, this location is referred to as the Kanarraville site.

The longest and best preserved scarps formed on unconsolidated deposits on the Utah portion of the Hurricane fault are at Murie Creek (Figure 2.3). The scarps are located where the fault bends to the east at the northern terminus of fault subdivision 5. A three-meter-high scarp displaces geologically young, likely latest Pleistocene or early Holocene, alluvial-fan deposits at the mouth of a small ephemeral drainage about 0.5 kilometers south of where Murie Creek enters Cedar Valley (FS5-6; Appendix 1). North of the young scarp, a second scarp is formed in colluvium at the base of the Hurricane Cliffs (FS5-7; Appendix 1). This scarp is more than 200 meters long, generally 10 or more meters high, and has a pronounced bevel, indicating multiple surface-faulting earthquakes.

Fault Subdivision 6: Murie Creek to Cedar City

At Murie Creek, the Hurricane fault begins a pronounced 16.5-kilometer-long bend to the east and north, trending as much as N45°E, before turning back to the north near Shurtz Creek (sec. 9, T. 37 S., R. 11 W.), and finally trending nearly due north at Cedar City. For this report, this portion of the fault is considered a single fault subdivision, but about a kilometer north of Shurtz Creek, a large, prehistoric landslide complex in the Hurricane Cliffs extends to Cedar Valley (Averitt, 1962; Averitt and Threet, 1973; Harty, 1992) burying the trace of the Hurricane fault and dividing this fault subdivision into two unequal parts.

Between Murie Creek and the southern limit of the landslide complex, the Hurricane fault passes close to and east of the North Hills (Figure 2.3), a structurally and stratigraphically complex range of low hills (Anderson and Mehnert, 1979) in the hanging wall of the fault. Relatively soft Mesozoic sedimentary rocks crop out in the Hurricane Cliffs along this subdivision of the fault, giving the cliffs a less steep and rugged character. Both perennial and ephemeral streams cross the Hurricane Cliffs and alluvial fans have formed at the mouths of most drainages. Shurtz Creek is the largest of these drainages. Averitt (1962) mapped an extensive pediment deposit in the Shurtz Creek drainage basin and in the drainage basin of an adjoining, smaller ephemeral stream to the north. The Hurricane fault displaces the pediment deposit at the base of the Hurricane Cliffs both at Shurtz Creek (FS6-6; Appendix 1) and where the smaller ephemeral stream issues from the cliffs about a kilometer north of Shurtz Creek (FS6-8; Appendix 1). Both streams have incised the fault scarps, and younger alluvial fans have formed on the downthrown side of the fault. Poorly preserved stream terraces along both Shurtz Creek (FS6-7; Appendix 1) and the small drainage to the north (FS6-8; Appendix 1) may be tectonically related. The site north of Shurtz Creek, which consists of three subparallel scarps, is referred to as the Middleton site, after the owner of the property.

About 2.5 kilometers south of Shurtz Creek, the Hurricane fault displaces an alluvial-fan deposit at the mouth of a second small, ephemeral drainage. Here, as at the Middleton site, the alluvial-fan surface is displaced across three subparallel fault scarps (FS6-1; Appendix 1). This location is referred to as the Bauer site, also after the property owner. Between the Bauer site and Shurtz Creek, small fault scarps may be present on alluvial deposits at the base of the Hurricane Cliffs (FS6-2, FS6-3, FS6-5; Appendix 1). However, the area has been chained and rough graded for agricultural purposes, making identification of scarps uncertain.

The landslide complex begins just north of the Middleton site, and obscures the trace of the fault for a distance of about 4 kilometers. Interpretation of aerial photographs revealed numerous scarp-like lineaments within the landslide complex (FS6-11, FS6-12; Appendix 1); however, they are not on trend with the Hurricane fault either to the north or south, and do not appear related to faulting. They more likely are related to movement of the landslide complex. The landslide surface is rugged and heavily forested. A scarp, especially a small one, could possibly be obscured by the trees, or not be visible on 1:24,000-scale aerial photographs for some other reason. Therefore, the relation between the age of the landslide complex and the age of most recent surface faulting on the Hurricane fault remains undetermined.

North of the landslide complex, basin-fill deposits conceal the Hurricane fault (Averitt and Threet, 1973). Squaw Creek flows west until issuing from the Hurricane Cliffs just east of Cedar City (FS6-13; Table 2.1). The stream then makes a sharp bend to the north and parallels the cliffs until reaching Coal Creek. A graben along the fault may divert Squaw Creek, but the area is now urbanized and highly disturbed making geologic relations obscure. This stream diversion is the only evidence of possibly young faulting observed north of the landslide complex. Mesozoic-age sedimentary rocks crop out in the Hurricane Cliffs east of Cedar City. They strike north and dip east before swinging to strike northwest and dip northeast, forming what appears to be the east limb and nose, respectively, of a north-plunging anticline (although it was not mapped as such by Averitt and Threet [1973]). The nose of the anticline is cut by a number of minor faults, but is not displaced by the Hurricane fault. Therefore, the Hurricane fault must either end abruptly at Cedar City (Averitt and Threet, 1973), or swing sharply to the west beneath Cedar Valley and away from the Hurricane Cliffs and toward the East and West Red Hills faults (Maldonado and others, 1997). Resolution of that issue is beyond the scope of this study.

Discussion

Age of Young Faulting. Fault scarps, particularly on unconsolidated deposits of geologically young age, provide strong evidence for recent surface faulting. Correspondingly, the absence or near absence of scarps is an indicator of reduced activity or fault quiescence. Long, high, continuous scarps on alluvium and other geomorphic evidence of young displacement are characteristic of the active Wasatch fault in northern Utah (Personius, 1990; Machette, 1992; Personius and Scott, 1992; Nelson and Personius, 1993; Harty and others, 1997). Consequently, the Wasatch fault has been the subject of detailed paleoseismic study (for example, Lund and others, 1991; Black and others, 1996; Lund and Black, 1998). Results of those studies show that the Wasatch fault has experienced numerous prehistoric surface-faulting earthquakes, and can be divided into seismogenic segments based on differences in the timing of those events. The seismogenic segment boundaries are in general accord with recognized geometric and structural discontinuities along the fault. The six central segments all have had at least one surface-faulting earthquake in the Holocene and most have had two or more Holocene events.

Comparatively, the Hurricane fault has few young scarps along its length in Utah, and an even smaller number of those are formed on unconsolidated deposits. Prior to this study, only one scarp on unconsolidated material, at Shurtz Creek (Averitt, 1962; Anderson and Christenson, 1989), was recognized in Utah. We identified an additional five locations, all toward the north end of the fault. At Murie Creek, probable latest Pleistocene or early Holocene alluvial-fan deposits are displaced across what appears to be a single-event scarp. Additionally, we identified a number of previously unrecognized, likely bedrock-cored scarps at other locations (Appendix 1). This new information on scarp abundance, location, and type shows that: (1) at a minimum, the northernmost part of the Hurricane fault experienced at least one surface-faulting earthquake in the early Holocene or latest Pleistocene, and (2) the height, and at some locations the beveled nature, of many scarps indicates that multiple surface-faulting events have occurred on the Utah portion of the fault in the late Quaternary. Clearly, the Hurricane fault has not been as active during the late Quaternary as the Wasatch fault to the north (Anderson and Christenson, 1989). However, some parts of the Hurricane fault have been active more recently, possibly during the Holocene, than previously thought (Anderson and Christenson, 1989), and multiple large events have occurred within a time frame of importance to seismic-hazard analysis.

Variations in Slip Rate Along the Fault. Stewart and Taylor (1996) used differences in fault slip rate expressed by the presence and absence of fault scarps, as one line of evidence for placing a segment boundary on the Hurricane fault near Anderson Junction (Figure 2.3). Because they used slip rate as one criterion for their boundary, it is implicit that they were defining a seismogenic boundary separating fault segments independently capable of producing surface-faulting earthquakes. Based largely on fault-bend geometry, they speculate that the adjoining Ash Creek segment to the north is 24 kilometers long, and the Anderson Junction segment to the south is 19-45 kilometers long, but note that "the non-adjacent segment terminations remain poorly defined."

For the 11 historical earthquakes in the Basin and Range Province, structural and geometric segments fall into three groups: 8.5-12 kilometers, 17-23 kilometers, and 30-39 kilometers (dePolo and others, 1991). In several of those historical events, surface faulting ruptured through or occurred on both sides of pronounced geometric and structural fault discontinuities, indicating that some seismogenic segment boundaries may be difficult to identify and that significant faulting may occur beyond recognized discontinuities (dePolo and others, 1991). Therefore, while several lines of supporting evidence are preferred when establishing fault segment boundaries, the only conclusive evidence for a seismogenic boundary is a difference in timing of surface faulting on either side of the suspected boundary established by detailed paleoseismic studies. Corroboration of the strong structural and geometric evidence for a segment boundary at Anderson Junction with information on earthquake timing is particularly desirable because scarps north of that proposed boundary are formed on resistant Paleozoic bedrock, not unconsolidated Quaternary gravel and alluvium as thought by Stewart and Taylor (1996). Conversely, scarps are absent south of Anderson Junction where bedrock consists chiefly of the

Mesozoic Moenkopi Formation, units of which are described by Anderson and Christenson (1989) as being less resistant to scarp degradation than some coarse-grained alluvial deposits found elsewhere along the Hurricane fault. Information on earthquake timing would show if the absence of scarps south of the boundary is due to erosion of soft bedrock or to a real difference in earthquake recurrence.

In Utah, lengths between major geometric bends in the Hurricane fault range from about 10 to 22.5 kilometers, well within the parameters reported by dePolo and others (1991). Based on our reconnaissance, possible seismogenically significant differences in the number and type of scarps on either side of major geometric bends in the fault exist between subdivisions 1 and 2, 3 and 4, 4 and 5, and 5 and 6. However, as noted above, further detailed study is required to determine if differences in scarp abundance actually reflect differences in slip rate or are the result of factors unrelated to tectonic deformation.

Scarps on fault subdivision 1 are more abundant and better preserved than on subdivision 2, particularly as subdivision 1 is followed south into Arizona. No, or poorly preserved scarps on subdivision 2 give way to no recognizable scarps on subdivision 3, although some small or indistinct scarps may have been obscured by urbanization along fault subdivision 3. The bend between subdivisions 3 and 4 is at Anderson Junction; as previously discussed, no scarps are evident south of the bend but scarps are present north of the bend. Fault subdivision 4 also includes the first scarp recognized on unconsolidated deposits north of the Utah/Arizona border at the Water Tank site. Subdivision 5 has relatively abundant scarps and includes two locations, Kanarraville and Murie Creek, with scarps on unconsolidated deposits. The fact that both fault subdivisions 4 and 5 contain scarps on unconsolidated materials may indicate the two subdivisions represent a single seismogenic fault segment. However, the scarps at Murie Creek and Kanarraville are much better preserved than the alluvial scarp at the Water Tank site, suggesting a difference in earthquake timing between them.

The scarps at Murie Creek are immediately south of the fault bend separating fault subdivisions 5 and 6. Based on location, the Murie Creek scarps are part of subdivision 5; however, fault subdivision 6 includes well-preserved scarps on unconsolidated deposits at three locations (Shurtz Creek and the Middleton and Bauer sites) suggesting a possible affinity between those sites and Murie Creek. As has been demonstrated in historical Basin and Range earthquakes, surface-fault rupture initiated on one segment may spill over for some distance onto an adjoining segment. This may be the case between fault subdivision 6 and the scarps at Murie Creek. However, the scarps at Murie Creek appear younger, in one instance considerably younger, than the scarps on fault subdivision 6, and it may be that two adjacent fault segments at the north end of the Hurricane fault have both had relatively recent, but different surface-faulting earthquakes.

Scarcity of Fault Scarps. Results of this reconnaissance show that some parts of the Hurricane fault in Utah have experienced at least one surface-faulting earthquake in the early Holocene or latest Pleistocene, and that other parts of the fault have experienced multiple surface-faulting events in the late Quaternary. Yet fault scarps are scarce along much of the fault in Utah. Possible reasons for the poorly preserved record of surface faulting include: (1) individual surface-faulting earthquakes in the late Quaternary have been small (< M7) and fault scarps have been correspondingly small, (2) displacements are spread across multiple small scarps in a wide zone of deformation, (3) the recurrence interval between surface-faulting earthquakes is long, providing ample time for scarps, especially scarps formed on unconsolidated deposits, to erode or be buried, or (4) surface displacement may occur within the rugged bedrock higher up in the Hurricane Cliffs, thus bypassing unconsolidated basin-fill deposits altogether and leaving little or no record of surface faulting. Further detailed study is required to determine which of these or other processes are acting along the Hurricane fault to limit preservation of fault scarps.

Scarps On Unconsolidated Deposits

Scarps on unconsolidated deposits are now recognized at six sites on the Hurricane fault in Utah. The large scarp on coarse pediment deposits at Shurtz Creek was mapped by Averitt (1962); our study identified the other five locations. All six sites are on the northern 50 kilometers of the fault at elevations greater than 1500 meters. The scarps are short, the longest being about 200 meters long, and are widely separated (one to several kilometers apart) with little or no evidence of geologically young displacement between them. Scarp morphology indicates some sites may have different surface-faulting histories. Other scarps identified during this study are clearly formed on bedrock and are mantled with colluvium. However, geologic relations for some scarps remain equivocal, and while most are probably on bedrock, a few may be on unconsolidated deposits.

Scarps formed on unconsolidated deposits by normal-slip faults degrade to produce characteristic, scarp-related sedimentary deposits (colluvial wedges), which may incorporate carbonaceous material suitable for radiocarbon dating (Machette and others, 1992; McCalpin, 1996). Such sites are preferred locations for paleoseismic trenching studies necessary to determine the size and timing of past surface-faulting earthquakes. Bedrock-cored scarps have been trenched with some success (see Chapter 3, this report), but generally prove problematic and are less likely to produce useful results (Olig and others, 1996; McCalpin, 1998). Therefore, the six sites with scarps on unconsolidated deposits offer the best opportunity for evaluating the late Quaternary history of the Hurricane fault in Utah.

A preliminary evaluation of the six sites, based chiefly on geologic and geomorphic relations, is presented below; none of the scarps were trenched. Two sites, Shurtz Creek and Murie Creek, have the greatest potential for providing useful information about the history of the Hurricane fault; consequently, we focused our efforts there and they are discussed in the greatest detail.

Shurtz Creek

Site Geology. At Shurtz Creek, scarps are formed on both alluvium and bedrock (Figure 2.4). A coarse-grained pediment deposit (Averitt, 1962) is displaced across a 13-meter-high scarp. To the north, the same fault is expressed as a sharp, linear contact between Mesozoic sedimentary rock and valley-fill alluvium. Southward, the fault splits, forming western and eastern strands. Beyond

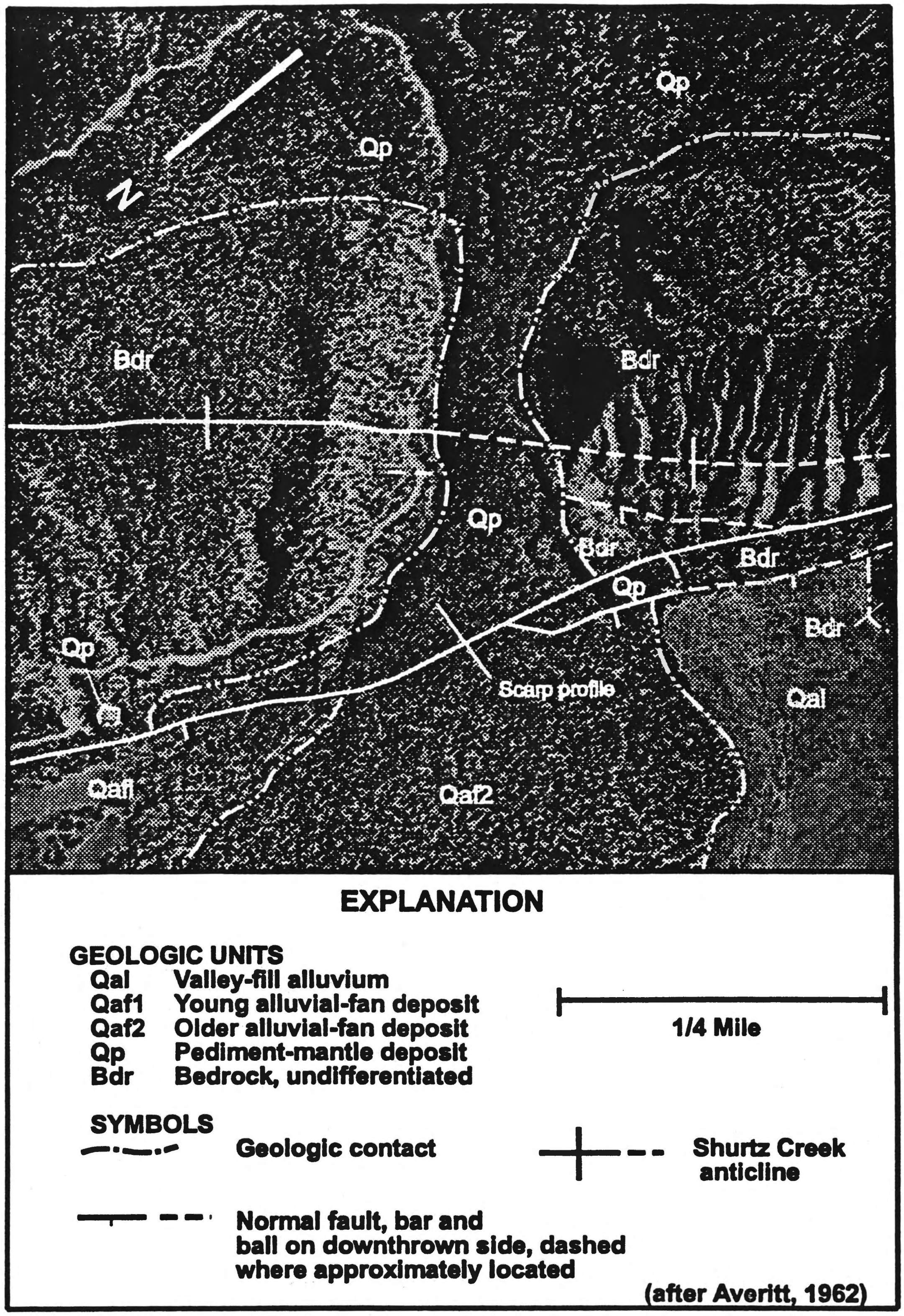

Figure 2.4. Aerial photograph geologic map of the Shurtz Creek site, Hurricane fault,Utah.

the pediment deposit, the western strand follows the base of the Hurricane Cliffs, separating Mesozoic bedrock from valley-fill alluvium. The bedrock forms a distinct, but dissected and rounded scarp. Pinyon and juniper trees growing in alluvium on the hanging wall have been chained and that area is highly disturbed. Any scarps present on the alluvium have been largely obscured. The eastern scarp trends into bedrock in the lower part of the Hurricane Cliffs. There it brings the Lower Red Member of the Moenkopi Formation into fault contact with the Timpoweap Limestone Member, repeating part of the stratigraphic subdivision.

The surface of the pediment deposit on the upthrown side of the fault is heavily forested and covered with basalt boulders, the largest standing more than a meter above the ground surface. Other rock types present are principally sandstone and minor limestone derived from Mesozoic and Cretaceous sedimentary rock units. Few of those specimens are more than 10 centimeters in diameter. Basalt is one of the least abundant rock types in the drainage basin, cropping out only in a small area near the top of the Shurtz Creek drainage divide. The abundance and size of the boulders on the pediment reflects the greater resistance of basalt to erosion. Most boulders show evidence of long exposure at the ground surface. Many have split into two or more pieces; some are actively spalling so that multiple levels of patina development are evident and most support growths of lichens and moss. Shurtz Creek has eroded a stream terrace into the pediment deposit along both sides of its channel just upstream from the fault scarp.

Two ages of alluvial deposits are present on the downthrown side of the fault. A young alluvial fan has formed where Shurtz Creek has incised through the fault scarp. The fan alluvium is mostly loose sand and gravel with relatively few cobbles and boulders. During periods of high water, this surface receives active deposition. An older alluvial deposit lies immediately south and a few meters higher than the young alluvial fan. Like the pediment on the upthrown side of the fault, this surface is forested and covered with large, weathered basalt boulders. Along its northern edge, adjacent to the young alluvial fan, the older alluvial surface is partially incised by two former channels of Shurtz Creek that are now abandoned above the active alluvial fan.

Mesozoic sedimentary rocks crop out in the Hurricane Cliffs east of the Shurtz Creek site. Formations include the relatively soft Moenkopi and Chinle Formations with the Moenave, Kayenta, and Navajo formations cropping out higher in the drainage basin. These units have been affected by deformation associated with the Sevier orogeny. The axis of the Shurtz Creek anticline (Averitt, 1962) is just east of and parallels the Hurricane fault at Shurtz Creek (Figure 2.4). Above these deformed units lie relatively undeformed Cretaceous and Cenozoic rocks including Quaternary basalt. The Schurtz Creek pediment (Averitt, 1962) developed in the Shurtz Creek amphitheater, an area of relatively low elevation formed in the Hurricane Cliffs on the softer Mesozoic rock units.

Correlating Displaced Surfaces. The pediment surface on the upthrown side of the fault and the older alluvial surface on the downthrown side are similar in appearance. Both are covered with large basalt boulders that show evidence of long exposure at the ground surface. On both surfaces other rock types are less abundant than basalt and seldom exceed cobble size. Sheet wash is active on both sides of the fault, producing a lag gravel or desert pavement appearance on both surfaces.

Based on surface morphology, we initially hypothesized that the two surfaces are correlative. If so, and if the age of the pediment surface could be determined, a slip rate could be calculated for the Hurricane fault for the time interval represented by the surface. To test this hypothesis, soil scientists from Davis Consulting Earth Scientists and Utah State University (USU) excavated a soil pit on each surface, logged the soil profiles in detail, and collected samples for laboratory analysis at USU. Soil morphology data are shown in Appendix 2A and laboratory results are shown in Appendix 2B. Both soils had moderate to well-developed argillic and calcic horizons, and gypsum is leached from both profiles confirming they are both older than Holocene (Dr. Janis Boettinger, USU, written communication, 1998). Soil colors are lighter (indicating more $CaCO_3$), moist consistence is firmer (indicating higher secondary clay content), and clay films are more abundant in the soil on the upthrown side of the fault. Additionally, pH is <8 to 26 centimeters on the upthrown side, but only <8 to 8 centimeters for the soil on the downthrown block. The $CaCO_3$ data follow the pH; removal of $CaCO_3$ has been more extensive from near-surface soil horizons on the upthrown block, as indicated by the lower $CaCO_3$ content in the upper 26 centimeters of that soil. Calcium carbonate reaches a maximum of 23 percent (Stage II carbonate morphology; Machette, 1985a) in a thin zone between 80 and 91 centimeters in the soil on the downthrown block. In contrast, $CaCO_3$ exceeds 30 percent (Stage III carbonate development; Machette, 1985a) in all horizons below 45 centimeters on the upthrown block and reaches a maximum of 43 percent between 66 and 100 centimeters. A drop in $CaCO_3$ content at the base of the test pit on the downthrown side of the fault (Appendix 2A) also argues for a younger soil there. With increasing depth, a buried soil (original pediment surface) may be encountered below the modern soil (Dr. Janis Boettinger, USU, written communication, 1998). Therefore, based on differences in soil-profile development, the surfaces across the scarp at Shurtz Creek are not correlative, and the soil on the upthrown block is estimated to be up to twice as old as the soil on the downthrown block (Dr. Janis Boettinger, USU, written communication, 1998). Comparatively recent additions of material to the downthrown surface could explain the differences in the two soils. The surface on downthrown block is considered an alluvial fan rather than a pediment.

Surface Ages. Concurrently with the soils investigation, we undertook a study to determine the ages of the upper and lower, boulder-covered surfaces at Shurtz Creek. Tom Hanks of the U.S. Geological Survey sampled sandstone cobbles, chiefly from the Cretaceous Straight Cliffs Sandstone, and to a lesser extent from the Jurassic Navajo Sandstone, on both the up- and downthrown surfaces for ^{10}Be and ^{26}Al isotope abundances. He also sampled a basalt boulder on the upthrown surface for ^{36}Cl isotope abundance. Lawrence Livermore National Laboratory is performing the laboratory analyses.

Preliminary data for ^{26}Al abundances in Straight Cliffs Sandstone samples from both surfaces range from 12,000 to 22,000 years, clustering around 15,000 to 18,000 years (Dr. Thomas Hanks, U.S. Geological Survey, written communication, 1998). These ages are unexpectedly young in light of our soil-profile data. The well-developed argillic Bt and Stage II (lower surface) and Stage III (upper surface) Bk horizons in the soils at Shurtz Creek argue for significantly older, although not equivalent, ages for both surfaces. Based on soil-profile development, the age of the upper surface is estimated at 80,000 to 100,000 years, and the age of the lower surface is estimated at about 50,000 years (Dr. Janis Boettinger, USU, verbal communication, 1998). These estimates are in general agreement with ages assigned by Machette (1985a, 1985b) to soils with similar $CaCO_3$ accumulations in the Beaver Basin 90 kilometers north of Shurtz Creek. There, he estimated soils exhibiting Stage II carbonate morphology are about 80,000 to 140,000 years old, while soils with well-developed Stage III morphology could be as old as 250,000 years.

The difference between the estimated soil ages and the cosmogenic isotope data likely reflects the affect of ongoing geomorphic processes on the two surfaces. Numerous basalt boulders standing greater than one meter above the ground surface, and a much smaller number of sandstone clasts, few larger than about 10 centimeters, is not the configuration expected for a surface formed chiefly by debris flows from a basin where basalt represents only a small percent of the outcrops, and sandstone makes up 50 percent or more of the drainage basin. Yet basalt boulders dominate the morphology of both surfaces. The young cosmogenic ages for the sandstone probably reflect the sandstones greater susceptibility to erosion when exposed at the ground surface. Most of the large sandstone boulders and cobbles originally deposited on the surface have likely disintegrated leaving behind smaller core remnants. Other sandstone clasts may have been transported to the surface by freeze-thaw action, and therefore exposed at the surface for a comparatively short time.

Net Vertical Tectonic Displacement and Preliminary Slip-Rate Estimate. We profiled the Shurtz Creek scarp using a meter rod and Abney hand level (Appendix 3A). The scarp is 13 meters high, has a maximum slope angle of 28 degrees, and an apparent net vertical tectonic displacement (NVTD) of 10.5 meters (Table 2.1). Calculating an accurate slip rate requires that net vertical displacement be known for a closed interval of time (a seismic cycle or cycles). Because the alluvial surfaces on either side of the Hurricane fault at Shurtz Creek are not correlative, the scarp height and NVTD obtained from the scarp profile are minimum values. Calculating a slip rate at Shurtz Creek is further complicated by two additional considerations:

Table 2.1. Scarp profile data

Location	Scarp Height	Net Vertical Tectonic Displacement	Maximum Slope Angle	Remarks
Shurtz Creek	13 m	10.5 m	28°	Bedrock cored?
Murie Creek				
Coyote Draw	3 m	~2.75 m	14°	Possible single-event scarp
Colluvial apron	10 m	---	21.5°, 14°	Beveled, multiple-event scarp
Middleton Site				

Table 2.1. Scarp profile data				
East Scarp	4 m	2.7 m	19°	Alluvial fan
Middle Scarp	4 m	2.7 m	18°	Alluvial fan
West Scarp	9.5 m	7.3 m	27.5°	Bedrock
Bauer Site				
East Scarp	5 m	2.3 m	22°	Alluvial fan
Middle Scarp	5 m	2.3 m	20°	Alluvial fan
West Scarp	2 m	0.9 m	16°	Alluvial fan
Water Tank Site				
East Scarp	12.7 m	7.3 m	20°	Bedrock, colluvium mantled
West Scarp	4.5 m	1.8 m	13°	Alluvium
Near Pintura	39 m	~26 m	30°	Bedrock, colluvium mantled

(1) the time interval since the most recent surface-faulting earthquake is unknown and open ended, and (2) the time interval between pediment development and the first surface-faulting earthquake is also unknown. Both time periods could be considerable, and each may represent thousands of years. For large cumulative displacements and long periods of time, for example hundreds of meters over many hundreds of thousands of years for the basalt flows displaced across the Hurricane fault, the effect of these time considerations is small. However at Shurtz Creek, the pre- and post-faulting time intervals may account for a significant portion of the age of the pediment deposit. Because the two intervals tend to cancel each other when calculating slip rates, their effect may be minimal if the intervals are roughly equivalent. However, the length of both intervals are presently unknown, so their combined effect on the slip rate at Shurtz Creek is also unknown.

Using available profile data, and assuming that the upthrown (pediment) surface is 100,000 years old, and that the pre- and post-faulting time intervals effectively cancel each other, the minimum late Quaternary slip rate at Shurtz Creek is about 0.11 mm/yr. That value is roughly one-third the average slip rate calculated for the Hurricane fault over the past million years by Hamblin and others (1981) using displaced basalt flows near the town of Hurricane and about one-tenth or less the average slip rate for the most active segments of the Wasatch fault during the Holocene. Interestingly, it is about the average (calculated from limited data) for the Wasatch fault between 100,000 to 200,000 years ago (Machette and others, 1992). If the pediment surface is younger than 100,000 years, the apparent slip rate will be higher, as will the true slip rate in any case, because the NVTD measured at Shurtz Creek is a minimum value. The assumptions stated above are significant, and all parameters are subject to later verification by detailed paleoseismic trenching studies.

Murie Creek

Site Geology. At Murie Creek, the Hurricane fault displaces a young alluvial-fan deposit across a 3-meter-high scarp at the mouth of Coyote Draw, a small drainage from the Hurricane Cliffs (Figure 2.5). The scarp is generally on strike with the bedrock/alluvium contact at the base of the Hurricane Cliffs that marks the main trace of the fault. Near the fan apex, the scarp is partially buried by post-faulting alluvium deposited before the ephemeral stream from the draw incised through the scarp. Other areas have received little or no post-faulting sediment, so a scarp profile measured there (Appendix 3B) provides a good estimate of scarp height and NVTD. This is the youngest scarp recognized along the Utah portion of the Hurricane fault, and it may represent a single surface-faulting earthquake.

A few tens of meters north of the scarp at Coyote Draw, colluvium at the base of the Hurricane Cliffs is displaced across a large scarp that diverges to the northwest from the cliff front for a distance of a few hundred meters. This scarp is generally 10 meters or more high and has a pronounced bevel (Table 2.1; Appendix 3C), indicating multiple surface-faulting earthquakes. The trace of the scarp is gently sinuous, reflecting the effect of post-faulting erosion. The hanging wall appears to tilt gently eastward toward the fault and has received considerable post-faulting sedimentation, indicating the possible presence of a buried graben and antithetic fault. The scarp ends abruptly to the north at a contact with the main Murie Creek alluvial fan (Figure 2.5). Although older than the young alluvial fan at Coyote Draw, there is little evidence to indicate that the Murie Creek fan is faulted. A near right-angle bend in a small ephemeral stream channel on the fan lines up with the scarp, indicating a possible continuation of faulting, but there is no scarp or other evidence of displacement. The age relation between the Murie Creek alluvium and the faulted colluvium is unknown. Possibly the fault cutting the colluvium is inactive and that the Murie Creek alluvium is younger than the most recent surface faulting. In the Hurricane Cliffs east of Murie Creek, Paleozoic and Mesozoic sedimentary rocks are overturned in the east limb of a recumbent anticline. The anticline is associated with the Sevier orogeny, and the west limb has been displaced down-to-the-west by the Hurricane fault. Limestone of the Permian Kaibab Formation (Kurie, 1966; Hintze, 1988) crops out in the cliffs immediately east of the large scarp formed on colluvium. Red siltstone and claystone, and yellow-buff limestone of the Triassic Moenkopi Formation crop out in the Coyote Draw drainage.

Age Estimates from Soil-Profile Development. We excavated two soil test pits at Murie Creek, one on the young alluvial-fan deposit at Coyote Draw and the other on the colluvium at the base of the Hurricane Cliffs. Both soil pits were on the upthrown side of the fault. Soil

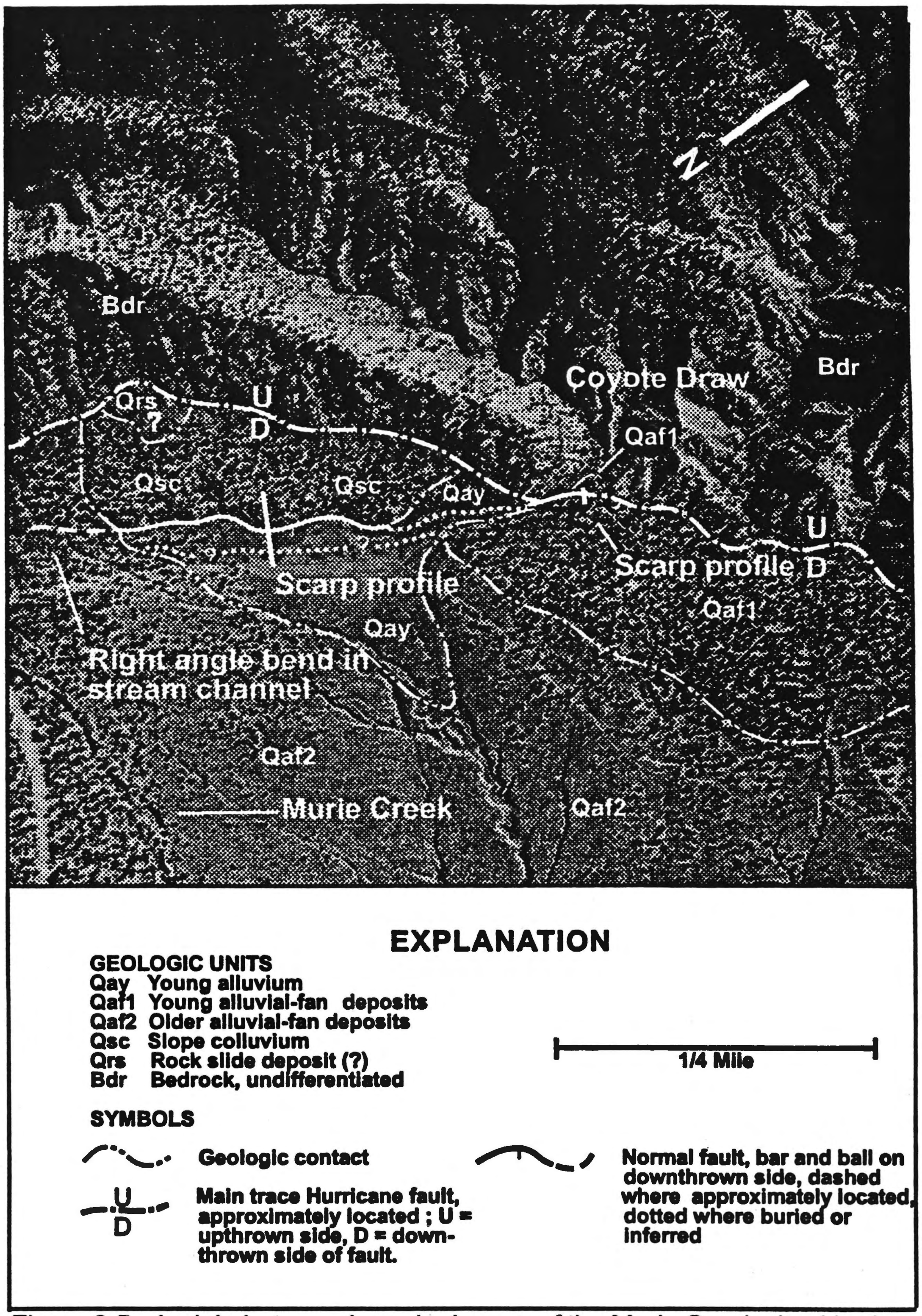

Figure 2.5. Aerial photograph geologic map of the Murie Creek site, Hurricane fault, Utah.

morphology data for the two soils are shown in Appendix 2C. No laboratory analyses were performed.

Due to the red, clay-rich nature of the parent material derived from the Moenkopi Formation, the soil on the Coyote Draw alluvial fan is red in color and clayey throughout. The 80-centimeter-deep test pit exposed weak soil-profile development. A thin (8 cm), slightly organic A horizon overlies Bw1 and Bw2 horizons that exhibit a slight change in color, but no discernable difference in clay content from the A horizon. The Bw2 horizon is distinguished by the presence of weak soil structure. Below the zone of color change, a weak Bk horizon extends to the bottom of the test pit. The Bk horizon exhibits weak Stage I carbonate morphology characterized by short, thin, discontinuous filaments of $CaCO_3$ in the soil matrix, and very thin, discontinuous $CaCO_3$ coatings on the bottom of larger clasts. Based on the weakly developed soil, we estimate the age of the Coyote Draw alluvial-fan deposit as early Holocene or latest Pleistocene, and probably less than 12,000 years old.

The soil on the colluvium at the base of the Hurricane Cliffs has an A horizon nearly twice as thick (17 cm) as the soil on the young alluvial fan at Coyote Draw; a 29-centimeter-thick, clay-enriched Bt horizon; and below 56 centimeters, a Bk horizon that exhibits Stage II carbonate morphology. Both the Bt horizon and the Stage II carbonate morphology imply considerable age for the colluvium. Machette (1985a, 1985b) assigned an age of 80,000 to 140,000 thousand years to soils exhibiting similar soil-profile development in the Beaver Basin.

Net Vertical Tectonic Displacement and Preliminary Slip-Rate Estimate. Scarp profiles, measured with a digital total station, show a height of 3 meters and a NVTD of 2.75 meters for the small scarp at Coyote Draw (Table 2.1; Appendix 3B), and a height of 10 meters for the large scarp on colluvium (Table 2.1, Appendix 3C). The NVTD across the large scarp could not be determined due to deposition of an unknown thickness of young alluvium on the downthrown side of the fault. The height of the large scarp varies along strike. Possible reasons for the variation include: differences in the amount of displacement along strike, effects of near-fault deformation (for example, backtilting and graben formation), erosion, and local differences in the age of the colluvium.

The small scarp at Coyote Draw may represent a single surface-faulting earthquake, but is unlikely to represent more than two such events. Because the number of surface-faulting earthquakes is both small and unknown, calculating a slip rate is problematic. The principal difficulties are the effect of the open-ended time intervals that precede and follow faulting, and the unknown number of events that created the scarp. If it is assumed that the age of faulting is latest Pleistocene to early Holocene,12,000 to 8,000 years, a maximum (because the time interval since the last event is open ended) slip rate at Coyote Draw would range from 0.22 to 0.33 mm/yr; about one-quarter to one-third the Holocene slip rate for the most active segments on the Wasatch fault, but close to the average calculated by Hamblin and others (1981) for the past million years on the Hurricane fault. As at Shurtz Creek, all paleoseismic parameters are preliminary and subject to verification by trenching studies.

The slope of the surfaces on either side of the large scarp at Murie Creek are widely divergent (Appendix 3C) indicating the downthrown block is buried by younger alluvium, and that not even a tenuous correlation exists between the surfaces across the fault. Therefore, it is not possible to obtain a meaningful measurement of NVTD across the large scarp, and consequently, not possible to estimate a slip rate.

Middleton and Bauer Sites

The Middleton and Bauer sites are considered together because they are in relatively close proximity to each other and to Shurtz Creek (Figure 2.3), and because of the striking similarities in the geologic relations at the two sites. We measured scarp profiles at both sites, but did not excavate soil test pits.

Middleton Site. The Middleton site is about 1 kilometer north of Shurtz Creek. Bedrock and an old alluvial-fan deposit (Averitt, 1962) are displaced down-to-the-west across remnants of three subparallel scarps. The eastern scarp is about 9.5 meters high and has a maximum slope angle of 27.5 degrees (Table 2.1; Appendix 3D). It separates bedrock of the Moenkopi Formation in the footwall from alluvial-fan deposits in the hanging wall. The middle and western scarps are both on the alluvial-fan deposit. They are each about 4 meters high and have maximum slope angles of 18 and 19 degrees, respectively. From east to west, NVTDs across the scarps are 7.3, 2.7, and 2.7 meters. The 12.7 meters of total displacement recorded by the three scarps is about 2 meters more than estimated at Shurtz Creek (10.5 m). The larger displacement may reflect differences in slip between the two locations, or it may be a function of the eastern scarp at the Middleton site being formed on bedrock, and therefore, recording more events than the scarp on the Shurtz Creek pediment.

The alluvial-fan surface is now isolated above the present stream level and is inactive. The surface is covered with basalt cobbles and small boulders that exhibit strong patina development, indicating that the surface is old. Further evidence of age is the near absence of sandstone clasts on the surface; most of them apparently weathered away. Averitt (1962) mapped this deposit as an alluvial fan and it has many affinities with the alluvial fan at the Bauer site (see below), but he also mapped the Shurtz Creek pediment in the ephemeral stream drainage east of the fan and shows the Hurricane fault displacing the pediment where the stream issues from the Hurricane Cliffs. Based on the morphology of the surface, what Averitt (1962) mapped as an alluvial fan may actually be a remnant of the Shurtz Creek pediment. Cosmogenic isotope dating (^{36}Cl or ^{3}He) and/or detailed evaluation of soil development (laboratory analysis) would be required to determine if the alluvial surface at the Middleton site is similar in age to the Shurtz Creek pediment.

Bauer Site. The Bauer site is about 2.5 kilometers south of Shurtz Creek (Figure 2.3). An alluvial-fan deposit (Averitt, 1962) is displaced across the remnants of three subparallel scarps, much like at the Middleton site. The eastern and middle scarps are both about 5 meters high and have maximum slope angles of 22 and 20 degrees, respectively (Table 2.1; Appendix 3E). The western scarp, is more worn and eroded than the two scarps to the east, is about 2 meters high, and has a maximum slope angle of 16 degrees. From east to west, the NVTDs measured across the scarps are 2.3, 2.3, and 0.9 meters. The 5.5 meters of displacement recorded by the three scarps at the Bauer site is about half the net displacement at Shurtz Creek (10.5 m) and less than half the displacement at the Middleton site (12.7 m). The differences in displacement are large enough and the distance between the three sites short enough, that it seems unlikely such a large discrepancy can be attributed to local variations in slip along the fault.

The Shurtz Creek pediment does not extend south as far as the Bauer site (Averitt, 1962), so there is no question that alluvial-fan deposits are displaced at the Bauer site. Possible reasons for the large differences in displacement between the Bauer site and the Shurtz Creek and Middleton sites are: (1) the alluvial-fan deposits are younger at the Bauer site and therefore record fewer events, (2) the alluvial-fan deposit is the same age as the alluvial fan at the Middleton site, but the bedrock scarp at Middleton records more events (the NVTD recorded by just the alluvial-fan deposits at the Middleton site is 5.4 m), or (3) another scarp at the Bauer site wasn't identified. Possibility (3) is considered unlikely. Additional cosmogenic isotope dates and/or soil-profile analysis are required to evaluate the relative ages of the three deposits and the reason for the differences in displacement among them.

Water Tank Site

The Water Tank site (Figure 2.3) consists of two subparallel scarps: a large, probably bedrock-cored, eastern scarp, and a smaller, very worn, western scarp formed on alluvium. The southernmost of the sites on the Utah portion of the Hurricane fault recognized with scarps on unconsolidated deposits, the Water Tank Site is on Stewart and Taylor's (1996) Ash Creek fault segment. Both scarps are short (<100 m) and the scarp on alluvium is heavily eroded and partially buried in places. We measured a scarp profile were the western scarp is relatively unaffected by erosion or deposition. The western scarp is 4.5 meters high and has a maximum slope angle of 13 degrees (Table 2.1; Appendix 3F) . The eastern scarp is 12.7 meters high and has a maximum slope angle of 20 degrees. Net vertical tectonic displacements measured across the western and eastern scarps are 1.8 and 7.3 meters, respectively. The total net displacement of 10.1 meters is similar to the NVTD (10.5 m) measured at Shurtz Creek.

Kanarraville Site

At the Kanarraville site (Figure 2.3), a small remnant of an older alluvial fan at the mouth of a small drainage is truncated by faulting. The scarp is about 5 meters high and is incised by the ephemeral stream. A young alluvial fan has formed on the downthrown block with its apex where the stream issues from the scarp. The young fan is not faulted and buries the pre-faulting ground surface on the hanging wall. A seldom used, dirt farm road runs parallel to the base of the scarp and has diverted the ephemeral stream causing a gully nearly a meter deep to be eroded into the toe of the scarp. The faulted fan is estimated to be Pleistocene in age, but because of the scarp's highly modified nature, no further work was done at this location.

Discussion

The six sites in Utah with scarps on unconsolidated deposits represent the best locations for developing detailed paleoseismic information on the size and timing of past surface-faulting earthquakes on the Utah portion of the Hurricane fault. The kind, amount, and quality of information that can be obtained from a particular site depends on the geologic relations at that location. Discounting issues of access and land ownership, all six sites could be trenched and potentially would yield useful paleoseismic data. The six sites are on the three northern fault subdivisions (subdivisions 4, 5, and 6) established for this report. The fault subdivisions are all bounded by bends in the fault, so comparing information on earthquake timing among sites will help show which bends may be seismogenic boundaries.

The Shurtz Creek, Middleton, and Bauer sites are at the extreme north end of the Hurricane fault on subdivision 6. All three sites offer the opportunity to trench large, multiple-event scarps that could provide information on the size and timing of several past earthquakes. Trenching at Shurtz Creek has the advantage that all surface-faulting earthquakes in the late Quaternary (past 100,000?) are likely on a single fault strand, so a single, deep trench should expose evidence for several events. Excavation at Shurtz Creek would be hampered by very large boulders in the pediment deposit and the possibility of encountering bedrock on the upthrown side of the fault. Generally, the likelihood of obtaining useful paleoseismic information by trenching bedrock scarps is lower than for scarps on unconsolidated deposits (Olig and others, 1996; McCalpin, 1998), although Stenner (Chapter 3, this report) had reasonable results at Cottonwood Canyon in Arizona (Figure 2.3). A deep test pit on the hanging wall may uncover the original, prefaulting pediment surface, allowing determination of a more accurate NVTD across the fault. That information, combined with a better estimate of the age of the pediment surface from ^{36}Cl and/or ^{3}He cosmogenic isotope abundances would provide an accurate late Quaternary slip rate for the Hurricane fault. The Middleton and Bauer sites are in close proximity to Shurtz Creek and could serve as alternate sites if trenching at Shurtz Creek is not possible. Alternatively, an investigation at one or both locations could help verify and possibly expand the paleoseismic information obtained at Shurtz Creek. Access is a serious issue at Shurtz Creek where large boulders on the ground surface and a dense pinion/juniper forest would necessitate extensive road construction to reach a suitable trench site. Access to both the Middleton and Bauer sites is good, mostly across private property.

Murie Creek, with its young, possibly single-event scarp; adjacent beveled, multiple-event scarp; and possible graben and antithetic fault(s), has the best potential for providing detailed paleoseismic information on the size and timing of past surface-faulting earthquakes of any site on the Hurricane fault in Utah. Graben often serve as traps for organic mater, and if a graben is present at Murie Creek, it may provide material suitable for radiocarbon dating. The potential for obtaining useful paleoseismic information at the Kanarraville site exists, but is comparatively low. Gullying at the toe of the scarp probably has removed a large part of the youngest colluvial wedge, and possibly part of any wedge associated with an earlier surface-faulting earthquake. Both the Murie Creek and Kanarraville sites have good access and are located on private property.

The Water Tank site is on fault subdivision 4, separated from the Murie Creek and Kanarraville sites by the fault bend at Locust Creek (Figure 2.3). Information on the timing of past surface-faulting earthquakes from this location would help establish if the bend at Locust Creek is a seismogenic boundary and would do the same for the fault bend at Anderson Junction. A trench or trenches here could investigate both an alluvial and a probable bedrock scarp. The Water Tank site is on private property.

Scarps On Bedrock

Colluvium-mantled scarps on bedrock are present at several isolated locations along the Hurricane fault in Utah (Appendix 1). Because there are few scarps of any kind in Utah, trenching bedrock scarps may be the only alternative, if a good understanding of the fault's earthquake history and segmentation characteristics is to be obtained.

Bedrock or suspected bedrock scarps where trench studies may be possible are found on fault subdivisions 1, 2, and 4. No scarps of any kind were recognized on fault subdivision 3. Bedrock scarps on fault subdivisions 5 and 6 are not considered because: (1) topographic constraints make many of them inaccessible, (2) in several instances, it is not clear if the feature observed is a fault scarp, (3) they lack a cover of unconsolidated material from which a colluvial wedge might form following a surface-faulting earthquake, and (4) scarps on unconsolidated deposits are sufficiently abundant that trenching bedrock scarps will likely prove unnecessary. Additionally, there are four natural or manmade exposures, one on fault subdivision 2 and three on fault subdivision 3, where bedrock is in fault contact with unconsolidated deposits. These exposures could be cleaned and evaluated in a manner similar to trench sites.

We identified two possible bedrock scarps on fault subdivision 1 in Utah (FS1-1 and FS1-2; Appendix 1). They are the northernmost of a relatively large number of scarps that extend southward into Arizona. The trench site at Cottonwood Canyon (Chapter 3) is on this fault subdivision. If additional trenching is required, the characteristics of the scarps in Arizona as well as those in Utah should be evaluated to select the best trench site.

Other than small inflections in slope near the heads of some alluvial fans, only one suspected fault scarp is recognized on fault subdivision 2 (FS2-2; Appendix 1). It is about 5 meters high and formed on very coarse colluvium near the base of the Hurricane Cliffs. The scarp is incised by an ephemeral stream; no evidence of faulting was observed in the walls of the stream channel. A second incised stream at the base of the cliffs exposes bedrock and older colluvium in fault contact, and both units are overlain by younger, unfaulted deposits (FS2-3, Appendix 1). Cleaning and logging the stream exposure may prove more informative than trenching a feature that may not be a fault scarp.

Two construction cuts (FS3-3 and FS3-4; Appendix 1) and one natural exposure (FS3-6; Appendix 1) on fault subdivision 3 expose bedrock in fault contact with unconsolidated material. All three sites are accessible and could be cleaned and logged. The availability of carbonaceous material for radiocarbon dating is unknown, but all three sites contain fine-grained sediments that may be suitable for thermoluminescence dating.

Fault subdivision 4 north of Anderson Junction contains the largest and best preserved bedrock scarps on the Hurricane fault in Utah (FS4-4, FS4-11, and FS4-16; Appendix 1). Some of these scarps are very large; one near Pintura is 39 meters high and has a slope angle of 30 degrees (Table 2.1; Appendix 3G). Net vertical tectonic displacement measured across this scarp is more than 26 meters. At other locations scarps are on the order of 3 to 6 meters high and have slope angles ranging from 15 to 30 degrees (Stewart and Taylor, 1996). All of the scarps are mantled by colluvium. With the exception of the large scarp at the Water Tank site (FS4-16; Appendix 1), the bedrock scarps on fault subdivision 4 are largely inaccessible due to topographic or landowner constraints.

Ash Creek Graben

Anderson and Christenson (1989) recognized and mapped scarps formed on Quaternary/Tertiary alluvium (Hurlow, 1998) antithetic to the Hurricane fault southwest of Pintura. Interpretation of aerial photographs shows that these east-facing antithetic faults are: (1) more prevalent and longer than previously mapped, (2) in a few instances 60 or more meters high and commonly greater than 10 meters high, (3) formed on basalt as well as alluvium, and (4) in many places accompanied by smaller, west-facing scarps sympathetic to the Hurricane fault, resulting in the creation of smaller subsidiary graben. Taken as a whole, these faults form a broad, complex zone that begins in the south on the east side of Interstate 15 near Anderson Junction and extends to the northwest across the Interstate and along the west side of Ash Creek Canyon at the base of the Pine Valley Mountains past Pintura to south of New Harmony, a minimum distance of 17 kilometers (Figure 2.3). The faults form the west side of a large, complex graben that is narrow at its south end (Figure 2.6) and wider at its north end. The graben encompasses the whole of Ash Creek Canyon between the Black Ridge and the Pine Valley Mountains, and is here named the Ash Creek graben. Locally, the west edge of the Ash Creek graben extends into the foothills of the Pine Valley Mountains, where a small normal fault exposed in the walls of Leap Creek Canyon (Figure 2.3) displaces a Quaternary basalt flow several meters down-to-the-east.

Determining NVTD down-to-the-east across the Ash Creek graben is beyond the scope of this study, but is critical to eventually determining long-term (750,000 to one million year plus) slip rates for the adjacent section of the Hurricane fault. The Hurricane fault displaces Quaternary basalt down-to-the-west at two locations along Black Ridge (see below). The basalt on the hanging wall has also been displaced down-to-the-east by antithetic faults and tilted to the east toward the Hurricane fault. The effects of antithetic faulting and tilting accentuate the apparent displacement of the basalt across the Hurricane fault, and must be accounted for (subtracted) to determine the NVTD of the basalt across the Hurricane fault. Accurately assessing down-to-the-east displacement across the antithetic faults would require identifying, mapping, and profiling all the fault scarps and calculating the total NVTD along several transects normal to the trend of

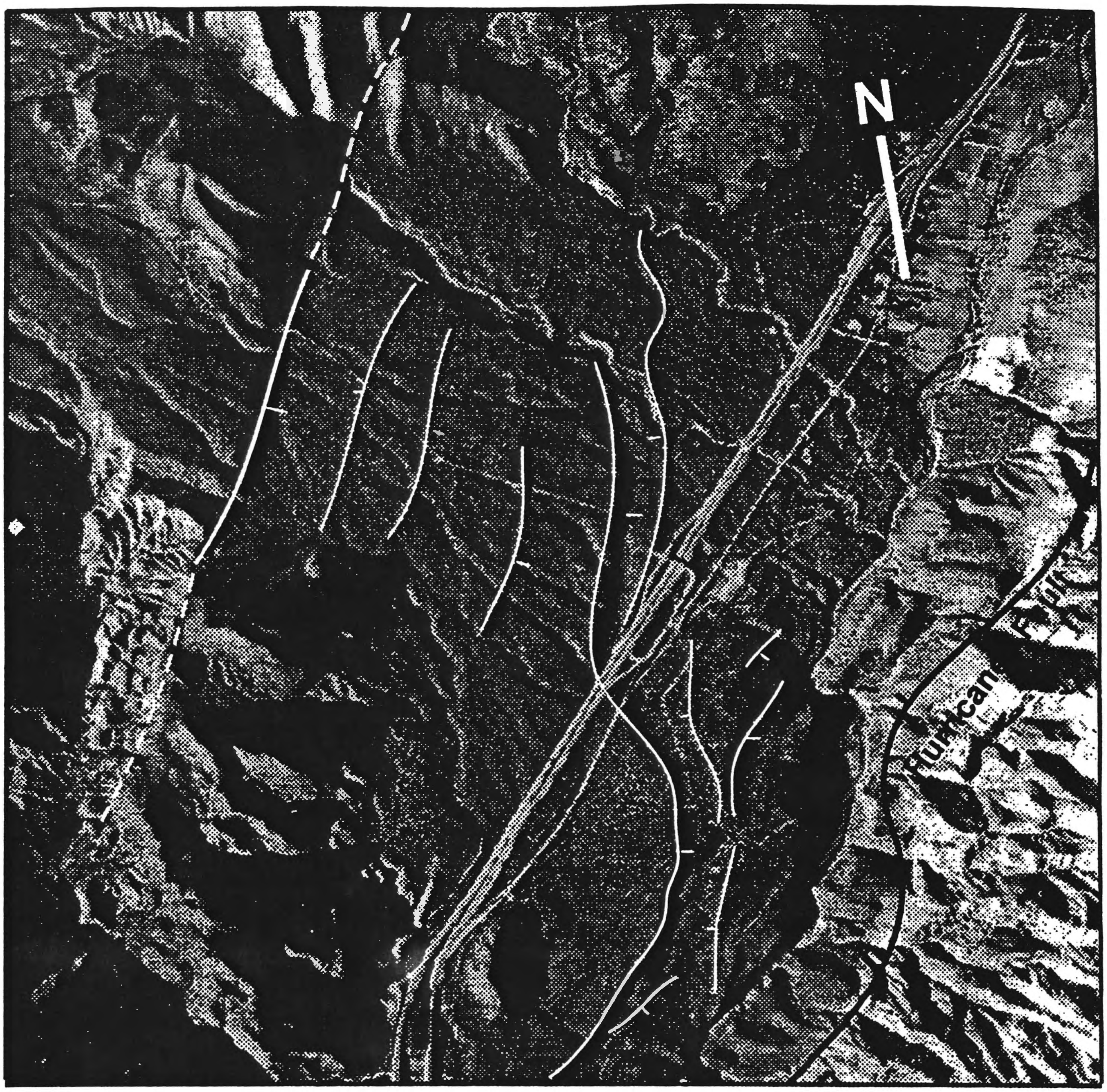

Figure 2.6. Oblique aerial view of the Hurricane fault (black) and antithetic and sympathetic faults (white) at the south end of the Ash Creek graben near Anderson Junction.

the Ash Creek graben. Road access to most scarps is limited and the area is rugged and thickly vegetated. A reconnaissance showed that scarps 10 meters high or larger routinely appear on 1:24,000-scale aerial photographs of the area, but that numerous smaller scarps are present and only a few of those can be identified on aerial photographs. Identifying all of the scarps will require both larger scale aerial photographs and intensive field work. Likewise, few scarps can be profiled with modern surveying instruments unless permission is obtained from land owners to clear sight paths through the brush.

Displaced Quaternary Basalt Flows

The Hurricane fault displaces several basalt flows of Quaternary age in Utah. The flows range from a few hundred thousand to more than a million years old (Hamblin, 1970a; Best and Brimhall, 1974; Anderson and Mehnert, 1979; Best and others, 1980; Hamblin and others, 1981; Anderson and Christenson, 1989; Sanchez, 1995). At some localities, what appear to be the same flow or series of flows are present on both sides of the fault, providing an ideal situation, if the flows can be positively correlated, for estimating NVTD and slip rates in the time range from about 0.2 to 2 million years.

The displaced flows have drawn the attention of geologists interested in rates of Colorado Plateau uplift (Hamblin and others, 1981) and in the slip behavior of basin-and-range faults (Anderson and Bucknam, 1979; Anderson and Mehnert, 1979; Anderson and Christenson, 1989). A study of basalt-capped inverted valleys associated with the Virgin River by Hamblin and others (1981) shows that for the past few millions of years, the western part of the Colorado Plateau has been rising along several major bounding faults, among them the Hurricane fault. They estimate that the block east of the Hurricane fault near Hurricane, Utah, is rising at an average rate of 300 m/m.y. (0.3 mm/yr). Their study takes the affect of backtilting (Hamblin's [1965] reverse drag) of the hanging wall toward the fault into account. Anderson and Christenson (1989) used radiometric ages on displaced basalts near the towns of Hurricane and Pintura, and in the North Hills south of Cedar City to estimate that stratigraphic throw on the Hurricane fault in Utah ranges from 300 to 470 m/m.y. (0.30 to 0.47 mm/yr). They acknowledge that these are probably maximum values because stratigraphic throw exceeds tectonic throw, the calculation of which requires subtracting the effects of fault-related flexing and antithetic faulting. They settled on an adjusted tectonic displacement rate of 300 m/m.y. (0.3 mm/yr) for the Hurricane fault as a whole. However, obtaining slip rates of sufficient accuracy to characterize the Hurricane fault's Quaternary slip history in detail requires that basalts on either side of the fault be correlated on a basis other than simply physical proximity, that the age of the basalt be determined isotopically, and that the NVTD recorded by the basalt be carefully determined.

Pintura Volcanic Center

Field study centered around the Pintura volcanic center (Figure 2.7), where basalt flows have been displaced vertically by about 450 meters across the Hurricane fault (Kurie, 1966; section

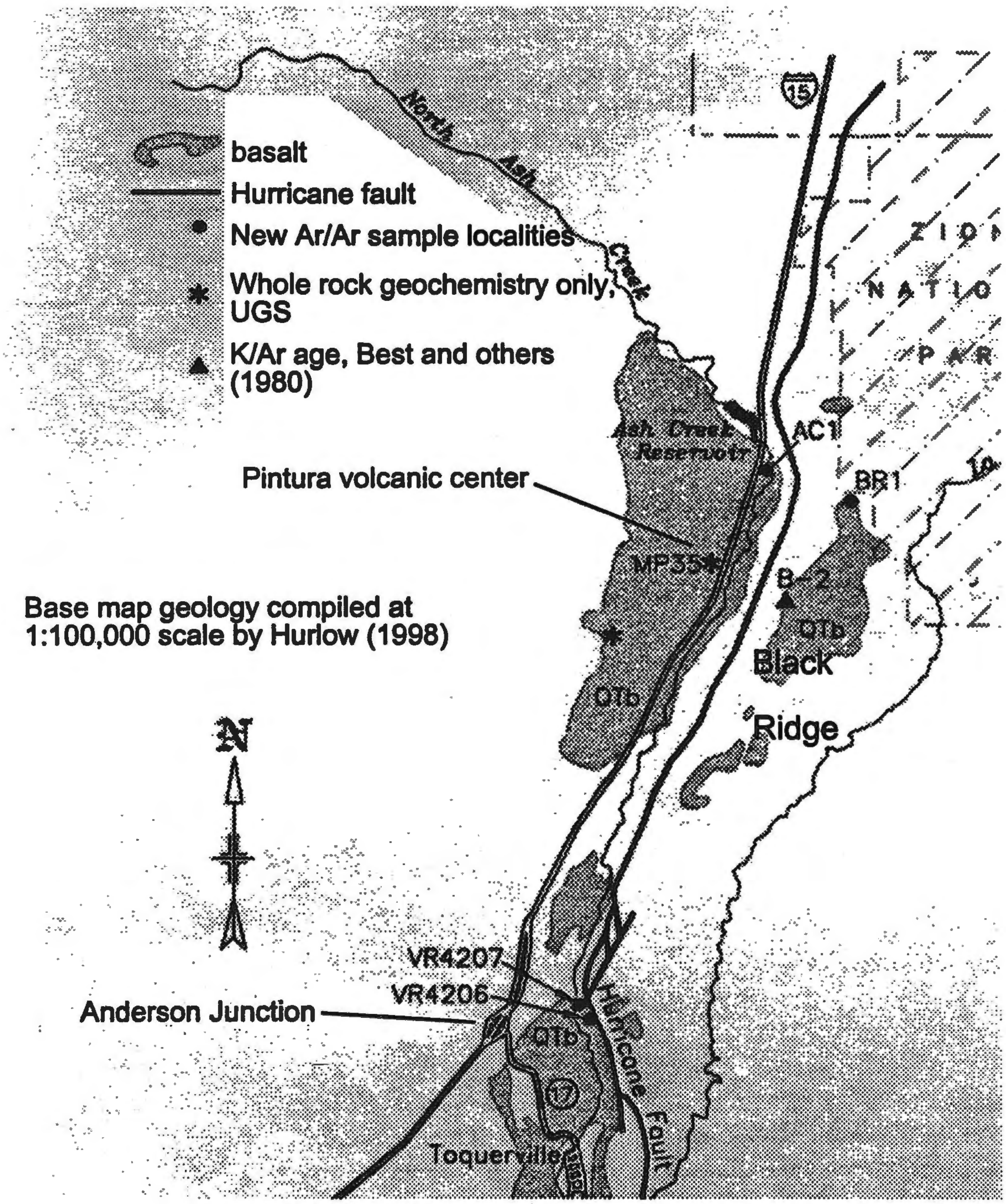

Figure 2.7. Basalt sample locations from the Pintura and Anderson Junctions areas along the northern Hurricane fault.

C-C'). Grant (1995) mapped part of this volcanic center in the southeast corner of the New Harmony 7.5' quadrangle. The center consists of a vent or cluster of vents, surrounded by lava flows which appear to thin radially away from the vent(s) in all directions.

The Pintura volcanic center holds some important geomorphic and geochronologic clues to the history and geometry of the Hurricane fault. While along most of the fault the hanging wall has been buried by Holocene alluviation or smoothed by erosion of soft sedimentary strata, near Pintura the hanging-wall block consists of resistant basalt flows that have preserved a record of tectonic deformation since their extrusion. The area contains the corners of four 7.5 minute quadrangles, only one of which has been mapped geologically at 1:24,000 scale (Grant, 1995). The Black Ridge has been mapped in detail by Kurie (1966), and the entire volcanic center has recently been mapped at 1:100,000 by Hurlow (1998).

Vent

The main vent is immediately west of Interstate -15 milepost 35 (MP35 Figure 2.8), and is mapped by Grant (1995) as basaltic breccia, consisting of "....scoriaceous basalt, poorly consolidated, in partially buried cinder cones. Possible source for nearby younger basalt flows." Anderson and Christenson (1989) show a vent on the top of the Black Ridge at the same latitude, but we did not visit it during the present study, and it is not shown on regional geologic maps of the area (Cook, 1960; Hintze, 1963, 1980).

In the vent area near milepost 35 (MP35 in Figures 2.7 and 2.8) flow rock is interbedded with layers of red and black scoriaceous basalt (cinders). East-dipping beds of cinders exposed in an abandoned borrow pit appear to slightly exceed the natural angle of repose, suggesting post-depositional tilting eastward toward the Hurricane fault. The vent has been modified by subsequent erosion. No crater remains, and the summit is underlain by flow rock rather than cinders. The summit of the vent is at an elevation of about 1493 meters. The surface of the basalt rises to the north and west, and exceeds 1615 meters 5 kilometers to the north. No scoriaceous basalt has been found at these higher elevations, suggesting no additional local source for the lava. The present elevation difference between the MP35 vent and the higher basalt flows is most likely the result of a combination of erosional lowering of the vent area, southeastward tilting of the entire volcanic field toward the Hurricane fault, antithetic (down-to-the-east) faulting in the Ash Creek graben, and possible subsidence over a cooling magma chamber.

Basalt

The volcanic rock is a dark gray, alkali olivine basalt (Grant, 1995). Up to 60 meters of layered flows are exposed in the footwall of the Hurricane fault, and the canyons of Ash Creek and its tributaries. In most areas, individual cooling units separated by breccia zones can be identified. Individual flows are very similar in composition, although some can be distinguished in thin section by plagioclase phenocrysts or alteration rinds on olivine, and by geochemical analysis (Schramm, 1994). At its northern margin, the volcanic package is both underlain and overlain by alluvium (Grant, 1995; cross section A-A'). No interbedded soils or gravels have been found, indicating that at least the upper 60 meters of flows were deposited in rapid succession.

Watson (1968) assigned the Pintura volcanic center basalts to Hamblin's (1963) Stage II-c basalt category. The age of the basalt is estimated at about 1 million years, based on the reversed magnetic polarity of the flows at Anderson Junction (Dr. Michael Hozik, Richard Stockton College of New Jersey, unpublished data), which likely originated from the Pintura volcanic center, and on a K-Ar date of 1.0±0.1 million years (B-2 in Figure 2.7) on a basalt from the middle of a stack of flows on Black Ridge, high on the footwall of the Hurricane fault (Best and others, 1980).

As part of this study, two samples, AC1 and BR1 (Figures 2.7 and 2.8), were submitted for $^{40}Ar/^{39}Ar$ isotope analysis. The purpose for dating the basalt was twofold: (1) to date the probable culmination of volcanic activity in the Pintura field, and (2) to test the age equivalence of the flow rock on the west and east sides of the fault. The sample ages (Table 2.2) are analytically indistinguishable (Lisa Peters, New Mexico Geochronological Research Laboratory, written communication, 1998).

Table 2.2. $^{40}Ar/^{39}Ar$ ages of basalt from the Pintura volcanic center

Sample #	Field Station	Location	Elev. (m)	Age (myr)
BR1	HFKA5	39S,12W, SW1/4sec 9 north end of Black ridge	1951	0.84 +/- .03
AC1	HFKA6	39S,12W, sec 7 west edge Ash Ck. Canyon	1439	0.88 +/- .05

The Pintura basalts were extruded onto an irregular topographic surface, and fill several pre-existing canyons in the foot slope of the Pine Valley Mountains. Along Ash Creek upstream from Ash Creek Reservoir they overlie a pre-basalt alluvium (Grant, 1995; cross section A-A'). The basal contact of the basalt is exposed at the mouth of Leap Creek (Figure 2.3), where it overlies a baked red soil. A tongue of basalt extends into the Pine Valley Mountains along the north side of Leap Creek Canyon, thinning rapidly upstream. In many places the basalt surface is littered with quartzite cobbles, and in Leap Creek Canyon is locally overlain by up to 30 meters of alluvial gravel containing boulders of Pine Valley latite. Flow direction indicators in the basalt

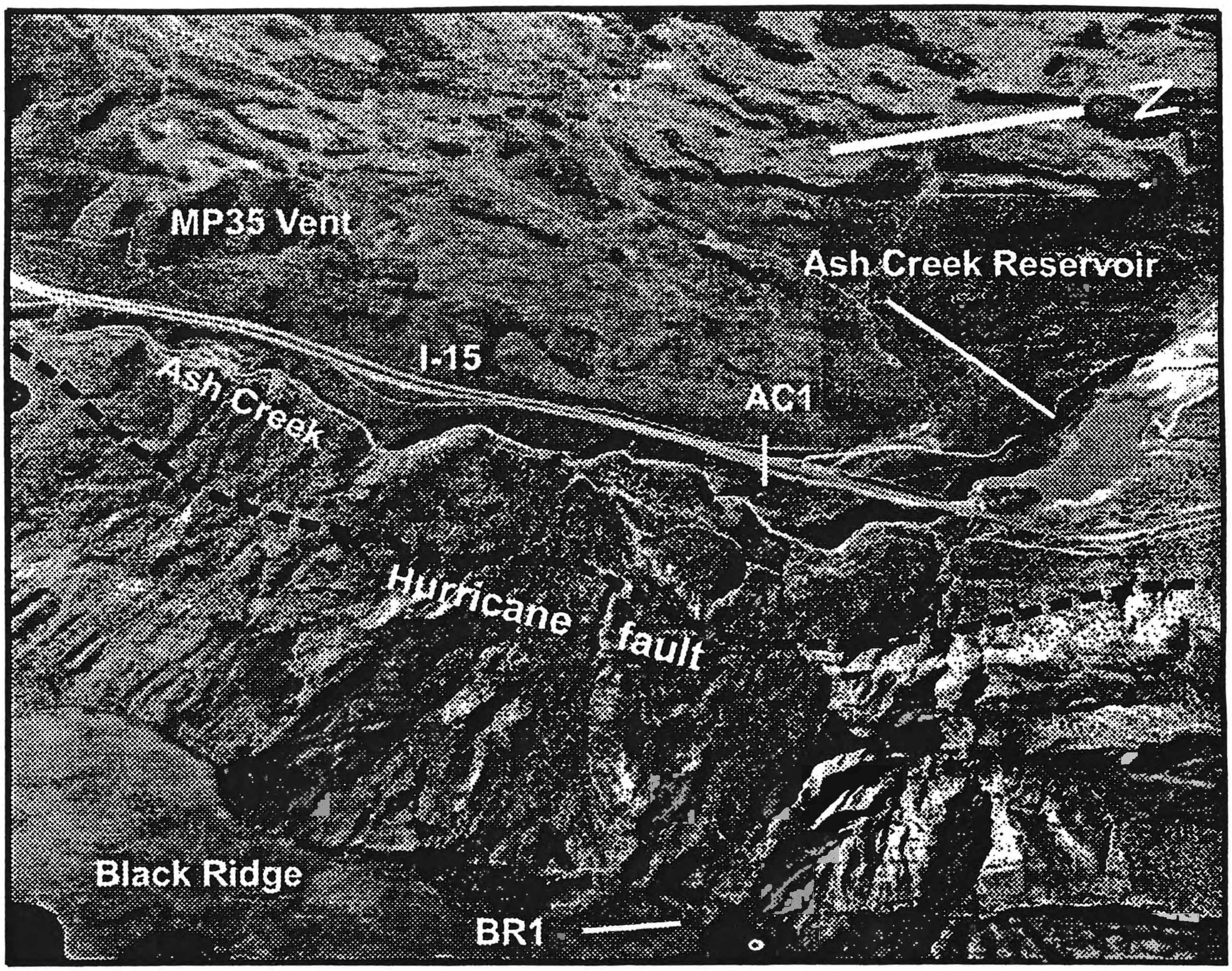

Figure 2.8. Oblique aerial view of the Pintura volcanic center showing the location of the MP35 vent and 40Ar/39Ar isotopic sample locations BR1 and AC1.

give a variety of directions, suggesting that flow was affected by local topography. We found no evidence for a vent in Leap Creek Canyon, and consider it most likely that the flow originated from the east and moved upstream. Following an initial period when the flow blocked the drainage and coarse sediment accumulated, Leap Creek subsequently eroded its modern canyon along the south margin of the flow.

Near Anderson Junction, an abandoned meandering stream channel is incised into the top of a basalt flow that occupies the ancestral channel of Ash Creek. This incised channel is partly filled with boulder gravel similar in composition to that of modern Ash Creek. It is interpreted as a post-basalt course of Ash Creek, altered by subsequent surface faulting on the Hurricane fault, which both fractured the basalt and tilted it toward the fault plane, causing the modern course of Ash Creek to migrate to the east and more closely follow the trace of the fault. This shows that by the end of basalt time, approximately 0.86 million years ago, there was a long-established escarpment along the Hurricane Cliffs, and that Ash Creek flowed south on the hanging-wall block near its present course. Therefore, offset on the Hurricane fault predates, was coincident with, and continued after, extrusion of the basalts.

Source

X-ray fluorescence spectrometry analyses of three basalt samples collected during this study (Figure 2.8): MP35, a volcanic bomb from the milepost 35 cinder pit; BR1, from the uppermost flow at the north end of Black Ridge (fault footwall); and AC1, from the uppermost flow in Ash Creek Canyon (fault hanging wall) due west of BR1. AC1 and BR1 are virtually identical in both major element and trace element composition, and MP35 is similar to them (Table 3). Therefore, we believe that these basalts are genetically related. They are also similar in composition to the samples from the Pintura locality of Schramm (1994).

Table 2.3. X-ray fluorescence spectrometry results (%) - Pintura volcanic center

Sample Number	Al_2O_3	CaO	Cr_2O_3	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	SiO_2	TiO_2	Total
MP35	15.80	7.27	<0.01	9.62	1.65	6.31	0.15	3.47	0.50	51.67	1.53	98.39
BR1	16.41	8.17	<0.01	9.38	1.45	6.71	0.15	3.58	0.44	51.60	1.60	99.43
AC1	15.84	8.16	0.01	9.37	1.51	6.92	0.14	3.59	0.41	51.96	1.52	99.07

The geologic, geochemical, paleomagnetic, and geochronologic data developed during this study suggest that the basalts which extend from north of Ash Creek Reservoir south to

Anderson Junction and possibly to Toquerville are genetically related and comprise a single source-related unit, herein called the Pintura volcanic center. The primary vent area was on the downthrown side of the Hurricane fault (MP35 vent, figures 7 and 8), and therefore lava was largely confined to the Ash Creek Valley by the rising Hurricane fault escarpment. Locally however, the stacked basalt flows achieved a thickness sufficient to allow basalt to flow across the escarpment such as at the north end of Black Ridge. Elsewhere, basalt flowed into and ponded in small reentrants along the Hurricane Cliffs and was left stranded on the fault footwall by subsequent faulting. Due to the close proximity of a source for the basalt on the west side (hanging wall) of the Hurricane fault, and the absence of a recognizable source on the east side (footwall), we assume no basalt cascading occurred over the Hurricane Cliffs, and that the present elevation difference between basalt on either side of the fault is entirely due to tectonic deformation.

Preliminary Slip-Rate Estimate

The Pintura volcanic center preserves abundant evidence of post-basalt deformation in the hanging-wall block of the Hurricane fault, extending from the Hurricane Cliffs westward to the foot slope of the Pine Valley Mountains across the Ash Creek graben. Deformation is characterized by antithetic faulting and a general eastward tilting of the ground surface, which becomes more pronounced toward the Hurricane fault. This monoclinal flexure is expressed in many locations along the fault, and has been much discussed in the literature, where it has been variously called "down bending" (Gardner, 1941) and "reverse drag" (Hamblin, 1965). This fold is cut by numerous parallel and presumably contemporaneous normal faults in the Ash Creek graben, that dip to both the east and the west. The basalt flow in Leap Creek Canyon is displaced by a down-to-the-east fault and declines in elevation eastward. If our preliminary assessment, that this basalt flowed upstream along Leap Creek from the east is correct, then its slope has been reversed in the past million years. This suggests that the zone of deformation extends considerably west of Ash Creek Canyon into the Pine Valley Mountains.

The difference in elevation of basalt sampled on the upthrown and downthrown side of the Hurricane fault (Table 2.2) is 512 meters. Because of the down bending of the hanging-wall block and antithetic faulting, however, this is not a good measure of the net vertical component of tectonic displacement. West of sample site AC1, basalt, assumed to be the same age, rises to an maximum elevation of 1615 meters. We believe the difference in elevation between the basalt that caps the north end of Black Ridge at 1951 meters, and the basalt on the downthrown block at 1615 meters, or 336 meters, is a more realistic estimate of the maximum NVTD recorded by the basalt across the fault. It should be noted however, that we have neither chemistry nor an age estimate for the basalt at 1615 meters. A vertical offset of 336 meters in 0.86 million years (new $^{40}Ar/^{39}Ar$ age estimate) yields an average slip rate of 0.39 mm/yr, which is consistent with earlier slip-rate estimates for the Hurricane fault in this area (Anderson and Mehnert, 1979; Hamblin and others,1981; Anderson and Christenson, 1989).

Extrusion of lava is frequently accompanied by subsidence. Therefore, displacements measured across the Hurricane fault in basalts associated with the Pintura volcanic center possibly contain a component due to subsidence over the emptying magma chamber. We are unable to evaluate the magnitude, if any, of this component.

Anderson Junction

Presently, the only other location in Utah where basalt has been unequivocally correlated across the Hurricane fault is at Anderson Junction. There, Stewart and Taylor (1996) used whole-rock trace-element analysis to show that basalts adjacent to each other on the footwall and hanging wall are correlative. They document 450 meters of stratigraphic separation in the basalt, but the basalt in the hanging wall is clearly tilted toward the fault. A study of remnant paleomagnetism (Dr. Michael Hozik, Richard Stockton College, unpublished data) in the same basalt analyzed by Stewart and Taylor (1996) shows that the hanging-wall basalt immediately adjacent to the fault is inclined 25 degrees toward the east. Additionally, several antithetic faults in the Ash Creek graben have displaced the hanging-wall basalt down-to-the-east by an unknown amount, but possibly more than 100 meters. The basalts on either side of the fault are paleomagnetically reversed and therefore are probably between 730,000 and 1.2 million years old. The basalt has been sampled for $^{40}Ar/^{39}Ar$ isotopic analysis by the Utah Geological Survey (VR4206 and VR4207, Figure 2.7), but those results are not yet available.

More work remains to be done at Anderson Junction, but when the $^{40}Ar/^{39}Ar$ laboratory analyses become available and the effect of antithetic faulting and backtilting are evaluated, it will be possible to calculate an accurate slip rate for the Hurricane fault at this location.

Results

The present study serves as a systematic reconnaissance of the Hurricane fault in Utah, allowing identification of critical areas for future study and providing a more detailed analysis at a few locations. Results of this study are summarized below.

(1) Fault scarps on unconsolidated deposits are more common than previously realized; a total of six sites are now known, five identified during this study.

(2) The youngest alluvial deposits displaced by the fault are latest Pleistocene or early Holocene; accurate age determinations of the deposits await detailed paleoseismic (trenching) studies.

(3) Large, multiple-event scarps, both bedrock-cored and on unconsolidated deposits, indicate that portions of the fault in Utah have experienced recurrent late Quaternary surface faulting.

(4) Differences in the abundance, type, and preservation of scarps along the fault suggest variations in slip rate and indicate that the Utah portion of the fault may consist of multiple seismogenic segments.

(5) The greatest number and best preserved scarps in Utah are at the north end of the fault, indicating that part of the fault is likely the most recently active.

(6) A well-developed graben (herein named the Ash Creek graben) parallels the fault for at least 17 kilometers through Ash Creek Canyon. Net vertical tectonic displacement down-to-the-east across the graben may exceed 100 meters in some locations. Locally, the west edge of the graben extends into the foot slope of the Pine Valley Mountains.

(7) A volcanic center (herein named the Pintura volcanic center) consisting of a main and possibly several smaller vents, lies immediately west of the fault in Ash Creek Canyon and is the most likely source of the basalt flows displaced across the fault along Black Ridge. The volcanic center's location west of the fault precludes the possibility of basalt cascading over the Hurricane Cliffs.

(8) New $^{40}Ar/^{39}Ar$ isotope age estimates and geochemical analyses on basalt flows associated with the Pintura volcanic center correlate basalt displaced across the Hurricane fault and provide a preliminary long-term (past 850,000 years) slip rate for the fault of 0.39 mm/yr.

(9) Preliminary ^{26}Al cosmogenic isotope dates from sandstone cobbles on the alluvial surfaces on either side of the Hurricane fault at Shurtz Creek indicate both surfaces are about 15 to 18 thousand years old. Soil-profile data show both surfaces are considerably older, but not age correlative. The upthrown surface may be as old as 100,000 years, and the downthrown surface may be as much as 50,000 years old. Additional ^{26}Al, ^{10}Be, and ^{36}Cl isotope analyses are pending from the two surfaces.

(10) Numerous uncertainties regarding geologic relations at Shurtz Creek remain to be resolved by additional age dating and possible detailed paleoseismic studies. However, a preliminary, minimum late Quaternary slip rate of 0.11 mm/yr was obtained there assuming: (a) an age for the upper surface of 100,000 years, and (b) that the interval between deposition of the pediment deposits and the onset of surface faulting is roughly equivalent to the interval since the most recent surface-faulting earthquake.

(11) Slip-rate estimates of 0.11 to 0.33 mm/yr for the latest Pleistocene to early Holocene at Murie Creek are preliminary maximum values and require confirmation by a detailed paleoseismic study.

Conclusions And Recommendations

In Utah, the Hurricane fault has had at least one large, surface-faulting earthquake since the latest Pleistocene or early Holocene. The event(s) were at the north end of the fault. Additionally, most, if not all, of the fault has experienced recurrent surface-faulting earthquakes in the late Quaternary, a time frame of interest for seismic-hazard analysis. Existing data (Hamblin and others, 1981; Anderson and Mehnert, 1979; Anderson and Christenson, 1989) and preliminary information developed during this study indicate a slip rate for the Hurricane fault over the past about one million years of 0.3 to 0.4 mm/yr. That rate is roughly one-third the Holocene slip rate for the most active central segments of the Wasatch fault in northern Utah, and about twice the late Quaternary slip rate estimated for the Wasatch fault from limited pre-Lake Bonneville data (Machette and others, 1992). Preliminary data indicate a late Quaternary (~ past 100,000 years) slip rate of 0.11 mm/yr for the northernmost part of the Hurricane fault, about one-third the fault's long-term rate, and about one-tenth the rate of the Wasatch fault's most active segments during the Holocene. These findings do not contradict the previously observed disparity between long-term slip rates calculated from displaced basalt flows (0.3 to 0.4 mm/yr) and a general lack of strong evidence for repeated latest Pleistocene or Holocene surface faulting on the Hurricane fault. This suggests that fault slip has been episodic or variable through time, or that the displacement of basalt may, at least locally, include a component of sag over a cooling or drained magma chamber(s). Determining the extent to which this difference in tectonic activity is real or perceived awaits completion of future detailed paleoseismic studies along the fault, as does resolving the question of seismogenic segmentation.

The potential for developing detailed paleoseismic information about the size and timing of prehistoric surface-faulting earthquakes on the Utah portion of the Hurricane fault is good. Although lacking the abundance of young scarps on unconsolidated deposits characteristic of the more active Wasatch fault, several sites (both alluvial and bedrock) exist along the Utah portion of the fault with the potential to provide detailed paleoseismic information. The distribution of those sites is such that it should be possible to test the hypothesis that large bends in the trace of the fault are seismogenic segment boundaries. Much of the land along the Hurricane fault in Utah is privately owned, and land ownership considerations may present a constraint on future trenching studies.

Although not as active as faults near plate boundaries, Basin and Range normal faults represent a significant earthquake hazard in the western United States. Because their recurrence intervals are long, typically thousands to tens of thousands of years or more, characterizing their long-term behavior is often difficult. Unanswered questions include whether Basin and Range faults behave regularly through time or if they "speed up and slow down," or even "turn on and off," and if so, on what sort of schedule. The Hurricane fault is an ideal candidate for studying the long-term behavior of Basin and Range normal faults because it offers the opportunity to develop and compare long-term (displaced basalt), medium-term (displaced older alluvial and colluvial surfaces) and short-term (displaced young alluvium) slip rates, thus allowing characterization of the fault's movement history from the mid-Quaternary (past million years) to the latest Pleistocene or Holocene. The new slip-rate data developed by this study and the data that will become available when additional cosmogenic isotope (Shurtz Creek) and $^{40}Ar/^{39}Ar$ isotope (Anderson Junction basalt) analyses are complete represent a first step toward evaluating the long-term slip history of the Hurricane fault.

Recommendations for future study of the Hurricane fault in Utah include:

(1) Trench single and multiple-event scarps at as many of the six sites with scarps on unconsolidated deposits as possible to develop information on the size and timing of individual past surface-faulting earthquakes. Bedrock-cored scarps should be trenched as necessary to fill data gaps along the fault.

(2) Identify the source, age, correlation, and NVTD of basalts displaced across the Hurricane fault. In addition to the flows in the Pintura volcanic center and at Anderson Junction, it may be

possible at a minimum of three other locations to correlate basalt flows across the fault and calculate long-term slip rates.

(3) Use cosmogenic isotope abundances, soil chronosequences, or other methods to estimate the age of late Quaternary surfaces displaced by the fault and survey scarp profiles to determine NVTD across the fault; calculate medium-term slip rates.

(4) Map the Ash Creek graben in detail and measure the total down-to-the-east NVTD across the graben along transects tied to displaced basalt flows along the Hurricane fault. This information is critical to determining the NVTD of the basalt across the Hurricane fault and to understanding the subsurface geometry of the fault and the width of the zone of deformation.

(5) Make a detailed study of reverse- and normal-drag flexing associated with the fault in areas adjacent to displaced basalt flows to help determine NVTD. Hozik (unpublished data) has had good initial success at Anderson Junction and at other locations along the fault using divergence of paleomagnetic vectors between basalts in the hanging wall and the footwall of the fault to detect and measure both normal- and reverse-drag folding and footwall rebound.

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CHAPTER 3. PALEOSEISMOLOGY OF THE SOUTHERN ANDERSON JUNCTION SECTION OF THE HURRICANE FAULT, NORTHWESTERN ARIZONA AND SOUTHWESTERN UTAH

by Heidi Stenner and Philip A. Pearthree

Introduction

Normal slip along the Hurricane fault during the late Cenozoic has produced an impressive escarpment in northwestern Arizona and southwestern Utah (Figure 3.1). This major west-dipping normal fault within the transition zone between the Colorado Plateau and the Basin and Range physiographic provinces of the U. S. has not ruptured historically. However, unconsolidated alluvial deposits of different ages are vertically displaced across the fault. Late Pleistocene alluvium is displaced up to 20 m and alluvium likely to be Holocene is vertically offset by less than one meter. The different displacements provide evidence for recurrent slip in the Quaternary and Holocene activity is probable.

Previous workers have documented displaced Quaternary basalt flows and alluvial deposits along the Hurricane fault (Stewart *et al.*, 1997; Stewart and Taylor, 1996; Schramm, 1994; Menges and Pearthree, 1989; Anderson and Christenson, 1989; Hamblin, 1984; Menges and Pearthree, 1983; Hamblin *et al.*, 1981; Huntoon, 1977; Hamblin, 1965). However, data are currently lacking for magnitude, timing, and along-fault position of late Quaternary surface-rupturing earthquakes. Developing this information for a portion of the fault is the purpose of this study and is an essential step toward an assessment of the area's potential seismic hazard. Results of the first trenching studies of the Hurricane fault, topographic scarp profiling, soil analyses, cosmogenic isotope dating, and geomorphic modeling of displaced, unconsolidated, late Quaternary alluvial units are discussed in this paper. A site at Cottonwood Canyon, Arizona, is examined in detail and a 30-km-long portion of the fault is evaluated at a reconnaissance level (Figure 3.1).

Cottonwood Canyon Site

Cottonwood Canyon is a large drainage cut through the Hurricane Cliffs on the southernmost portion of the Anderson Junction section (Figure 3.2). At the canyon mouth, the Hurricane fault displaces several alluvial surfaces of different ages. A detailed study using trench analysis, scarp profiling, cosmogenic isotope dating, and soil analysis at the Cottonwood Canyon site produced an estimate of the timing and size of the most recent event (MRE) and an assessment of the late Quaternary tectonic activity for the area.

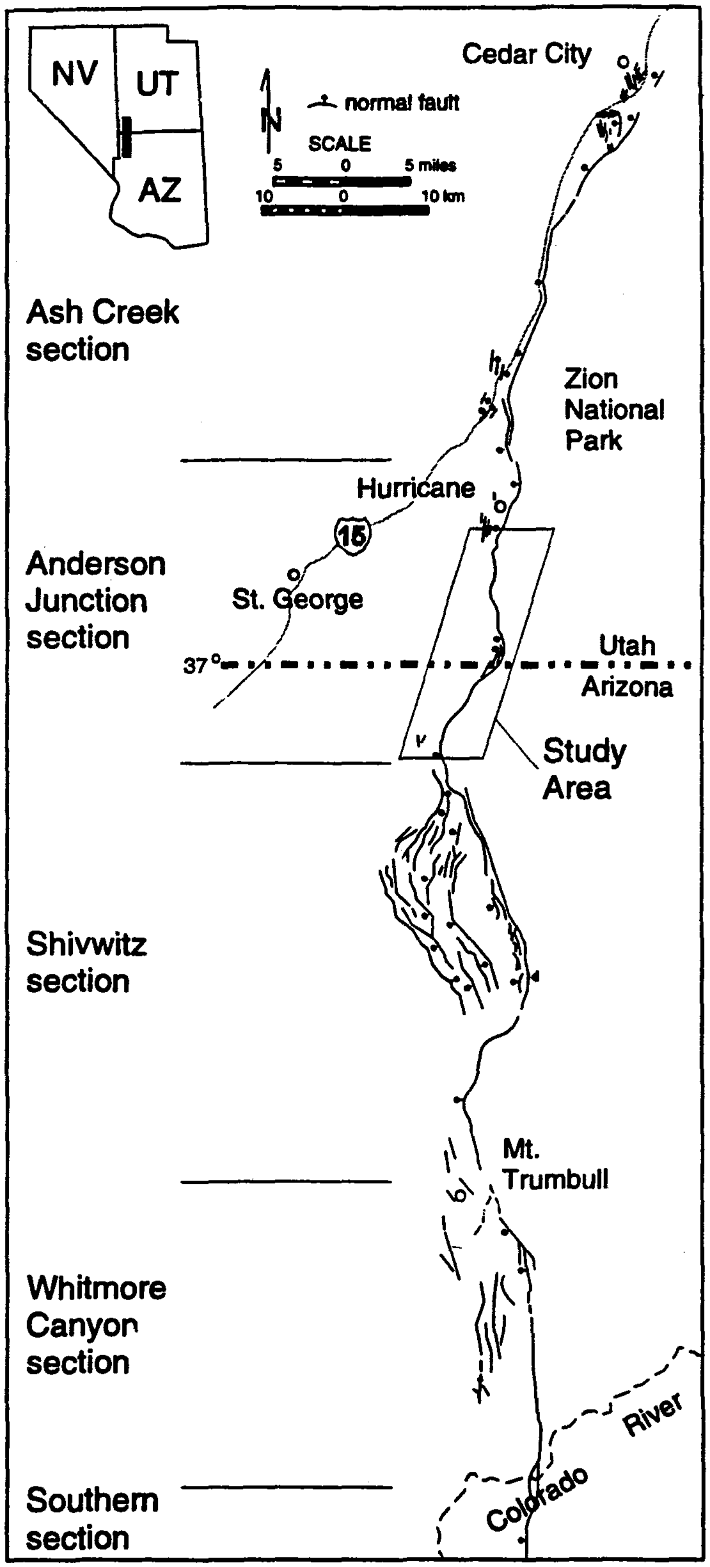

Figure 3.1. Map of the Hurricane fault location and the five sections that it is separated into. The boxed study area is the site of detailed work and is shown in Figure 2.

The Cottonwood Canyon site is suitable for detailed study because of the multiple well preserved fault scarps present in different aged units (Figure 3.2). Faulting in this area is confined to a single strand, and the observed fault scarps represent all of the fault slip. These scarps delineate a fault trace that continues relatively consistently for 2 km to the south/southwest. Younger deposits cover the fault trace to the northeast near the modern active channel for the Cottonwood Canyon drainage (Figure 3.3). Northeast beyond Cottonwood Canyon and the young deposits, the fault scarps reappear for another 9-10 km. Most of the faulted landforms are buried minimally on the downthrown side, enabling near-total surface displacement measurements to be made from topographic scarp profiles.

The large Cottonwood Canyon drainage that has incised through the cliffs has produced terrace landforms at the canyon mouth which are well suited for paleoseismic studies. Stream terraces composed of fluvial and debris flow deposits provide landforms of low slope which are useful in providing evidence of the most recent event. Scarps formed on gently sloping surfaces are not as rapidly modified by surface processes to merge with the surrounding landform, as in steeply-sloping alluvial fan and colluvial deposits. Also, soil develops more slowly and unpredictably on steep slopes than on gently-sloping surfaces because increased runoff over steep landforms decreases moisture infiltration. Gentle slopes are better suited for estimating the time during which the surface was stable. In addition to alluvial terraces there are also abandoned low to moderately sloping alluvial fans at the mouth of Cottonwood Canyon and nearby at the base of the cliffs which record fault displacement. Holocene and latest Pleistocene terraces (surfaces Q1 and Q2) as well as a late Pleistocene alluvial fan (Q3) at Cottonwood Canyon were profiled, examined for soil development, and two trenches were excavated for paleoseismic information of the MRE (Figure 3.3).

Topographic and Quaternary Surface Map

A topographic map of the Cotonwood Canyon site was produced to illustrate the relationships between fault scarps at the site and the Quaternary units mapped over the topography (Figure 3.3). Three faulted deposits, one unfaulted deposit, their relative elevations, and how they fit into the landscape are shown. Surface Q3 on the map is an alluvial fan that has developed at the base of the Hurricane Cliffs which supplied the material source for deposition. Surface Q4 is a remnant of an older alluvial fan similarly formed at the cliff base. Neither fan currently receives active deposition and both have been displaced by the Hurricane fault. Inactive alluvial fan/fluvial terrace units Q2, Q1, and Q0 are formed from the accumulation of debris flows and fluvial deposits that originated from the ephemeral Cottonwood Canyon wash. Both Q3 and Q2 surfaces contain fault scarps large enough that the scarp faces are covered in a colluvium which is distinguished from the rest of the surface on the map. Generally the surfaces are older and higher in elevation away from the active drainage. The Permian Hermit Shale crops out between the Q3 and Q2 surfaces in a bedrock fault scarp that has retreated away from the fault due to erosion.

The 1:3050 scale topographic map of the Cotonwood Canyon area was produced using a laser-based total station (Figure 3.3). Overall data density for the topographic survey is

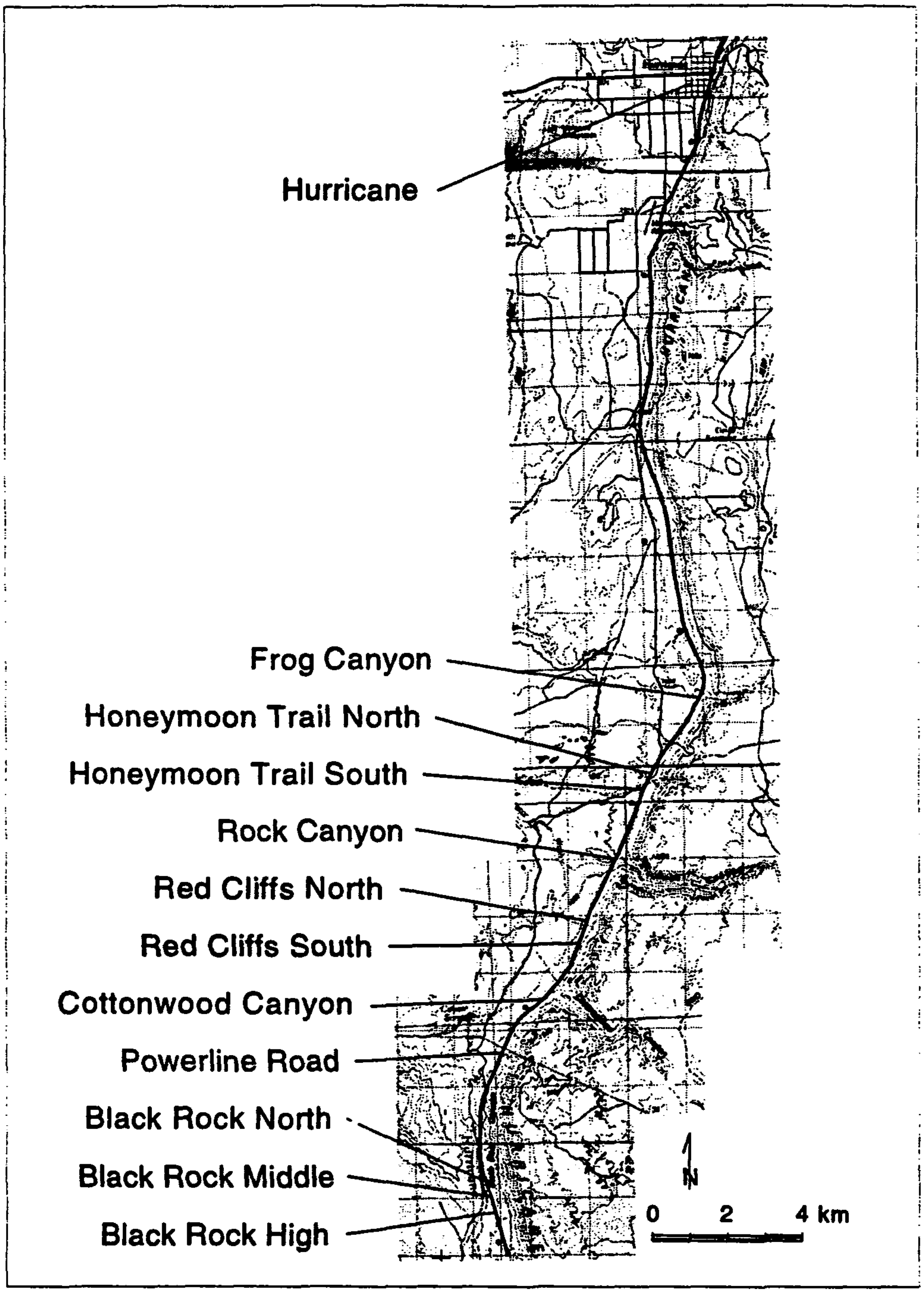

Figure 3.2 Topographic map of the study area within the Anderson Junction section of the Hurricane fault. Locations of sites containing late Quaternary fault scarps discussed in text are shown. Contour interval of the topographic base is 50 m.

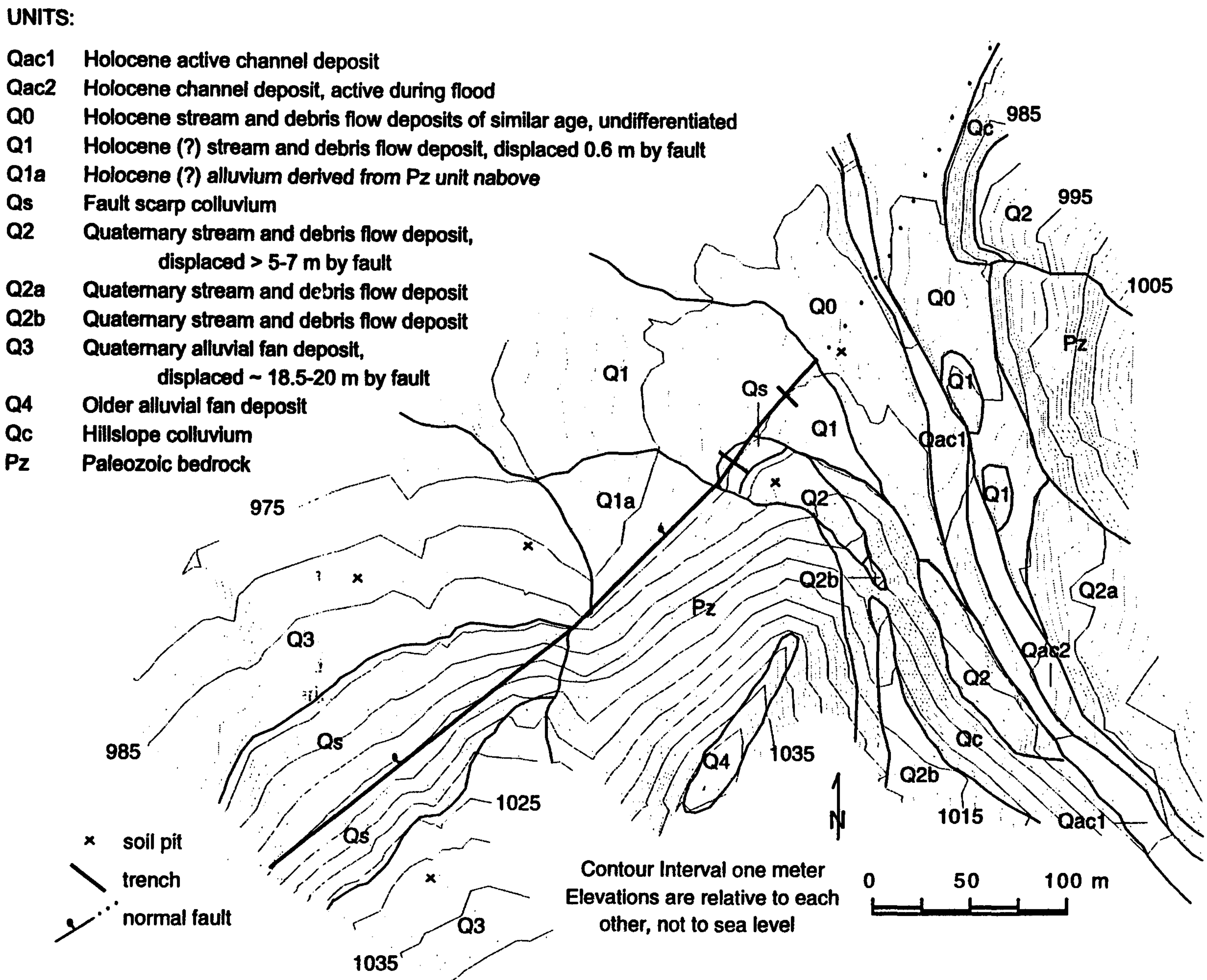

Figure 3.3. Detailed topographic and geologic map of the mouth of Cottonwood Canyon, southern Anderson Junction section, Hurricane fault.

approximately one point every five meters. Data are spaced approximately one meter apart where topography changes abruptly, particularly on fault scarps. Topographic scarp profiles were also constructed using the total station.

Surface Displacement

In order to measure the amount of displacement that each alluvial surface records, topographic profiles were surveyed across fault scarps produced in them. Using a total station a profile line was selected perpendicular to the trace of the fault and parallel with the gradient of the landform, which were essentially coincident. The profile line was placed in a location representative of the landform (drainages were avoided) and was kept as straight as possible. Net vertical tectonic displacements from the profiles were obtained by extrapolating the up- and down-thrown surfaces into the fault and measuring the vertical offset (Figures 4 and 11). Evidence for significant lateral offset was never observed.

At Cottonwood Canyon, depositionally abandoned alluvial fan surface Q3 contains the largest scarp and has the highest surface elevation of the faulted deposits. A displacement of 18.5-20 m across the Hurricane fault is estimated for the fan deposit (Figures 3 and 4a). The down-thrown portion of Q3, away from the fault scarp, has not been buried by a significant amount of younger material, indicated by similar morphology. Parallel with the fault, the surface on both sides have the same length and convex-up shape. Surface smoothness and degree of desert pavement development are also similar across the fault.

Surface Q2, an alluvial terrace at an elevation intermediate between that of Q3 and Q1, has a surface displacement of at least 5 m (Figures 3 and 4b). A 14-m-long trench excavated to a depth of 2 m across the Q2 scarp did not expose strata within the hanging wall that is also present at the surface of the footwall. This means that the total displacement is probably >7 m with burial of the down-faulted surface. However, it is possible that the original down-dropped surface has been eroded at the base of the scarp by periodic stream flow that also deposited the material now seen exposed in the hanging wall.

The Q1 landform is an alluvial terrace produced from fluvial and debris flow deposits. It is low in elevation relative to the others, and is of probable Holocene age based on weak soil development (Appendix 4). Roughness of the surface as a result of its youth causes the fault scarp to be difficult to distinguish from other boulder-produced bumps on the profile. In the field, however, the fault scarp is continuous for ~13 m and the trend is on a straight line with the larger scarps in surfaces Q2 and Q3. Net vertical displacement estimated from the profile yields 0.6-0.7 m (Figure 3.4c). This small displacement formed during the MRE on the fault in this area.

Southwest of Q3 are two other surveyed scarps within half of a kilometer, Q4 and Q6. With a displacement of ~10-12 m, Q4 is younger and lower in elevation than surface Q3, but higher than Q2 (Figure 3.4d). Surface Q6 is an alluvial fan that is steeper than that of Q3 but is displaced the same amount, 18-20 m (Figure 3.4e).

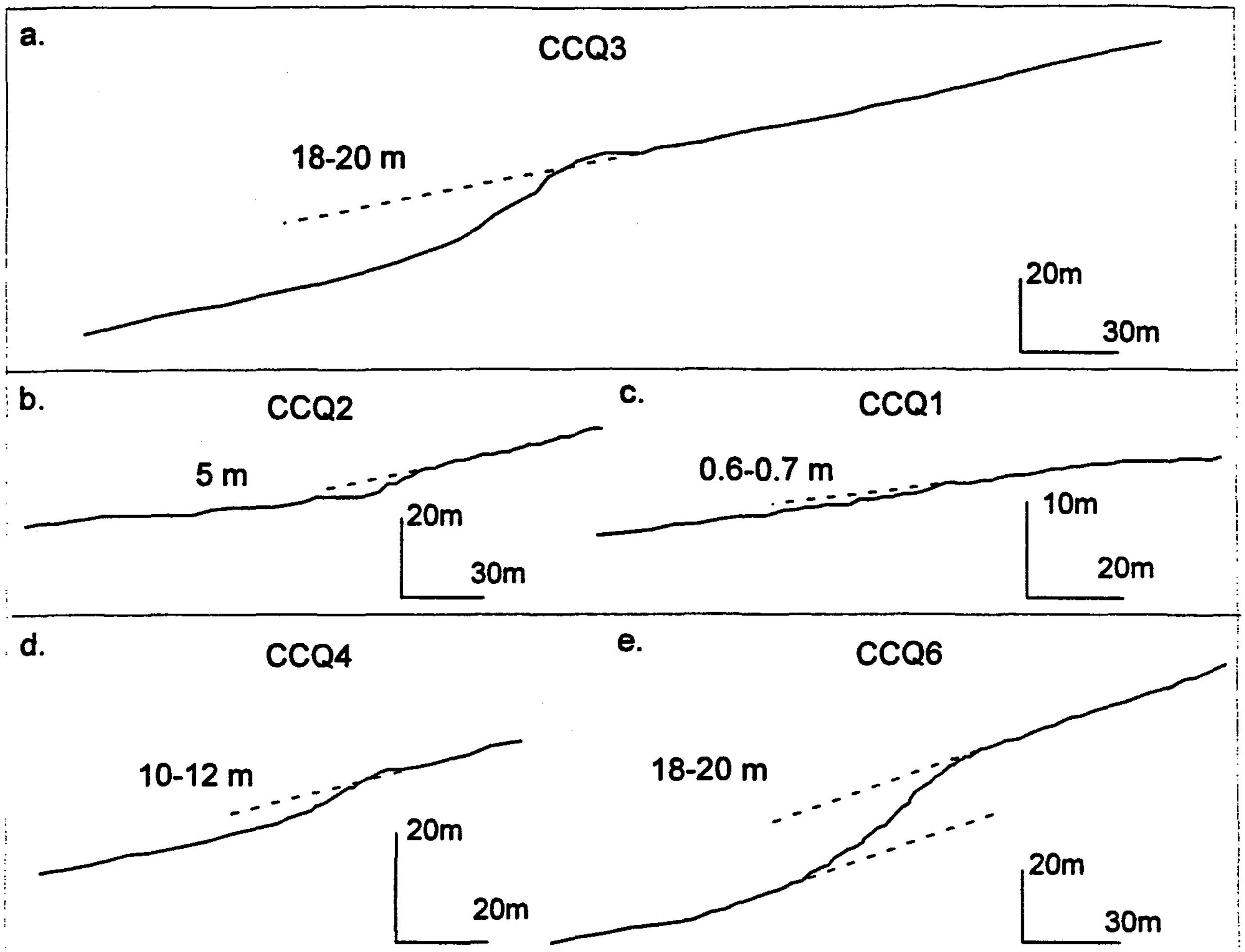

Figure 3.4. Topographic profiles and net vertical tectonic displacement measurements of late Quaternary alluvial surfaces (a) CCQ3, (b) CCQ2, (c) CCQ1, (d) CCQ4, and (e) CCQ6 at the Cottonwood Canyon site, Arizona.

Soils for Surface Dating Estimates

The degree of soil development for the Cottonwood Canyon surfaces Q3, Q2, Q1, and Q0 is used to estimate the amount of time elapsed since each unit was actively aggrading (Figure 3.3). This soil age is an approximation of the amount of time passed after the surface was first faulted, and is used to estimate fault slip rates. Fault displacement is likely to cause abandonment of a surface from active deposition because of the increase in relative elevation on the up-thrown side of the fault, so soil age is a reasonable estimate of the time of cumulative fault movement recorded by the fault scarp. It is possible that the surface had been abandoned and soil development began before the surface was faulted. In this case, the soil age is a maximum for the time of cumulative fault slip on that surface, and the resulting slip rate from the age is a minimum.

With 20 to 28 cm of precipitation per year, a mean annual temperature of 15 to 17 C, and an elevation of 1100 m the study area is arid to semi-arid (Gile and Grossman, 1979; www.wrcc.dri.edu for La Verkin and St. George, Utah, 9/30/98). In arid and semi-arid climates the relative abundance, location, and structural development of pedogenic calcium carbonate at depth within soil profiles is a primary indicator of soil development. Evidence of clay eluviation is another important indicator. Clays tend to move downward over time in a soil profile to accumulate below the A horizon (Birkeland, 1984; Birkeland *et al.*, 1991). The migration is due to clay forming as dissolved weathering products from above, and precipitating into, the zone of clay accumulation (Birkeland *et al.*, 1991). Eluviation also results from existing clays moving in suspension of percolating water until flocculation, constriction of flow pathways, or evaporation/transpiration of the water forces clay deposition (Birkeland *et al.*, 1991).

Soils containing high calcium carbonate content usually develop without considerable clay migration (Gile and Grossman, 1979; Birkeland *et al.*, 1991). The clays commonly exchange ions with the readily available calcium ions present in the soil and the resulting calcium-rich clays are frequently flocculated (Gile and Grossman, 1979; Birkeland *et al.*, 1991). These clay aggregates are less likely to migrate through soil pore space and along ped faces than dispersed clay (Birkeland *et al.*, 1991). The flocculated condition of the clay usually remains until much of the calcium carbonate is leached to lower in the soil column, allowing clay to exchange many Ca^{2+} with other ions and disperse (Birkeland *et al.*, 1991). Sediment in the studied area of the Hurricane fault contains abundant calcium carbonate derived from the limestone and calcareous sandstone and siltstone parent material. Calcium-rich to begin with, the soils showed little evidence of clay accumulation.

Without clay illuviation to indicate soil development, and therefore time, calcium carbonate accumulation is particularly useful as an age indicator for the Hurricane fault soils. In addtion to the lithic fragment contribution of calcium to the soils, more is introduced by rainwater and aeolian dust (Birkeland, 1984). Carbon dioxide, in the atmosphere and in the soil from microorganism and root respiration and decomposition, reacts with water to form bicarbonate (Birkeland, 1984). Both calcium and bicarbonate are carried downward by percolating water in the soil column. As water is lost due to evaporation and transpiration, calcium carbonate precipitates (Birkeland, 1984). Precipitation begins as thin filaments within the fine grained alluvium and over time continues to accumulate, first on the bottoms of gravel clasts, then as continuous carbonate coatings around the clasts which thicken with time, until eventually there is enough carbonate in the matrix and on the clasts that the wetted horizon to which precipitation reaches becomes cemented and plugged (Birkeland, 1984). The carbonate plug prevents moisture from penetrating and further carbonate accumulates on the top of the plug. Alternating dissolution and reprecipitation causes lamination of the cemented carbonate (Gile and Grossman, 1979; Birkeland *et al.*, 1991). As long as the climate does not become substantially wetter for the stable surface, the soil will continue to accumulate calcium carbonate.

Because carbonate accumulates in a soil consistently with time for that region, comparison of the carbonate stage is used to correlate deposits (Birkeland *et al.*, 1991). Soil descriptions were taken to compare similarities of carbonate content, texture, soil structure, and color with other soils of known numerical age (descriptions in Appendix 4). The Desert Project and area near Las Cruces, New Mexico, is a close analog to the climate of the studied portion of the Hurricane fault (Gile and Grossman, 1979; Gile, 1994). Based on the ages of described soils of the Desert Project, correlative ages are estimated for the soils at Cottonwood Canyon (summarized in Table 3.1).

Surface	Carbonate Development	Estimated Age (ka)
Q0	stage I; thin, discontinuous coatings on clast bottoms (sparse)	2-6
Q1	stage I; thin, discontinuous coatings on clast bottoms	8-15
Q2	stage I to I+; thin, discontinuous to continuous clast coatings	20-50
Q3	stage (II+ to) III, strongly cemented horizon	70-125

Table 3.1. The carbonate development for soils at the Cottonwood Canyon, Arizona, site and the age for the surfaces estimated from comparison of the soil characteristics with those of known age (Gile and Grossman, 1979; Gile, 1994).

Soils were studied on the upthrown sides of the fault for the displaced surfaces Q3, Q2, and Q1 at Cottonwood Canyon as well as the downthrown side of Q3. Soil of surface Q0, which has not been faulted, was also analyzed (Figure 3.3). Locations of the soil pits were chosen for their adequate representation of each surface. The pits were located 1) away from the crest or toe of the fault scarp to minimize the impact on the soil of diffusive erosion or deposition from the scarp slope, 2)away from any channels on the surface, and 3) where grain size was typical for that surface. Soils of Q1 were described in exposures in a trench across the fault. Although the description is based on a profile 3 m away from the fault zone, the scarp height is only ~50 cm and the effect of diffusion across this size scarp is interpreted to only have significant potential impact on soil development for a distance of ~1 m. A pit was excavated and interpreted on surface Q0, an alluvial terrace not displaced by the fault and therefore younger than the MRE (Figure 3.3). An age estimate for surface Q0 provides constraint on the recency of the MRE.

All soils are moderately coarse to coarse (all with an average >2mm grain size fraction of 60-75%, typically with >30% gravels of size larger than 5 mm). An exception is the soil within the fault zone of trench Q2 (fine to very fine grained with 5-20% gravel). The trend is for soils at Cottonwood Canyon of increasing elevation (and increasing age) to have an increased reaction to hydrochloric acid (increased carbonate accumulation) as well as displaying redder hues and higher chromas (Appendix 4). Soil profile development is invariably expressed as an A horizon overlying a weak B horizon that is based on color and/or weak to moderate structure, followed by carbonate rich horizons. In the bottom of the younger soil profiles the presence of gypsum with minor carbonate is observed. Accumulations of significant amounts of clays to form Bt horizons was not observed within the study area.

On the up-thrown slope of the Q3 alluvial fan, the soil has reached stage III carbonate development, with strong but unlaminated carbonate cementation at 35-69 cm depth (CCQ3U, Figure 3.3; Appendix 4). On the lower slope of the Q3 landform, the orange-brown soil has a less well developed carbonate horizon, but still contains a strongly cemented horizon reaching stage II+ to III development at a depth of 44 to 62 cm (CCQ3D, Figure 3.3; Appendix 4). The CCQ3D soil pit was excavated near the margin of the alluvial fan instead of on the apex where the correlative pit on the up-thrown portion of the surface is placed. A more shallow pit was excavated near the apex and although it was not excavated through the zone of maximum carbonate content, it did show more advanced accumulation of carbonate. It is likely that the differences in development across the fault are the result of lateral variation in the surface and due to the position of pit CCQ3D near the fan edge. Increased runoff/reduced infiltration on the fan edges because of its greater slope may be the reason for reduced soil development. Smoothness, desert pavement character, and overall shape of the Q3 landform on either side of the fault are similar, and when combined with the soil analyses helps establish the correlation between the two surfaces.

The orange Q3 soil is estimated to have been forming for 70 to 125 ka, by comparison with those of south-central New Mexico (Gile and Grossman, 1979; Gile, 1994). In the Desert Project area soils of Jornada I age (200-300 ka; Gile and Grossman, 1979) display greater development than Q3, including laminated carbonate horizons. Color and carbonate content of the Q3 soil are similar or better developed than observed in early Picacho (25-75 ka; Gile and Grossman, 1979) and Organ I (>100 ka; Gile, 1994) soils.

The footwall surface of Q2 has developed a stage I to I+ carbonate, containing clasts with thin discontinuous to continuous carbonate coatings. Maximum carbonate content occurs at a depth of 39 to 59 cm (CCQ2U, Figure 3.3; Appendix 4). The down-faulted Q2 soil in the hanging wall has probably been buried by younger material of roughly Q1 type and age and was not exposed to a depth of 2 m. Hanging wall soil formation is similar to that of the fault zone exposed in the Q2 trench, containing moderately developed structure and stage I disseminated carbonate (CCQ2-Wedge, Appendix 4). This tan soil is estimated to have been forming for 20 to 50 ka. Desert Project soils of Picacho age are similar to Q2, with 15-25 ka Pacacho soil (pedon 66-1; Gile and Grossman, 1979) showing less development and 25-75 ka Pacacho soils displaying more development, namely plugged carbonate horizons (Gile and Grossman, 1979).

Moderately developed structure and stage I carbonate with thin discontinuous carbonate coatings on clast bottoms are representative of the surface Q1 soil (CCQ1, Figure 3.3; Appendix 4). Compared with soils in southcentral New Mexico, this surface is estimated to be 8-15 ka, probably Holocene. Desert Project area Isaacks' Ranch soils (8-15 ka; particularly pedon 67-5) show patchy cementation, greater development than Q1soil, but Leasburg soils of the same age (particularly pedon 66-3) have less development than observed for Q1 (Gile and Grossman, 1979). Soil was described within the footwall exposed in the Q1 trench. Similar development was exposed on both sides of the fault.

The fluvial terrace that is not displaced by the fault (Q0) shows a soil with weak structure and stage I- carbonate, displaying sparse carbonate coatings on clast bottoms (CCQ0, Figure 3.3; Appendix 4). The Holocene surface age is estimated to be 2 to 6 ka, based on Desert Project area similar soils of Organ age (2-6 ka) and showing less development than Leasburg soils (8-15 ka; Gile and Grossman, 1979). Soils Q0 and Q1 bracket the age of the MRE at Cottonwood Canyon. The MRE occurred 2-15 ka before present, 5-10 ka ago likely.

The soil-based surface ages estimates cannot be used for precise calculations of slip rates, but the ranges are rough numerical surface ages and useful for studying the Hurricane fault slip history. Surface ages may contribute to an underestimated slip rate because it is possible for the surface to have been isolated from active aggradation for an unknown amount of time before the fault ruptured. It is much less likely that the surface age is contributing to overestimation, because when a rupturing event occurs the up thrown surface frequently becomes higher in elevation and the site of slow degradation instead of deposition. A rupture would likely initiate channels that would begin incising into the footwall, as baselevel has been lowered for the footwall relative to its pre-rupture environment. This depositional isolation is the ideal situation for using the surface ages to evaluate the amount of time during which the fault scarp developed.

Carbonate Rind Methods

In addition to describing the soils using traditional classification methods a quantitative evaluation of soil development was undertaken. The purpose of this study is to develop a calibration curve that enables the approximation of a numerical development age for surfaces whose age is of interest in the future. This soil chronosequence study is based on the principle that in arid environments, calcium carbonate precipitates on clast surfaces within a soil, increasing over time in a consistent manner (Vincent et al., 1994; Birkeland et al., 1991). The methods of the study follow the work of Vincent et al. (1994). Clasts in the gravel-rich (>30% gravel) alluvium at Cottonwood Canyon were sampled and their carbonate coating thicknesses measured.

In the same soil pits as described above using the traditional classification scheme, 10 gravel clasts within the size range of 2 - 15 cm in length were sampled for each 10 cm depth increment. These samples were then broken with a hammer and the location identified of maximum carbonate rind thickness where the coating is planar, smooth, and parallel to the contact with the clast (not a pendant). The rind was measured using a minimicroscope with a 0.02 mm calibrated scale, allowing an precision of +/- 0.02 mm to be achieved. Maximum thickness occurs on the bottoms of the clasts because precipitation begins there, with continuous clast coatings occurring only after sufficient carbonate precipitates at that depth. The study by Vincent et al. (1994) shows that lithology of the clasts with the rinds being measured does not affect the thickness of the rind.

Resulting mean carbonate rind thicknesses for each 10 cm depth sampling interval is plotted versus depth for every soil pit (Figure 3.5; data in Appendix 5). This plot allows observations of changes in the mean carbonate accumulation with depth. Notice that as expected, the mean rind thickness increases to a depth of 20-30 cm where mean thickness is maximum. Below this maximum zone, rind thickness decreases as depths are reached in which less moisture has infiltrated and therefore less carbonate has precipitated. The possibility that unconsolidated alluvial surfaces may contain clasts with inherited carbonate rinds from their previous presence in stable soils or anomalous rinds from mixing of horizons due to bioturbation, adds uncharacteristic coating measurements but they do not overwhelm the results. Examination of the raw data allows one to see that even though rinds atypical in thickness are present, using the calculated mean over each sampled interval minimizes the influence of the atypical rinds (Appendix 5). As developed in Vincent et al. (1994), the mean rind thickness of the 20 cm interval with maximum accumulation for each pit is used in the development of the soil chronosequence. Each surface's mean thickness for the 20 cm maximum accummulation zone is plotted against the estimate of each surface's age range based on cosmogenic isotope methods (Q3 only) and soil development ages (Figure 3.6). Combining all of the analyzed soil pit information onto one plot allows a curve to be drawn that connects each surface pair of age and thickness. Some curve thickness is present due to uncertainties in surface ages and the curve is extrapolated to the origin as it is assumed that at the time of deposition, clasts had no coatings. The resulting calibration curve is applicable for soils of this climate, slope, aspect, and material (coarse alluvium). It can then be used in future studies (i.e. for the Hurricane fault or other faults

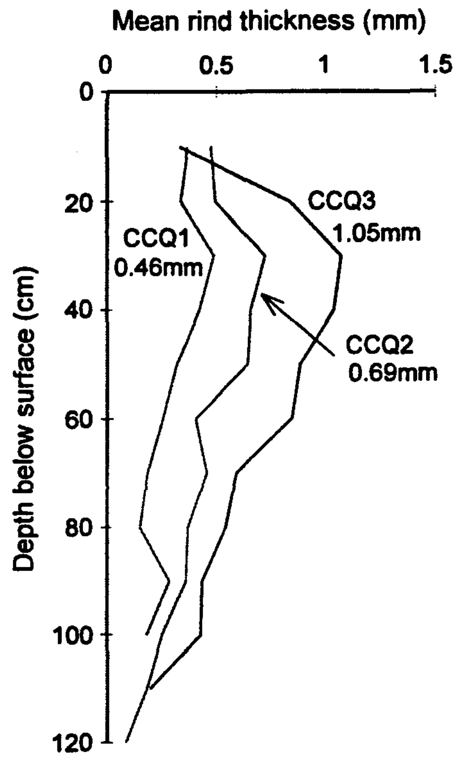

Figure 3.5. Plots of the mean carbonate rind thickness on clasts at depth in three Cottonwood Canyon surfaces. The rind thickness increases to a maximum depth for each surface. The maximum thickness for each surface increases with surface age (CCQ1 is the youngest, CCQ3 is the oldest), which is the basis for the chronosequence shown in Figure 6. The mean rind thickness over the 20 cm interval where rinds are thickest is given next to each plot. See Figure 3 for location of the surfaces and Appendix 2 for the raw data.

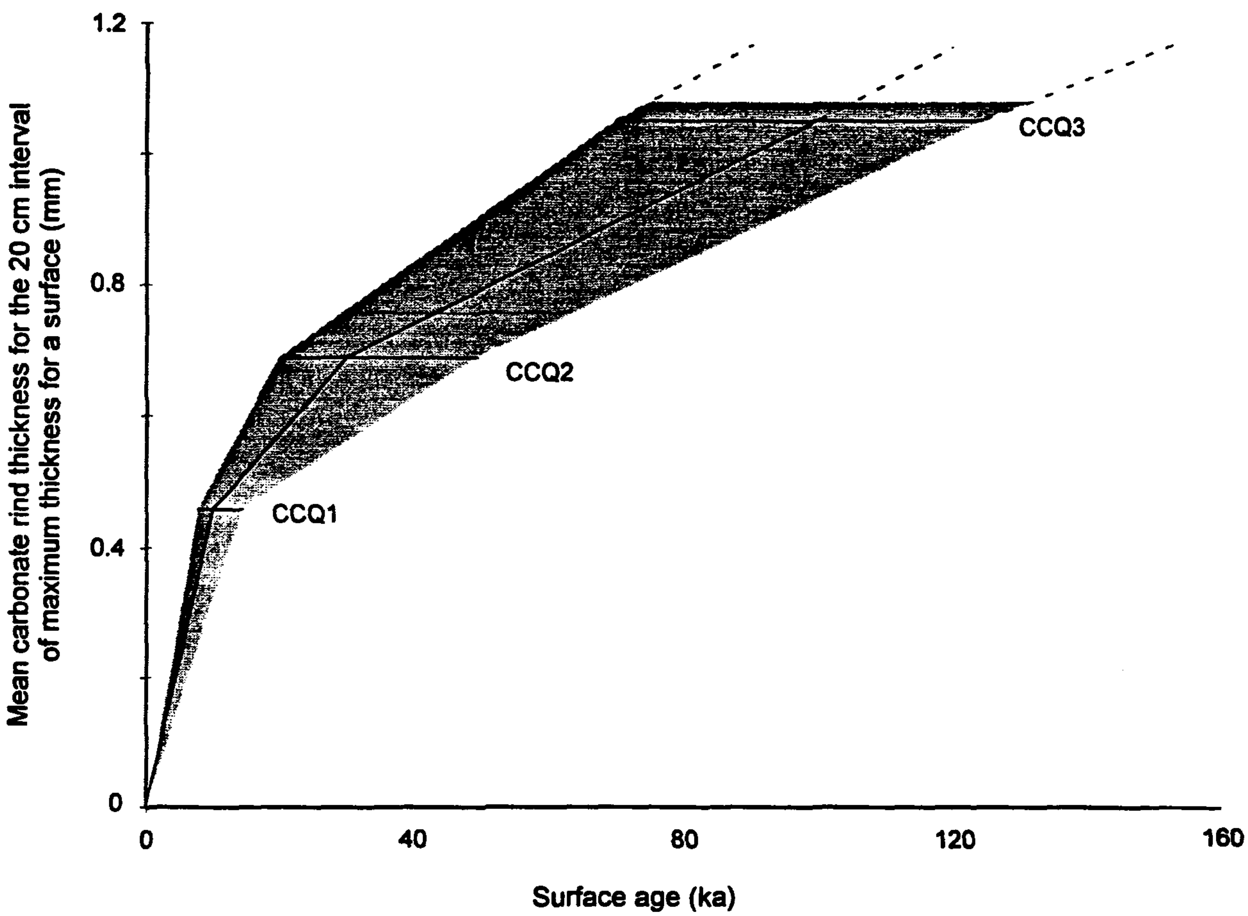

Figure 3.6. Soil chronosequence plot of the mean carbonate rind thickness (of the maximum 20 cm interval of the soil profile) and surface ages based on soil development and cosmogenic isotope dating. The relationship shown in the plot allows future surface ages to be estimated using rind thickness. Uncertainty in the surface ages causes the greyed width to the relationship curve, with the preferred curve shown as a solid line. Rind thickness measurements have an uncertainty of +/- 0.02 mm.

nearby) to estimate the numerical age range for soils within the same climate with similar characteristics. This is accomplished by measuring the rinds of clasts in the soil of unknown age, and finding where the maximum mean rind thickness plots on the calibration curve for age. This soil chronosequence is useful for estimating a numerical age for a surface based on soil development when traditional methods are difficult due to time, weather, or moisture conditions of the soil, as measurement can take place in a laboratory. Also, this technique can be performed with a limited knowledge of soils and still produce approximate numerical ages.

Cosmogenic Isotope Dating

To estimate a numerical age for surface Q3 at Cottonwood Canyon that is independent of soil formation, chert nodules were sampled for cosmogenic isotope dating analysis. The surface dating technique utilized in this study uses measured concentrations of accummulated ^{26}Al and ^{10}Be isotopes that are produced in chert. Bombardment from cosmogenic particles over time produce the isotopes (Bierman and Gillespie, 1997). Measurements of the relative amounts of the produced isotopes allow for calculation of the amount of time that a material has been bombarded from being at the surface (Bierman and Gillespie, 1997). Loose chert nodules, 2-10 cm in diameter, were collected off of the surface where they had remained as lag left from weathering of limestone boulders. In order for the chert nodules to have eroded out of the boulders a significant amount of time elapsed for the weathering to take place. Because the flux of cosmogenic radiation is exponentially attenuated at depth, chert nodule atoms within boulders are bombarded less than nodules at the boulder surface and accumulate isotopes more slowly (Cerling and Craig, 1994). Analyzing samples of the loose nodules that have eroded out of the boulders produces a minimum surface age because of the resident time within the boulders. The underestimation of surface age is reduced using mathematical models to correct the ages for the time that the chert nodules were within boulders. The ages are then useful as a check against the estimated soil age to increase confidence in the soil surface ages used in this study for slip rates and MRE timing.

The earth's atmosphere is constantly being bombarded by galactic and solar cosmic rays (>90% protons; Bierman and Gillespie, 1997). These particles interact with other nuclei in the stratosphere to produce meteoric and secondary cosmic rays (Bierman and Gillespie, 1997). The secondary rays interact with atoms in rock to produce in situ cosmogenic isotopes whose quantity relative to background isotope levels is measured to determine time of accumulation. The abundance depends on the 1) time to accumulate, 2) latitude, as the rigidity of the earth's magnetic field is strongest at the equator where only the highest energy cosmic rays can penetrate, cosmic rays at latitudes above 50° are not affected by the magnetic field, 3) amount of rays entering the atmosphere during different periods of geologic time because the strength of the earth's magnetic field is not constant with time, 4) elevation, as altitude decreases the attenuation of cosmic rays in the atmosphere increases, 5) shielding of the surface due to barriers, such as cliffs, that block or attenuate rays in the atmosphere coming from the direction of the barrier, and 6) the stability of the soil/rock surface - if the landform has been agrading or degrading then the history and accumulation of isotopes is more complicated (Bierman, 1994; Bierman and

Gillespie, 1997). These criteria need to be corrected for in order to produce meaningful surface ages.

The chemistry of the rock determines which in-situ isotopes will be produced in relative abundance. ^{26}Al and ^{10}Be are produced when cosmogenic rays bombard silicon atoms (Bierman and Gillespie, 1997). Sampling quartz-rich rocks, like chert, enables enough quartz to be concentrated to measure the number of ^{26}Al and ^{10}Be isotopes relative to background concentrations using an accelerator mass spectrometer (Bierman and Gillespie, 1997). Measuring both isotopes allows a check of the results as they should yield similar ages (^{26}Al ages are consistently greater than those calculate using ^{10}Be). At Cottonwood Canyon, limestone boulders are common deposits in the alluvial units. The Permian Kaibab and Toroweap limestone boulders contain nodules of white chert that are more resistant to weathering than the limestone. The difference in resistence causes the nodules to stand out in relief on boulder surfaces. Over time the nodules are left as lag on the ground surface as the surrounding limestone boulder has fractured and dissolved away. The nodules are undergoing cosmic ray bombardment and in situ comogenic isotope production the entire time of residence in the boulder and after they are removed but at different rates according to the nodule depth from the surface (exponential decrease with depth). The isotope production history means that the age indicated for the surface is a minimum. Each nodule remains in a boulder a different amount of time before being exposed to the surface and maximum isotope production, with some nodules beginning at the boulder surface.

Collections of chert nodules from surface Q3 were taken from both the up and down-thrown side of the Hurricane fault and analyzed at Lawrence Livermore National Laboratory for exposure age. Results of both ^{26}Al and ^{10}Be concentrations provide ages that are averages of the many nodules sampled to gather enough quartz for dating. The average of the ^{26}Al and ^{10}Be exposure ages for the footwall is 61.1 +/- 11.6 ka and 46.8 +/- 4.4 ka for the hanging wall. The difference in ages between the samples suggests that younger material may have covered the previous surface on the down-thrown side early in the surface's history or that recently exposed material was included in the collection perhaps from bioturbation, reducing the average age. Morphology (fan shape, aspect, smoothness, etc.) of the lower surface matches well with that of the upper, giving the impression that deposition other than slope wash from the scarp and surrounding surface has not occurred. Exposure ages have not been corrected for shielding factors, which means the ages are underestimated due to the shielding effects of the Hurricane Cliffs and for the probable shielding of the chert from the boulders that are liberating the nodules. The complicated exposure history of the many chert nodules sampled also causes the ages to be underestimated, a problem addressed by T. Hanks (written communication, 1998). His calculations to correct for the exposure history recommend adding ~25% to the ages, assuming 1) all isotope production occurred at the site with no exposure inheritence from earlier locations of stability, 2) the fraction of chert remaining in disintegrating boulders exponentially decreases over time, 3) a 'half life' decay rate for the boulders of 14 ka (half of the boulders have disintegrated after 14 ka), and 4) an average boulder diameter of 1 m (Appendix 7). The correction results in a surface age range of 62-91 ka for the up-thrown side of the fault, still a minimum due to the effects of shielding and bioturbation .

A minimum surface age of 62-91 ka for Cottonwood Canyon's Q3 is similar to the age estimated from soil development, 70-125 ka. The repetition of ages using different methods increases the confidence in both estimates of surface age.

Trench Investigations

Q1 trench. As discussed above, surface Q1 at Cottonwood Canyon contained a low fault scarp with <1 m of vertical displacement. A 14 m-long by 2 m-wide trench that was excavated across the fault on this surface demonstrated that the scarp was produced during one surface rupture, that of the MRE (Figure 3.3). A stratigraphic sequence of unconsolidated debris flow deposits and one interbedded water-lain gravel are exposed in the north wall of the trench (Figure 3.7; detailed unit descriptions in Appendix 6). All of the units, except for the uppermost 3 cm, have been displaced a total of 58-60 cm down to the west across the 2 m-wide fault zone. Displacement measurements were made by extrapolating the lower contact of the fluvial gravel into the fault zone and measuring the amount of vertical separation. Of the total vertical displacement, 37 cm was accommodated across two fault strands, and 23 cm more was accommodated by hanging wall drag folding of the western fault strand (Figure 3.7). No evidence for horizontal slip was observed.

Soil development of the units in the Q1 trench implies an age of 8-15 ka, probably early Holocene, for the surface. This implies that Holocene faulting has occurred on this portion of the Hurricane fault. Further refinement of the MRE timing is provided by the soil age of Q0, an abandoned alluvial surface younger than Q1. The Q0 surface age of 2-6 ka brackets the MRE timing to the early to mid Holocene. The degree of degradation of the Q1 fault scarp is consistent with this. Unfortunately, no carbon suitable for dating was found within the Q1 trench to help constrain the timing of the MRE further. The Q1 trench provides valuable constraints on the timing and size of the MRE. It also lends confidence to the inference that small scarps, on the order of 0.5 m in height, that are recognized in several other localities and are on strike with larger fault scarps, are indeed fault related.

Q2 trench. A second trench was excavated across a scarp 5 m high in the Q2 surface, 25 m southwest of the Q1 trench (Figure 3.3). The second scarp was trenched to: 1) provide additional information regarding the MRE, particularly in refining its timing; 2) allow a complete earthquake cycle to be observed to determine the time between the MRE and the previous (penultima*e) event; 3) provide information regarding the size and style of the penultimate event, and evaluate whether the 60 cm MRE is typical for the fault at this location.

Fractured and sheared Paleozoic bedrock overlain by a sequence of unconsolidated fluvial and debris flow deposits are exposed in the footwall of the Q2 trench (Figure 3.8; in pocket). None of the footwall deposits outside of the fault zone correlate with any unit in the exposed portion of the hanging wall (units 3a-4, Figure 3.8; Appendix 6 contains detailed description of units exposed in the trench). Hanging wall strata is dominated by water-lain gravels deposited from

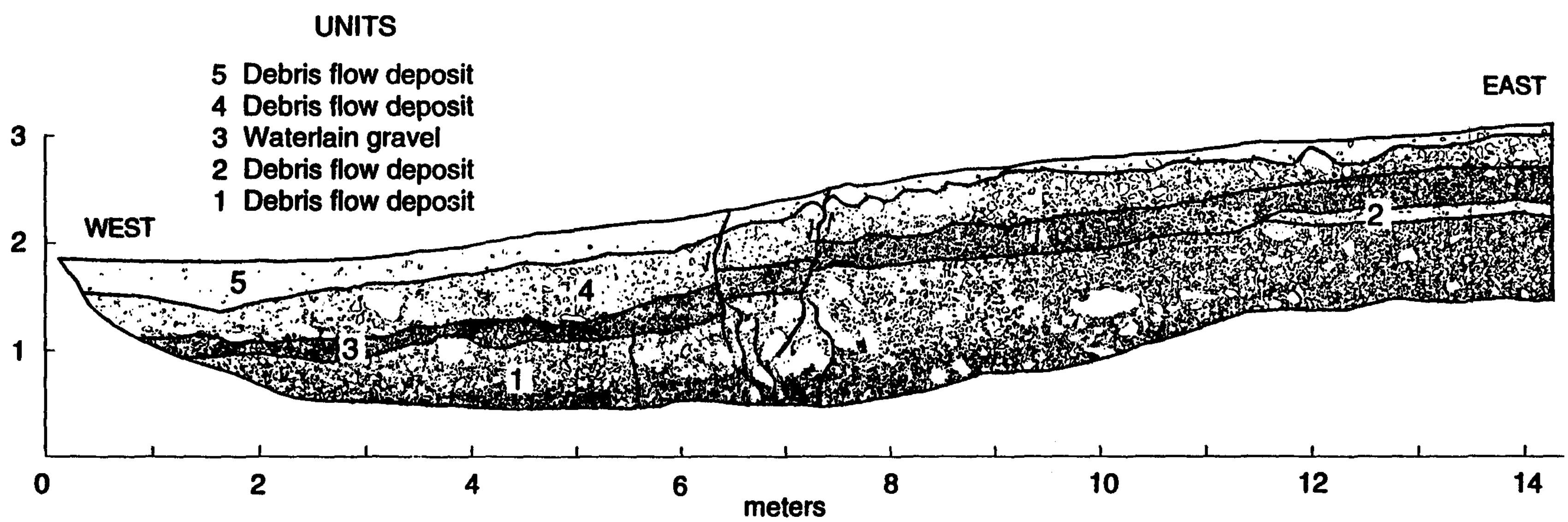

Figure 3.7. Log of Q1 trench, Cottonwood Canyon site, Arizona. One episode of faulting in this likely Holocene landform produced a displacement of 0.60 m, evident from vertically offset stratigraphy. Appendix 3 contains detailed descriptions of the units.

flow oblique to the trench as material from the then-actively agrading Q1 terrace/fan wrapped around the base of scarp Q2. The Q2 water-lain gravels are likely of similar age as the gravels exposed in the Q1 trench (units 9a-f; Figure 3.8). Q1 gravels probably bury the down-faulted Q2 alluvium which correlates to that observed in the up-thrown side of the fault. The trench was 2 m deep through the hanging wall and the correlative deposits were not exposed. Hanging wall gravels are overlain by fine grained deposits of probable scarp slope colluvial origin and overbank/debris flow outwash alluvium from the southeast. Within the fault zone, material is also very fine grained; dominated by fine sands, silts, and clays with occasional (5-20%) gravel particles supported by matrix.

While the Q2 trench does not provide as much information as desired, it does provide a second view of the MRE for this location on the fault. Expression of the movement during the MRE in the Q2 trench is different from that exposed in the Q1 trench. Unit 11 was probably the ground surface at the time of faulting (Figure 3.8). Movement during the MRE produced a 1 m-wide fissure at the surface where slip was concentrated. The fissure is filled by fine grained, loose material, including a coherent block of unit 11. Vertical displacement across the fissure is estimated at 20 cm. Although unit 11 may correlate across the fissure, it was likely deposited in the convex-down portion of an existing scarp, and is difficult to reconstruct. A small amount of slip, 15-17 cm, was accommodated by another fault 1 m to the east of the main fault during the MRE. This is indicated by a bedrock disturbance, vertically offset alluvium (unit 11), and splaying fractures. The MRE displacement through surface Q2 was distributed onto at least two slip planes with a minimum net vertical offset of 35-37 cm, but this offset is less robust than the displacement measurement in trench Q1.

Paleozoic bedrock in the footwall is highly sheared in the 5 m east of the main fault trace with the fissure, and somewhat sheared and fractured an additional 4 m to the east. The shears imply that repeated faulting has occurred within a zone of ~9 m through surface Q2. During at least the last few earthquakes, the majority of slip has occurred where the bedrock is faulted against young alluvium (i.e., the site of the fissure from the MRE). Down-to-the-west bedrock steps smaller than 1 m occur throughout the 9 m of sheared bedrock, including a fault that continues into the alluvium mentioned above with 15 to 17 cm of displacement during the MRE. Other bedrock steps to the east may be faults with possible MRE slip. Steps in the upper contact of unit 11 (probable ground surface at time of rupture) look tectonic in origin, as alluvium would not likely support such a rough ground surface. Shear fabric in alluvium was only observed associated with the fault accommodating 15-17 cm of slip, and only a rare possible rotated clast is present in the fine alluvium above the bedrock steps to encourage the interpretation of the steps as faults.

A scarp was probably produced about 3 m southeast of the main trace during the MRE because unit 13 is colluvium deposited solely in the fault zone and is believed to be a fault scarp derived colluvial wedge. Unit 13 thickens to the west, over the fissure and the scarp free face, but begins just downslope of a 1 m bedrock step. The alluvium above the step at this location (unit 11) does not have a step in its upper contact. However this does not preclude faulting because the small scarp would have been on a moderately steep slope in relatively loose material and may have eroded back to the surrounding landform rapidly. Unit 11 does have a conspicuous change in slope at this location. Unit 13 is too thick to be solely derived from a small fault scarp, suggesting that a significant amount of displacement possibly ocurred at the step.

One observation in the trench that is difficult to explain is the presence of arcuate fractures which merge downwards into the main fault zone at the bedrock/alluvium contact, and die out upwards (Figure 3.8). They are not continuous fractures, some are short and exist only at the apex of the arcuate feature or at the sides of the arc. One explanation is that the fractures are due to compaction of the loose fissure fill material below the arc. Material on either side of the fissure is more competent and consolidated (sheared bedrock and moderately cemented alluvium) which could allow for differential compaction in that area to occur. The arcuate fractures are not a common phenomena, however, and have not been documented along other faults where fissures exist (D. P. Schwartz, personal communication, 1998). The fractures not likely related to shear, because they exist in colluvial wedge material that post-dates the last earthquake.

A subtle color difference was noted between the package of material surrounded by the arcuate fractures and the material outside of the fractures. This can be interpreted that the material within the package is a relatively intact block that has fallen over the fault scarp shortly after formation (D. P. Schwartz, personal communication, 1998). Internal stratigraphy of the package was not observed but does not preclude the package being a single block. The arcuate fractures for this scenario could be exfoliation features around the original surface of the block.

Overall, this trench supports the conclusions drawn from trench Q1: that the MRE produced a small amount of displacement at the surface. The Q2 trench may eventually provide further information about timing of the MRE. Eleven samples were taken in the trench for possible future thermoluminescence dating analysis. A piece of charcoal, approximately 1 g, was found at the base of unit 13, above the fissure fill material. This sample was analyzed for its radiocarbon age, but the result of 870 years is much too young to be accepted as a record of the time in which the surrounding alluvium was deposited. Probably the charcoal was bioturbated into the position where it was found. Position of the sample would be interpreted as near-MRE in age, probably slightly younger because of its occurrence in colluvial wedge material above the probable ground surface during the MRE. If the MRE was indeed that recent, the scarps of Q1 and Q2 would likely appear much steeper and fresh. Furthermore, this age is not consistent with the conservative 2-15 ka fault timing derived from surface Q0 and Q1 soil ages and the quantity of material stratigraphically above the sample is large to have been deposited within 870 years. In summary, no further constraint on MRE timing was established and no information was found contradicting interpretations of trench Q1. Unfortunately, solid information regarding the penultimate event was also lacking.

Geomorphic Fault Scarp Modeling

One dimensional geomorphic profile modeling of large fault scarps in the Cottonwood Canyon area provides information about mass diffusivity values for large, multiple event scarps. Mass diffusivity values are a measure of the rate at which material will move down slope by processes such as slope wash, rainsplash, soil creep, and animal and plant disturbances. Quantifying mass diffusivities for a specific climate are critical for fault scarp modeling, because when calculating a model to assess the elapsed time for scarp formation, the rate of material transport across the slope dramatically affects the morphology of the scarp at different time intervals (Hanks, 1998). Without a mass diffusivity value that is appropriate for the climate in which the scarp formed, the scarp age calculated may be inaccurate. The Cottonwood Canyon area scarps are useful because surface ages have been estimated, from soil development and cosmogenic dating, allowing calculation of mass diffusivity values. These diffusivities can then be used in future studies where scarps (of like age, displacement, and climate) are modeled and the approximate age of formation calculated.

Methods. One dimensional diffusion modeling for continuous slip along a fault was performed based on methods described in Hanks (1998). Assumptions made for modelling the surfaces are that 1) conditions involved are transport, not weathering, limited; 2) mass is conserved in the system; 3) the mass diffusivity describing erosion at the crest of the scarp is equal to the mass diffusivity describing deposition at the scarp toe. Assuming a spatially constant mass diffusivity is valid when the profile of the scarp is symmetrical--the curvature of the upper slope is very close in shape to the lower slope curvature (Hanks, 1998). 4) Mass travels down slope at a rate proportional to the slope, and 5) the mass diffusivity does not vary with time (Hanks, 1998). Arrowsmith (1995) and Hanks (1998) are useful documents for further discussion of the basics of profile modeling and were used in equation derivations for this paper.

Multiple event fault scarps degrade over time differently than a scarp of the same height which formed during one instantaneous slip. Repeated slip is approximated as continuous slip through time in the models used in this paper. Conditions for modeling continuous slip are met by setting the surface offset to zero and allowing the contribution of surface displacement to be input as the continuous velocity of uplift/downdrop over time.

A plot of the model function was visually compared with the actual scarp profile. The κt value was accepted as appropriate if the model and profile were coincident within 1 m over 80% of the primary landform (excluding portions of the landform not representative of the faulted surface such as locations of burial on the down-faulted surface) and as close as possible elsewhere. If the fit was poor, then the κt value was modified and a new model calculated and compared with the profile data until a suitable fit was achieved. With the accepted κt value, the estimated surface age range was used to calculate a range of mass diffusivity values for the surface. That κ range is preferred, however there is a factor of two uncertainty in the results (T. Hanks personal communication, 1998). Uncertainty comes from approximating repeated faulting with continuous slip, from error in measurements of variables, and because non-diffusive processes may modify the landform.

Q6 model. Surface Q6 is a steeply sloping alluvial apron deposit, with a high fault scarp located approximately 400 m southwest of Cottonwood Canyon's Q3 surface (Figure 3.3). Figure 3.11b displays the profiles of Q3 and Q6 rotated such that the surfaces' fan slopes are the same. This allows the reader to see that the surfaces have essentially the same profile, only the overall slope is steeper for Q6. Notice the >6 m burial of the down-thrown surface of Q6 near the base of the

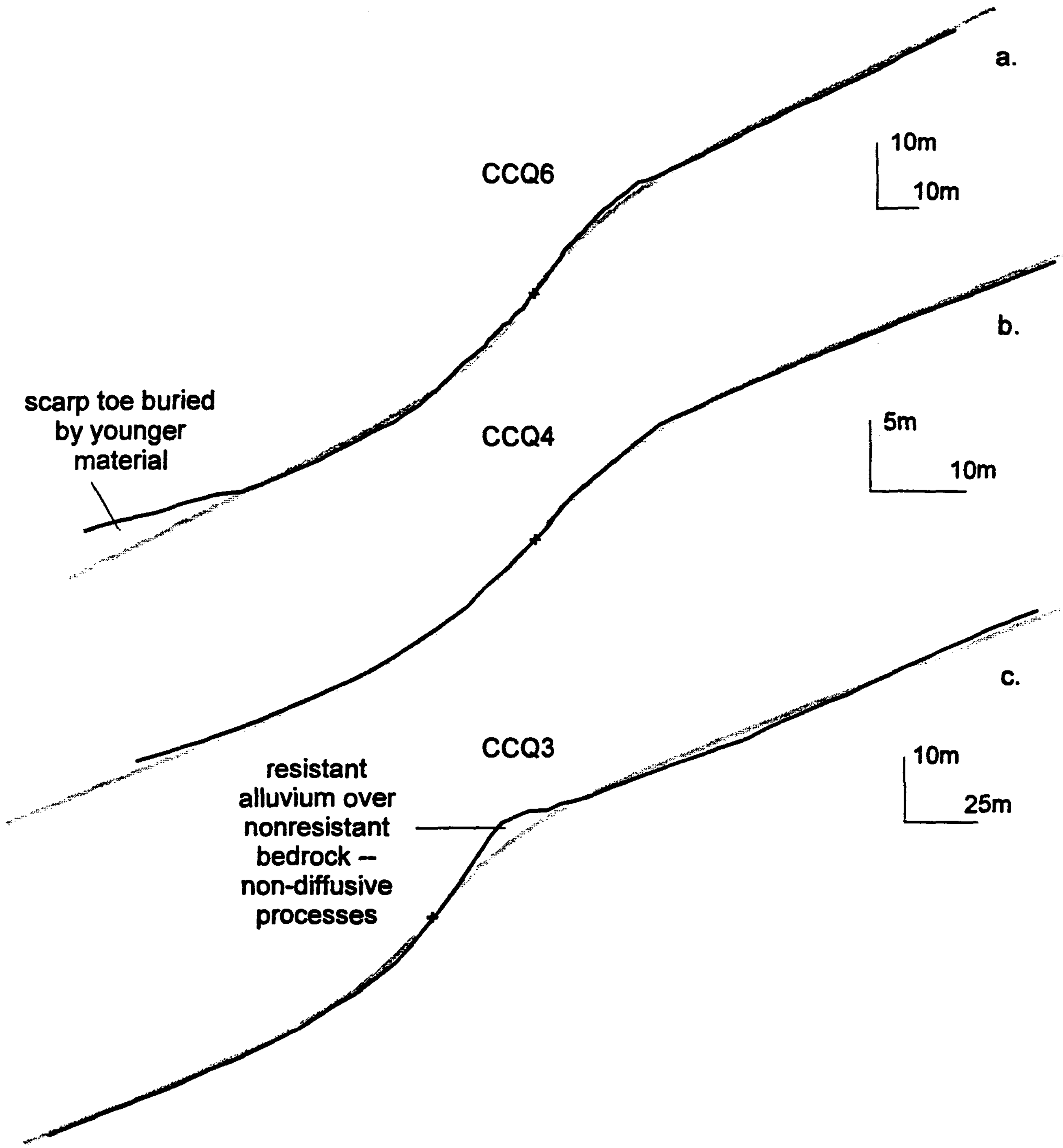

Figure 3.9. Geomorphic profile models (gray lines) of the Cottonwood Canyon fault scarps (a) CCQ6, (b) CCQ4, and (c) CCQ3 (black lines). Models produced mass diffusivity values of 2-3m^2/ka, 2-4 m^2/ka, and 7-12 m^2/ka respectively.

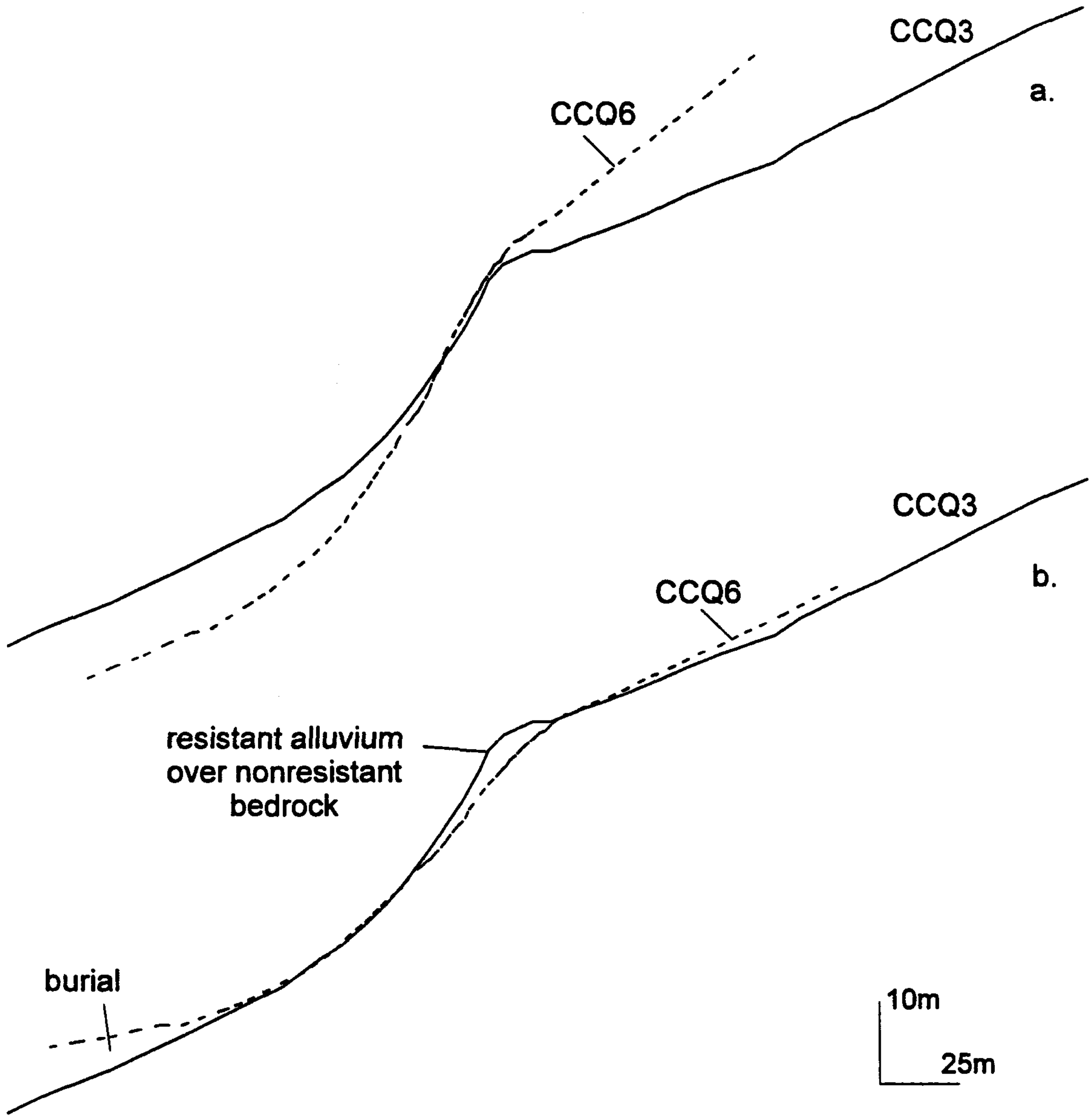

Figure3.10. Topographic profiles of the Cottonwood Canyon alluvial fan fault scarps CCQ3 and CCQ6. In (a) the scarp profiles are shown in their original surveyed form, with vertical exaggeration. Notice that the CCQ6 landform has a steeper overall slope. In (b) CCQ6 has been rotated to show that the two scarps have a similar shape and similar displacements. The close relationship between these two scarps forms the basis for using surface ages estimated for CCQ3 for CCQ6 as well. Differences between the two landforms exist at the base of the scarps, where CCQ6 has been buried by younger material (noted in the field as well), and at the crests where CCQ3 exposes resistant alluvium over nonresistant bedrock causing a steepened slope.

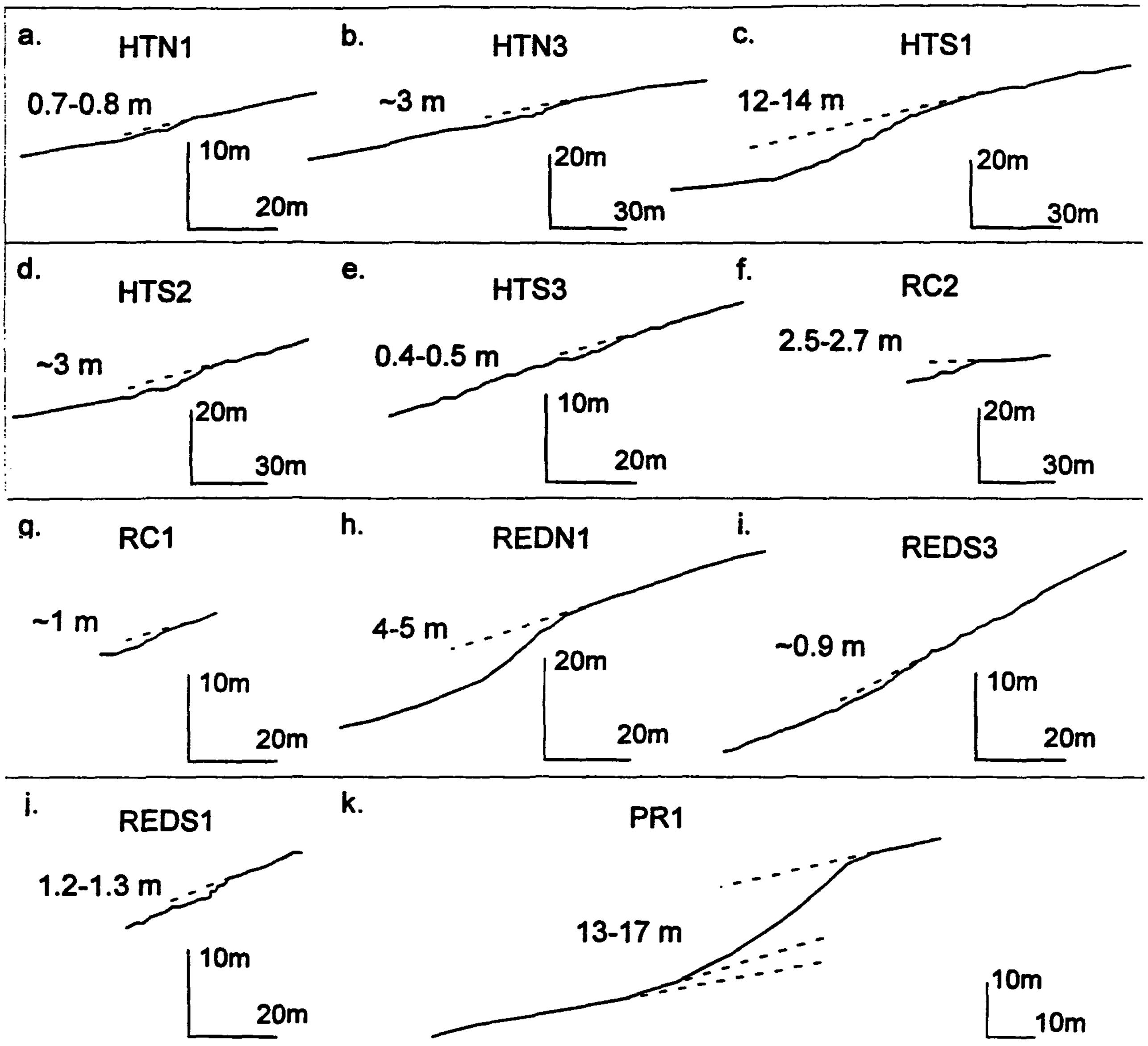

Figure 3.11. Topographic profiles and net vertical tectonic displacement measurements for fault scarps at the Honeymoon Trail North site (a) HTN1, (b) HTN3; Honeymoon Trail South site (c) HTS1, (d) HTS2, (e) HTS3; Rock Canyon site (f) RC2, (g) RC1; Red Cliffs North site (h) REDN1; Red Cliffs South site (i) REDS3, (j) REDS1; Powerline Road site (k) PR1; Black Rock North site (l) BRN6, (m)BRN7, (n) BRN8; Black Rock Middle site (o) BRM3, (p) BRM4, (q) BRM5; and Black Rock High site (r) BRH1.

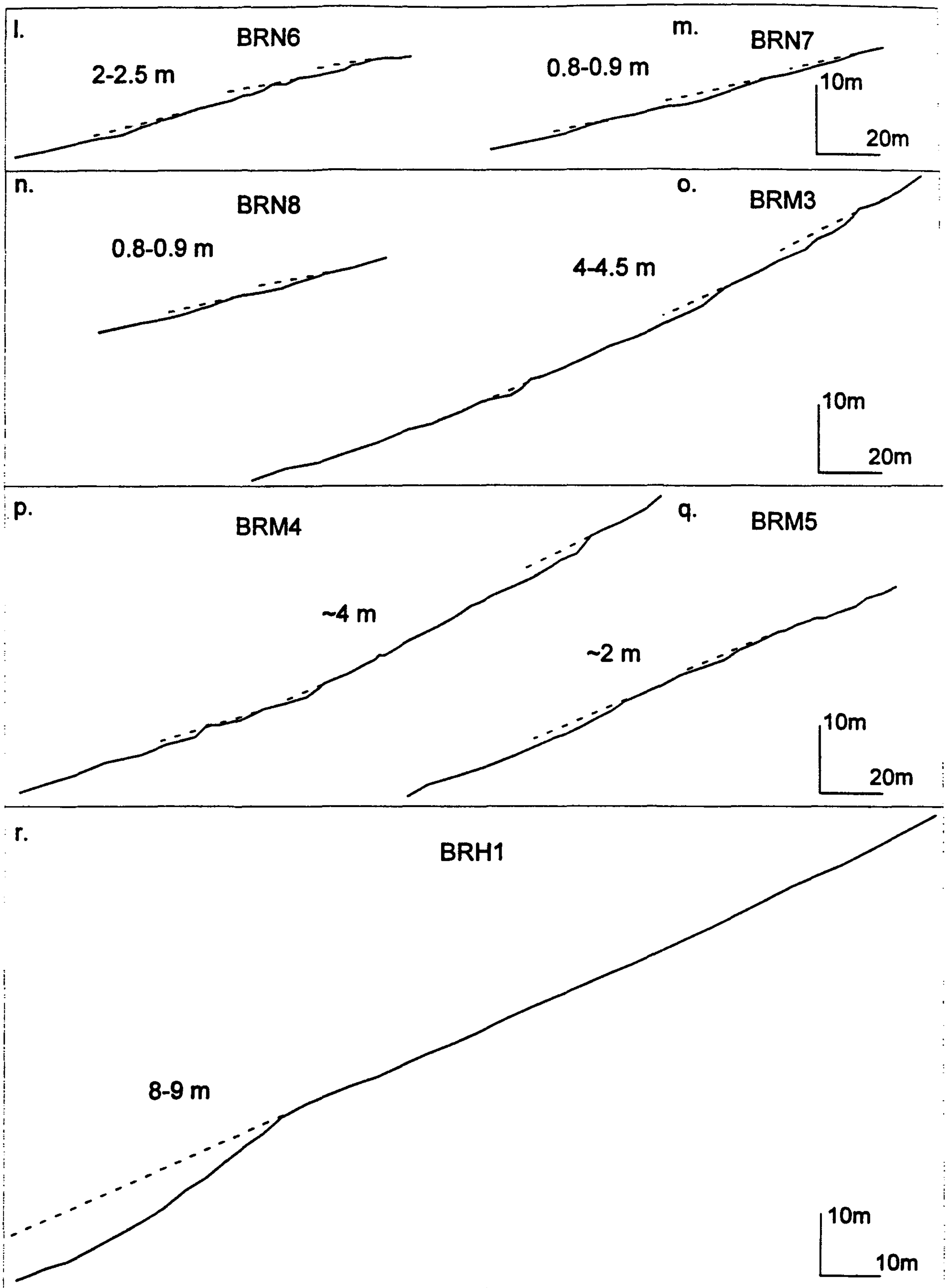

Figure 3.11. cont.

scarp (where model and profile diverge at scarp base; Figure 3.10). The lower curvature of the original scarp is still discernible. Because Q3 and Q6 have similar scarp morphology and record a similar net vertical tectonic displacement (NVTD), the age of Q6 is interpreted to be the same as Q3, 70-125 ka.

Scarp Q6 was modeled using an alluvial fan slope of 0.31and scarp slope of 0.69, as measured from the topographic profile (Figures 4 and 9a). The product of the uplift/downdrop velocity and scarp formation time is measured from the profile as half of the total vertical displacement, 9.25 m. Using equation 4, a κt value of 755 m2 was calculated. Visual evaluation of the resulting model from equation 5 identified a need for modification of the κt value. A κt of 260 m2 produces the best fitting model for the Q6 surface (Figure 3.9a).

A surface age of 70-125 ka is estimated for Q3 and is used for Q6 as well. Dividing the κt by the surface age results in a mass diffusivity of 2-3 m2/ka for the scarp. This diffusivity is similar to the 1.8 m2/ka value calculated for the Lake Bonneville/Lahontan shoreline scarps (of surface age 12-14 ka and surface offset of 5-12 m) that exist in a climate roughly similar to Cottonwood Canyon. The Q6 scarp is older and larger than the shoreline scarps and this may contribute to the larger diffusivity value (Hanks, 1998).

Q4 model. Approximately 25 m southwest of Cottonwood Canyon's surface Q3, surface Q4 records a minimum half-displacement of 5.25 m from the Hurricane fault. Although the down-faulted surface has experienced burial ~20 m from the base of the scarp, it can be modeled because the original scarp toe is preserved. As measured from the profile, the fan slope is 0.27 and the scarp slope is 0.69. Input of these variables into equation 4 produces a resulting κt of 50 m^2. Visual assessment of the model resulting from equation 5 indicates that the κt value needs modification. The best fitting model uses a κt of 110 m^2 (Figure 3.9b).

Soil development of surface Q4 was not investigated for surface age assessment. An approximate age range of 30-70 ka can be bracketed based on the amount of tectonic displacement recorded in Q4 relative to nearby scarps Q3 and Q2 with estimated surface age ranges. A mass diffusivity of ~ 2-4 m2/ka is estimated for surface Q4. This value is consistent with that found for surface Q6. It is possible that Q4 and Q6 differ in their mass diffusivities, but the precision of the diffusivity values estimated in this study is not high enough to allow for resolution between Q4 and Q6.

Q3 model. Cottonwood Canyon surface Q3's high fault scarp was modeled using an alluvial fan slope of 0.17 and a scarp slope of 0.54, as measured from the topographic profile (Figures 4a and 10c). The product of the uplift/downdrop velocity and scarp formation time is measured from the profile as half of the total vertical displacement, 10 m. Using equation 4, a κt of 930 m2 was calculated. Visual evaluation of the resulting model from equation 5 identified a need for modification of the κt value. A κt of 900 m2 produces the best fitting model for the Q3 surface (Figure 3.9c).

A surface age of 70-125 ka for Q3 is estimated based on soil development. Consistent with this age, cosmogenic isotope dating of chert nodules on the surface produced a similar minimum age of 62-91 ka. The resulting mass diffusivity of 7-12 m2/ka is calculated for the scarp. This diffusivity is much larger than 1.8 m2/ka of the Lake Bonneville/Lahontan shoreline scarps. Models of scarps Q6 and Q4 produce diffusivities of 2-3 m2/ka, much closer to the shoreline values. Non-diffusive processes acting over the scarp of Q3 are probably the reason for the large diffusivity value. Surface Q3 has channels forming through the crest and face of the scarp, causing material to be transported more rapidly and in specific areas (Figure 3.3). Also, mass failure of the nonresistant bedrock that crops out 2-3 m below the top of the scarp face and the more resistent unconsolidated alluvium cap produce the oversteepened slope observable in profile (Figures 4a and 10c). These non-diffusive processes contribute to the high diffusivity value.

Other models. The smaller fault scarps in the Cottonwood Canyon area would have been chosen for modeling if it had been suitable for analysis. Such models would have provided additional information for a discussion of mass diffusivity rates changing with different time scales of the same climate. A model for surface Q1 may also have given information on the timing of the MRE. However, scarp Q1 is not conducive to modeling because it is small and the surface is very rough.

The scarp in surface Q2 at Cottonwood Canyon is buried on the down-thrown side by younger material and the lower scarp curvature does not represent diffusive processes operating since initial scarp formation. Because the lower surface is buried under an unknown amount of younger material, not knowing the displacement (2At) means that many models could be fit to the profile with large differences in κt values.

Discussion. It is the models of Q4 and Q6 which produced valuable information regarding mass diffusivities. Surfaces Q4 and Q6 are suited to diffusion modeling, as transport over the surfaces is dominated by the diffusive processes of sheet wash, rain splash, soil creep, and animal/plant disturbances. Although the lower portions of the scarps have been buried, the burial occurs downslope of the lower scarp curvature, allowing the entire scarp to be modeled.

Mass diffusivity values of 2-4 m2/ka for Cottonwood Canyon have a factor of two uncertainty from approximating repeated faulting with continuous slip, error in measurements of variables, and because non-diffusive processes may modify the landform. But they provide values useful to estimate scarp formation ages in future models of other large scarps on the Hurricane or other faults in a similar climate.

Another issue regarding mass diffusivity values is that they tend to increase for older and larger scarps of the same climate (Hanks, 1998; Pierce and Colman, 1986). Hanks and Andrews (1989) found an increase in mass diffusivity with an increase in displacement for combined Bonneville/Lahontan shoreline scarps. Their scarps with ~1 m of surface offset record a mass diffusivity of 0.64 m2/ka. For scarps with surface offsets of 2.5-3.5 m and 5-12 m, the diffusivity is 1.1 m2/ka and 1.8 m2/ka, respectively. The large (NVTD of 10.5-20 m) Cottonwood Canyon scarps may support this relationship as the 2-3 m2/ka mass diffusivity is larger than those Bonneville/Lahontan shoreline scarps of similar environment but smaller apparent offset.

If instead of using known surface ages with the model to calculate the mass diffusivity for surface Q6, a diffusivity is chosen from previous studies, a formation time can be estimated. This is a check of the model κt value to determine if it produces a reasonable surface age from other worker's accepted diffusivities. Using a mass diffusivity of 8.5 m2/ka (based on a 17-30 ka scarp on the San Andreas fault in the Carrizo Plain, California of 8-20 m displacement; Arrowsmith, 1995) a scarp age of 30 ka is calculated. For a diffusivity of 1.8 m2/ka, based on combined Lake Bonneville/Lahontan shoreline scarps of 12-14 ka and surface offset of 5-12 m, an age of ~150 ka is calculated (of more similar climate to Q6 than the Carrizo Plain; Hanks and Andrews, 1989). These ages bracket the 70-125 ka estimated for the surface, lending confidence that the κt is possible.

Other Sites in the Southern Anderson Junction Section

Fault scarps of varying heights exist along much of the studied 30 km of the Hurricane fault. Although they are common along the southern 29 km of the area of focus, scarps are not continuous through the area. In addition to these gaps in the locations of scarps, the northern 9 km of the study area only contains one location where possible late Quaternary fault scarps occur (5 km north of Frog Canyon; Figure 3.2). At that site, six scarps ranging in height from 3-10 m occur in alluvial deposits (dominated by boulders up to 4 m wide) at the mouth of a small drainage off the cliffs. The scarps were not conducive to detailed study but have formed in unconsolidated late Quaternary deposits. A lack of landforms old enough to preserve evidence of rupture combined with the possibility of rupture occurring at the base of the cliffs where alluvium is not present or steeply sloping may be the reason (particularly for the northern 9 km of studied length) that fault scarps are discontinuous or absent through the studied section of the fault.

The following is a recount of the reconnaissance data obtained for notable fault scarps identified along the studied area of the Hurricane fault (Figure 3.2). Particular attention was paid to locate small scarps that are possibly the result of a single ground rupturing event so that an evaluation of the location and length of the most recent rupture can be made.

Honeymoon Trail North. Immediately to the northeast of the historical Honeymoon Trail at the base of the Hurricane Cliffs, there is a low scarp in fine grained terrace alluvium, HTN1, which is no longer actively aggrading. The HTN1 scarp has an estimated net vertical tectonic displacement (NVTD) of 0.7-0.8 m as measured from a topographic profile (Figures 2 and 11a). On line with this scarp is another in an older fine grained terrace alluvium, HTN3, with a NVTD measured to be ~3 m from the profile (Figure 3.11b). Both scarps appear to have the downdropped portion of the landform preserved - no burial seems to have taken place.

The Honeymoon Trail North site is useful because faulting appears to have occurred along only one strand. This increases the confidence that the scarps are representing the total amount of slip that has occurred since the surfaces formed. The two relatively small fault scarps suggest that slip during the MRE was small (<1 m) at this location and that repeated rupture has occurred in the late Quaternary. It is possible that rupture preserved in surface HTN1 is the same as the rupture that occurred at Cottonwood Canyon.

Honeymoon Trail South. Southwest of the Honeymoon Trail, three fault scarps of different sizes were profiled 200-300 m out from the base of the Hurricane Cliffs (Figure 3.2). The largest of the three, HTS1, is immediately south of the historic trail and as measured from the topographic profile the abandoned fan surface has been vertically displaced by a minimum of 12-14 m (Figure 3.11c). A soil pit was excavated in the up-thrown portion of HTS1. The calcium carbonate development reached stage III with a maximum accumulation at 80-102 cm of depth (Appendix 4). Soil development is similar to Cottonwood Canyon's surface Q3 and surface age is estimated at 70-125 ka. A slip rate of 0.08 - 0.14 mm/yr is calculated for this surface, but burial of the hanging wall makes the rate a minimum. Another reason that this slip rate may be underestimated is that faulting may have occurred along more than one strand. Additional slip may have occurred along a visible strand of fault that exists within the bedrock at the base of the cliffs, but because the fault is located in bedrock, it is not clear whether it has slipped in the late Quaternary.

About 75 m southwest, along strike with the large HTS1 scarp, is another fault scarp, HTS2, in an abandoned alluvial fan. HTS2 has a profile-measured NVTD of ~3 m (Figure 3.11d). This surface is buried on its down-thrown side, making the ~3 m a minimum displacement.

Another 15 m to the southwest is a third profiled scarp, HTS3, with a measured vertical offset of 0.4-0.5 m (Figure 3.11e). This abandoned alluvial fan/terrace was trenched to determine whether the scarp was tectonic in origin. Poorly sorted, poorly stratified, unconsolidated alluvium with ~25% gravel was exposed in the trench. Faulting has disrupted the deposit, but because the alluvium is not well stratified, displacement measurements were difficult. Rotated clasts, faint shear fabric, and an overall disturbed zone were evidence of slip. The possibility that this scarp does not necessarily reflect the total slip during the MRE, because of other potential fault strands, makes this site less useful for detailed study. Stratigraphy that was tentatively differentiated in the trench wall showed a displacement consistent with that measured from the profile, ~0.3-0.8 m across a fault and disturbed zone of probable rotated elongate clasts. The trench is particularly useful in supporting the inferrence that small scarps are fault related.

Soil described in the HTS3 trench reached stage I calcium carbonate development, with maximum carbonate accumulation at a depth of 22-40 cm (Appendix 4). This soil is similar in development with that of surface Q1 at Cottonwood Canyon so surface HTS3 is probably Holocene as well. It is likely that the rupture through HTS3 is the same rupture that displaces the surfaces at Cottonwood Canyon. It is clear from the multiple scarps that the Honeymoon Trail area has undergone recurrent faulting in the late Quaternary.

Rock Canyon. About two kilometers along the Hurricane Cliffs southwest of the Honeymoon Trail is Rock Canyon, which is similar in size to Cottonwood Canyon (Figure 3.2). Two abandoned alluvial fan/terraces are displaced by the Hurricane fault just north of the active channel coming out of the canyon. The most prominent of the two scarps, RC2, is displaced 2.5-2.7 m as measured from a topographic profile (Figure 3.11f). It is possible that the down-dropped portion of the surface has been buried (likely by a minor amount) by younger material, making the displacement a minimum.

The second scarp at Rock Canyon, RC1, is a small, subtle scarp with measured NVTD of ~1 m (Figure 3.11g). Scarp RC1 is developed in probable Holocene material and may be the result of the same rupture that produced the HTS3 and HTN1 scarps and the Q1 scarp at Cottonwood Canyon. The Hurricane fault at Rock Canyon is inferred to slip along one fault strand represented by the scarps described above.

Red Cliffs North. Along the Hurricane Cliffs about 2 km southwest of Rock Canyon is a prominent cliff face dominated by red sandstones and shales of the Hermit Shale (Figure 3.2). Near this cliff is a site with one profiled scarp, REDN1, showing 4-5 m of vertical displacement (Figure 3.11h). The down-dropped surface is not buried and slip occurs along one strand at this location.

Red Cliffs South. About 750 meters southwest of the Red Cliffs North site, is the southern site (Figure 3.2). Three surfaces with scarps in abandoned alluvial fan deposits were surveyed. The topographically highest and most rounded scarp, REDS3, is displaced 1.2-1.3 m as measured from a profile (Figure 3.11i). The down-dropped surface is believed to be correlative with the surface at the crest of the scarp, providing a measure of total displacement. This scarp may represent the penultimate rupture or a location where the MRErupture occurred as a narrow zone instead of one discrete scarp step. REDS1, ~5 m southwest of REDS3, is a more sharply defined scarp, and a NVTD of 0.9 m is measured for it, probably the result of the same MRE as at Cottonwood Canyon (Figure 3.11j).

Anderson Junction-Shivwitz Section Boundary Zone

A major convex bend of the fault trace 3 km south of Cottonwood Canyon marks the boundary between the Shivwitz and Anderson Junction sections of the Hurricane fault (Figures 3.1 and 3.2). From the structural geometry of the fault and the changing cumulative displacements in the Mesozoic and Paleozoic bedrock across the bend, the convex zone has been suggested to be a seismogenic segment boundary (Stewart et al., 1997). This study cannot conclude whether the boundary is truly seismogenic or interpret with confidence whether the MRE at Cottonwood Canyon ruptured into (or from) the Shivwitz section. Future detailed study of scarps south of the convexity is needed to closely constrain the timing of rupture events and allow for a conclusion to be reached. To identify the faulting style within the boundary zone, scarps were surveyed in the northern boundary area at the Powerline Road site and within the southern boundary area at the Black Rock sites (Figure 3.2).

Powerline Road. Two kilometers southwest of Cottonwood Canyon, a powerline road leads up to the base of the Hurricane Cliffs (Figure 3.2). Two scarps are present on the north side of the road and a third is present on the south side. This Powerline Road site is within 1 km of the apex of the fault's major plan convexity, and is within the possible seismological boundary zone. If the section boundary is indeed a segment boundary, one might expect ruptures to be smaller here, as ruptures get close to termination, or short ruptures may occur solely in this transitional boundary between two individually rupturing sections. Analysis of the site, however, lacks evidence for significant differences in fault behavior from that observed at Cottonwood Canyon.

Scarp PR3, the largest and most northern scarp at Powerline Road, shows a NVTD of 13-17 m (Figure 3.11k). Minimal burial of the down-thrown surface is evident. Scarp PR2 is the second largest scarp, immediately southwest of PR3. Although the PR2 scarp is along strike with the nearby large scarp and is easily recognized as a probable fault scarp, its morphology is disturbed by grading machinery and a profile would not represent the scarp's original shape or locations of the up and down-thrown portions of the displaced surface. A visual assessment of the NVTD is ~2-4 m. Immediately to the south of the road is scarp PR1, with a visually assessed NVTD of ~0.3-0.7 m. PR1 was not surveyed because of its small size (scarp ~1 m long, with up and down-thrown surfaces about 2 m2 in area) and rough surface (boulders cover ~75% of the surface). This scarp may not be fault related, but its location on line with two other more obvious fault scarps is suggestive. There is no clear evidence that would suggest that the feature is a debris flow lobe or erosional feature. Because materials are considerably coarser for PR1 than Cottonwood Canyon's Q1 it is difficult to make an age comparison. No evidence, however, was observed to imply a considerably older age for PR1. It is possible that PR1 records the same rupturing event as Cottonwood Canyon's Q1.

Black Rock North (BRN). Three abandoned alluvial fans/terraces are located 3.5 km along the fault trace south of the powerline road (Figure 3.2). Topographic profiles of BRN6, BRN7, and BRN8 are shown in Figure 3.11,l-n. Each fan/terrace displays multiple scarps. Not all of the scarps are necessarily fault related, but bedrock which appears faulted in multiple locations exists to both the north and south of site BRN. A maximum total displacement is measured for the profiles based on the assumption that all scarps are tectonic in origin. BRN8, the most northern of the three, is measured to have a maximum NVTD of 0.8-0.9 m. BRN6, the surface located between BRN7 and 8, has been displaced a maximum of 2-2.5 m. The third surface, farthest south, BRN7, is estimated to have a NVTD of 0.8-0.9 m. A soil pit excavated on surface BRN7 showed a zone of maximum calcium carbonate accumulation from 22-52 cm depth (stage I+). Based on the degree of carbonate development, surface BRN7 is older than Cottonwood Canyon's Q1 and younger than Q2. Because an unknown number of fault strands exist at this location, it is not possible to determine which scarp represents the MRE for this location. Therefore, no conclusions are made regarding the possible continuation of the Cottonwood Canyon most recent rupture through the BRN site.

Black Rock Middle (BRM). At a site, BRM, 500 m south of site BRN, along the Hurricane Cliffs, there are two abandoned alluvial fan surfaces containing scarps (Figure 3.2). The northern surface is a coarse-grained debris fan, profiled twice to see how the estimated NVTD compares in each (Figure 3.11,o and p). Multiple scarps are present in the surface, not all necessarily representing faulting. The estimated NVTDs for the surface includes all apparent scarp offsets to produce a maximum estimate. Scarps in profile BRM3 record a maximum displacement of 4-4.5m. Profile BRM4, on the same fan but over different coarse deposits, produces a maximum NVTD of ~4 m.

Soil investigated on the coarse fan allows for a relative age comparison with soils at Cottonwood Canyon. A stage I+ carbonate morphology was reached, with maximum accumulation from 30-48 cm depth (Appendix 4). Relative to Cottonwood Canyon soils, the coarse fan is intermediate between Q1 and Q2, closer in age to Q1. Soil development is similar to that of scarp BRN7 discussed above, except the BRM3/4 soil contains thicker continuous carbonate coatings on clasts. Displacement measurements for BRM3/4 are larger than on BRN7 and so BRM3/4 is likely an older surface that has been faulted more frequently.

To the north 100 m from the coarse fan is a second displaced fan profiled at the BRM site (Figure 3.11q). Two scarps are present in the smooth fan, BRM5, probably the result of two fault strands. Displacement is not well constrained for the smooth surface because of the ambiguity of the two scarps' origin and a possible third fault strand which may exist where the cliff meets the head of the fan. A displacement across the two scarps is measured to be ~2 m.

Black Rock High (BRH). A large fault scarp roughly 75 m long, BRH1, is preserved 400-500 m south of site BRM (Figure 3.2). The scarp is formed in an unconsolidated colluvial apron deposit of probable late Pleistocene age based on surface smoothness, deset pavement development, and scarp height. The lower surface is buried by younger material but a minimum NVTD of 8-9 m is measured from a topographic profile (Figure 3.11r). The large displacement indicates that a number of late Quaternary slip events have occurred at this location, probably associated with slip on the Shivwitz section of the Hurricane fault.

The above description is not a complete list of scarps present in the study area, but does document the most significant and representative for rupture interpretations. An attempt was made toward an even coverage of alluvial fault scarps studied. Additionally, fault scarps with small (~1 m) displacements were sought after to assess the MRE rupture length along the study area. Although scarps may be present between the described sites listed above, they were not investigated because: 1) the fault scarps were inferred to be the same age (displacement) as a nearby studied scarp, 2) they were developed in extremely coarse alluvium, 3) the scarps or surfaces were significantly modified by erosion, or 4) the remnant of the surface in which the scarp has developed was too small for robust displacement measurements. Table 3.2 lists all of the sites along the study length of the fault with estimated vertical displacements taken from profiles or trenches, an approximated soil age if collected, and a slip rate if appropriate.

Discussion of Paleoearthquake Parameters and Scenarios

As discussed above, within the studied area along the Anderson Junction section of the Hurricane fault there are numerous fault scarps of varying heights in various aged deposits. How do the scarps relate in terms of characterizing the most recent rupture? What magnitude and length was the Holocene MRE, rupturing over 2 ka ago? Where did it occur for the area studied (what is implied about the location and characteristics of the rupture boundaries)? Potential damage from an earthquake increases with its magnitude, therefore it is important to interpret the size of event that occurred along a fault in the past. Many faults have been shown to rupture characteristically, with similar rupture events repeating with time, making past earthquakes instrumental in understanding potential future events (Shwartz and Coppersmith, 1984; Schwartz and Crone, 1985; Sieh, 1996).

Magnitude Estimates for the Most-Recent Rupture Event

Trench studies at Cottonwood Canyon demonstrate that 60 cm of surface slip were accommodated during the MRE at that location. Assuming that the 60 cm displacement was the maximum for the rupture, the magnitude of the MRE can be calculated. Wells and Coppersmith's (1994) equation, $M = 6.61 + 0.71 * MD$, is used to estimate the moment magnitude (M) of the MRE based on the maximum displacement (MD) produced from an earthquake on a normal fault. A M 6.1-6.8 is calculated for the MRE. Wells and Coppersmith's (1994) equations and associated statistical variations are the result of their regression analyses of worldwide historical earthquake data.

Sixty centimeters is not necessarily the maximum displacement that resulted during the MRE; it is possible that elsewhere along the rupture displacement was greater. If 0.60 m is the average displacement (AD) that occurred during the MRE, then the event is calculated at a M 6.3-7.0, using the equation, $M = 6.78 + 0.65 * AD$ for normal faults (Wells and Coppersmith, 1994). Considering the similar heights of other low scarps within 10 km of Cottonwood Canyon, it is more likely that the 0.60 m surface displacement was an average, not maximum, for the rupture. A conservative range of values yields an earthquake of M 6.1 - 7.0 for the Anderson Junction section's MRE, with a M 6.6 preferred.

Magnitude and displacement of a single paleoearthquake is estimated for the Hurricane fault, and whether it ruptures characteristically remains unknown. If it is assumed that the 0.60 m event is characteristic of ground-rupturing earthquakes that occur at Cottonwood Canyon, then 31-33 events are required to have formed the Q3 scarp. For >30 events to have ruptured the surface during its 70-125 ka of existence, then a rupture had to occur about every 2.1-3.8 ka. If this recurrence interval is correct, two or three ruptures should have taken place during the Holocene. Cottonwood Canyon's Q1 surface of probable early Holocene age is displaced only once. In conclusion, the Cottonwood Canyon MRE was probably not a characteristic rupture and larger magnitude earthquakes probably occurred in the past. The Hurricane fault may rupture in characteristic large events, however the MRE was not such an event.

Location and Length of the Most-Recent Rupture Event

Although there are many late Quaternary fault scarps within the Anderson Junction section, as described above, they are not continuous along the trace of the Hurricane fault. Alluvial fault scarps are absent over the northern 9 km of the study area, with only one location containing possible late Quaternary fault scarps in the study area north of Frog Canyon (Figure 3.2). The

Fault Scarp Site		NVTD (m)	Estimated Age (ka)	Slip Rate (mm/yr)	Notes
Cottonwood Canyon	CCQ0	unfaulted	2-6		soil pit
	CCQ1	0.60	8-15		trenched; soil pit
	CCQ2	> 5	20-50	< 0.1-0.4	trenched; soil pit
	CCQ3	18.5-20	70-125	0.1-0.3	soil pit
	CCQ4	10-12	> CCQ2, < CCQ3		
	CCQ6	18-20	~ CCQ	0.1-0.3	
Honeymoon Trail	HTN1	0.7-0.8			
	HTN3	~ 3			
	HTS1	> 12-14	~ CCQ3	>0.01-0.2	soil pit
	HTS2	> 3			
	HTS3	0.4-0.5	>/~ CCQ1		trenched; soil pit
Rock Canyon	RC1	~ 1			
	RC2	> 2.5-2.7			
Red Cliffs	REDN1	4-5			
	REDS1	0.9			
	REDS3	1.2-1.3			
Powerline Road	PR1	13-17			
	PR2	~ 2-4			
	PR3	~ 0.3-0.7			
Black Rock	BRN6	< 2-2.5			
	BRN7	< 0.8-0.9	CCQ1, < CCQ2		soil pit
	BRN8	<0.8-0.9			
	BRM3	< 4-4.5	CCQ1, < CCQ2		soil pit
	BRM4	< 4	> CCQ1, < CCQ2		soil pit
	BRM5	~ 2			
	BRH1	> 8-9			

Table 3.2. Summary of sites along the Hurricane fault containing fault scarps profiled to enable measurement of the net vertical tectonic displacement (NVTD). Best estimates of surface ages using soil development is included where soils were studied (see notes column). Slip rate is also included for scarps where possible. See Figure 3.2 for site locations.

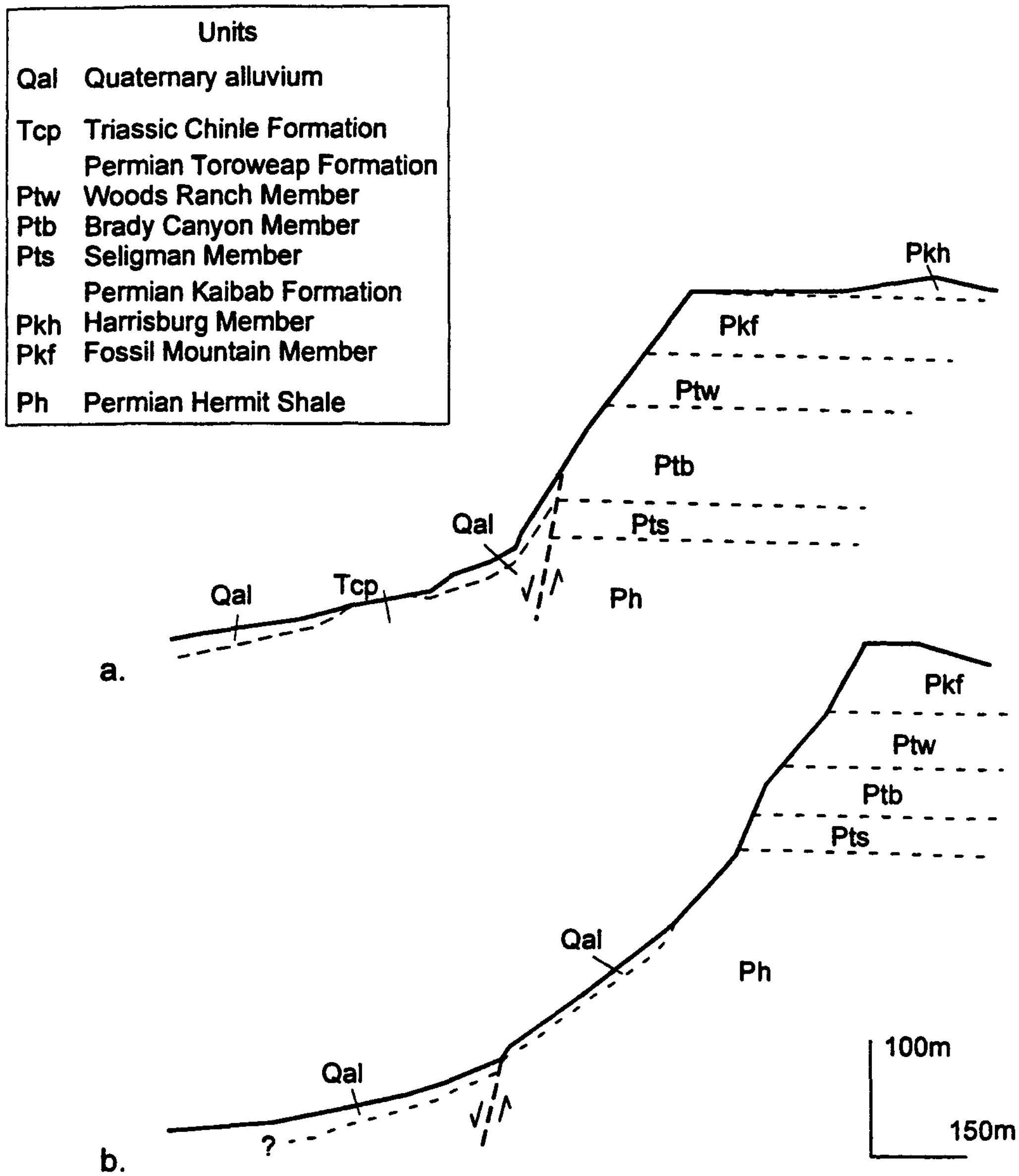

Figure 3.12. Schematic geologic cross-sections across the Hurricane fault. The Hermit Shale is less resistant to erosion than the Toroweap and Kaibab Formations. In (a) the Hermit Shale does not crop out and the cliff slope is steeper than in (b) where the Hermit Shale does crop out. The cliff has eroded farther away from the fault trace in situation (b) and preserves evidendce of late Quaternary rupture that may not be preserved in the steeper and bedrock conditions of (a). Surficial unit contacts are from Billingsley (1992), the geology is inferred at depth.

scarcity or possible absence of young scarps could suggest that the northern portion has not faulted as recently and/or as frequently as the southern portion of the study area. If this is the case, the northern limit of the MRE recognized in Cottonwood Canyon is the location 5 km north of Frog Canyon (Figure 3.2).

Alternately, it is possible that the northern area has ruptured just as frequently and recently as the southern area, but evidence is not preserved. Fault scarps exist where alluvium has been deposited across the fault, displaced, and preserved. These conditions are not always met along the Hurricane fault. Alluvium is deposited at the base of the cliffs in alluvial aprons and fans. The location of the fault relative to the position of the cliff base can mean the difference between the alluvium being displaced and preserving evidence of slip or not (Figure 3.12). Where alluvium at the base of the Hurricane cliffs is not observed to be displaced for a length of several kilometers, either a rupture has not occurred during the time since the alluvium was deposited or the rupture has not been preserved in the alluvium due to erosion. If rupture occurs directly at the base of the bedrock cliffs where there is thin to no alluvium (Figure 3.12a), then either the fault scarp would exist as a steep bedrock surface, much like the rest of the cliff, making identification of the rupture difficult, or form in steeply sloping alluvium that would rapidly erode back to the landform's pre-faulting slope angle, making later identification of the scarp difficult or impossible. In this scenario, the lack of alluvial fault scarps does not preclude late Quaternary ruptures occuring.

Landform and fault configurations in which Quaternary fault scarps are formed and preserved are those where drainages cut across the cliffs or where the trace of the fault is out front of the base of the cliff where thick and moderately to gently sloping alluvium is present. Where drainages have cut through the cliff, alluvial fans and terraces form in the gentle gradient conditions along the banks of the drainage and across the trace of the fault. These landforms are excellent slip recorders (e.g., Cottonwood Canyon Q0, Q1, and Q2 surfaces; Rock Canyon surfaces 1 and 3; Figure 3.12b).

Probably not coincidentally, the locations where alluvial fault scarps are common is along the portions of the Hurricane cliffs which expose the red and white sandstones, siltstones, and shales of the Permian Hermit Shale and Esplanade Sandstone. The correlation between alluvial fault scarps and outcrops of the red and white beds is possibly due to the decreased resistance to erosion of the cliffs where the sandstones, siltstones, and shales are exposed. When the cliffs erode back from the fault trace alluvial fans, aprons, and terraces are deposited over the fault, in front of the cliffs, preserve fault slip well (Figure 3.12b).

Because a lack of Quaternary fault scarps does not necessarily preclude late Quaternary rupture on that length of fault, determining the rupture length is problematic. But rupture length, as a measure of magnitude and potential damage, is an important aspect to assess. As rupture length increases, so does the earthquake magnitude produced and the hazard associated with the event (Working Group on California Earthquake Probabilities, 1995). Long normal faults have been shown from historic accounts and paleoseismic studies to rupture in segments at different times (Schwartz and Crone, 1985; Machette et al., 1991). The location of the segment boundaries remain fairly constant over time (Schwartz and Coppersmith, 1984; Schwartz and Crone, 1985).

When a segment of the fault ruptures, the same length will likely rupture as a whole in the future with a characteristic earthquake of similar size and resulting displacement as previous events (Schwartz and Coppersmith, 1984; Salyards, 1985; Schwartz and Crone, 1985). Identification of the segments, their boundaries, timing and size of previous ruptures are important for seismic hazard analyses because this information is used to forecast future events.

Instead of relying on direct physical evidence to evaluate the surface rupture length (SRL) of the MRE, the length can be approximated based on the relationship between rupture length and known displacement of historic earthquakes. Using Cottonwood Canyon's displacement, a minimum rupture length is calculated at 19.0-19.4 km, assuming 0.60 m is the maximum displacement and using the equation, $\log(SRL) = 1.36 + 0.35 * \log(MD)$, for normal faults. A more likely scenario in which 0.60 m is an average displacement, produces an estimated MRE rupture length of 28.5-28.9 km (using the equation $\log(SRL) = 1.52 + 0.28 * \log(AD)$; Wells and Coppersmith, 1994). Therefore a rupture length of 19-29 km is probable, with 28 km preferred.

Paleoearthquake Rupture Scenarios

Fault trace geometric bends, structural complexities, and locations where cummulative net slip changes along the Hurricane fault are areas where seismologic segment boundaries may occur. These characteristics provide the basis by which the Hurricane fault is divided into five sections (Figure 3.1; Taylor and Stewart, 1996; Stewart et al., 1997; Pearthree, 1998). The geometric sections may be rupture segments, however detailed information regarding the timing of ruptures on either side of a boundary is necessary before it can be considered a seismologic segment boundary. The studied portion of the fault is within the Anderson Junction section and its southern boundary zone (Figures 1 and 2). Five possible MRE rupture scenarios for the section are listed that remain consistent with the 0.60 m displacement at Cottonwood Canyon and with the location and size of scarps observed within the studied area (Figure 3.13). Note that presumed single event scarps along the fault are interpreted as a result of the same MRE as recorded in surface Q1at Cottonwood Canyon. 1) The long-dashed line in Figure 3.13 represents rupture during a small magnitude (<1 m displacement at maximum) event on the Anderson Junction section of the fault. 2) The thick line shows a small magnitude rupture across the segment boundary between the Anderson Junction and Shivwitz sections. 3) The short-dashed line scenario is one in which a larger magnitude (~2 m maximum displacement) event ruptures the Anderson Junction section with small displacement at its southern end. 4) A large magnitude rupture on the Shivwitz section that 'leaks' around the section boundary to the north with a 0.60 m displacement at Cottonwood Canyon is shown with a dash-dot patterned line. 5) Another possible scenario is shown by the thin lines in which a large rupture on the Shivwitz section triggers a separate, small rupture on the southern end of the Anderson Junction section. An analog to this scenario is the 1983 Borah Peak earthquake rupture along the Warm Spring segment of the Lost River fault in Idaho, triggered by rupture of the Thousand Springs segment (Yeats et al, 1997). Further investigations are needed to provide an understanding of which scenarios is the most likely for the Hurricane fault.

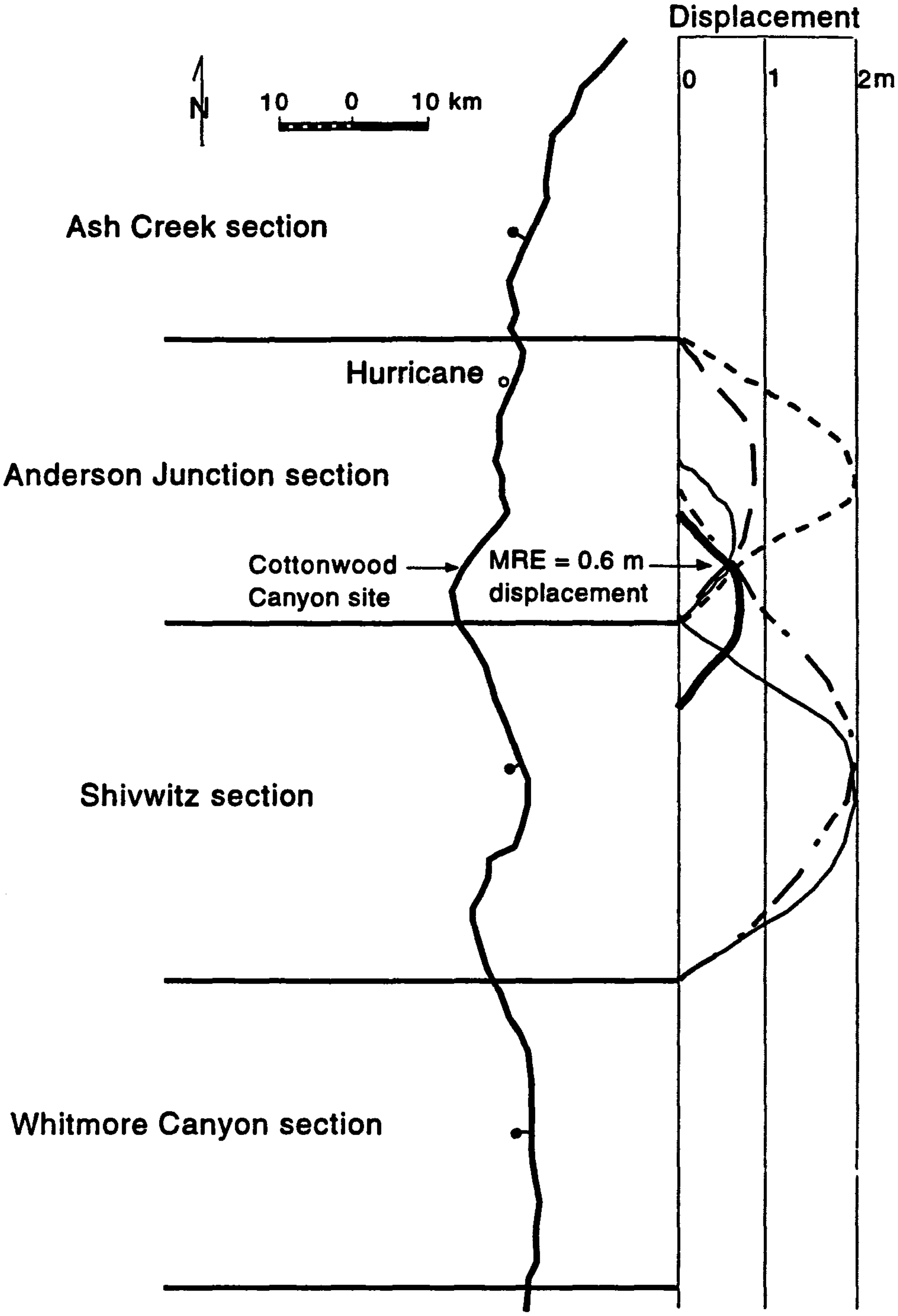

Figure 3.13. Possible rupture scenarios for the most recent event (MRE) recorded at the Cottonwood Canyon site where 0.60 cm of vertical displacement occurred. Each MRE rupture is consistent with the amount of displacement evident from other scarp sites along the Anderson Junction section. Represented are a small magnitude rupture on the Anderson Junction section (long-dashed line), a small magnitude rupture across the section boundary (heavy solid line), a larger rupture on the Anderson Junction section (short-dashed line), a large rupture on the Shivwitz section that leaks north of the section boudary (dash-dot line), and a large rupture on the Shivwitz section that triggers a small event on the southern Anderson Junction section (thin solid line).

Slip Rate Variations Over Time

Cottonwood Canyon provides information regarding the amount of slip that has occurred during different time intervals of the late Quaternary. Surface Q3 provides a slip rate of ~0.1-0.3 mm/yr, based on a displacement of 18.5-20 m and an age of 70-125 ka. Surface Q2 provides a maximum rate of 0.1-0.4, with >7 m vertical offset and a 20-50 ka age. Holocene surface Q1 has not existed through an earthquake recurrence period, it has only ruptured once, and cannot be used to estimate the slip rate. Rates of slip as calculated above show relative consistency throughout the last 100 ka, although uncertainty of the Q2 rate makes comparison difficult. A longer-term slip rate of 0.23-0.42 mm/yr over the last 293 +/- 87 ka is provided by an 87 m-displaced basalt flow near Hurricane, Utah, dated using K-Ar and thermoluminescence determinations (Hamblin et al., 1981). The slip rate has remained roughly the same over the last 300 ka, however the low data resolution may mask a variation of rate over time.

Summary of Results

The last large earthquake to rupture the ground surface along the southern Anderson Junction section of the Hurricane fault probably occurred 5-10 ka ago. Displacement during the Holocene event measured 0.60 m from vertically offset stratigraphic exposed in trenches at the Cottonwood Canyon site which is located at the southern end of the Anderson Junction section and the possible rupture segment. Similar sized displacements are found periodically along a stretch of fault 9 km to the north. Farther north within the section, no late Quaternary fault scarps are found but rupture from the most recent event may have continued through the area. Evidence for the rupture may have rapidly degraded or been hidden due to faulting within the thin alluvium and bedrock base of the large Hurricane Cliffs. Moment magnitude of the last large earthquake is estimated at 6.6 (6.1-7.0) with a possible length of 28 km (19-29 km). Different faulted deposits of increasing age and scarp height, at the Cottonwood Canyon site and elsewhere, provide views of recurrent late Quaternary slip. A large fault scarp developed in an 70-125 ka alluvial fan records displacement of 18.5-20 m, yielding a slip rate of 0.1-0.3 mm/yr. The large scarp suggests that the 0.60 m-displacement event is not likely to be typical of faulting recorded at Cottonwood Canyon. A scenario of 31-33 events occuring every 2-4 ka is required if the most recent event is characteristic. Existing evidence does not support this recurrence interval, as an ~8-15 ka surface is displaced only once at Cottonwood Canyon. It is probable that previous ruptures in the area were larger than the last and recur at intervals longer than 2-4 ka. More detailed investigations of the portions of the Hurricane fault to the nonh and south of this study are will be required to sort out the various scenarios presented for the most recent paleoearthquake, and to evaluate the seismogenic behavior of the proposed Anderson Junction - Shivwitz segment boundary.

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APPENDIX 1. HURRICANE FAULT RECONNAISSANCE OBSERVATIONS - UTAH

Field Number	Fault Sub-division	7.5' Quadrangle	Location	Feature Type	Remarks
FS1-1	1	The Divide	43S,13W,SW1/434	Fault scarp	~3 meters high, bedrock cored, slope angle ~22°
FS1-2	1	" "	43S,13W,NE1/434	" "	~6 meters high, bedrock cored; young stream terrace deposits in incised drainage cross the fault and are not displaced
FS1-3	1	" "	43S,13W,SW1/426	Stream channel	Large stream channel, fault not exposed, young stream terrace deposits cross the fault and are not displaced
FS2-1	2	" "	43S,13W,SW1/423	Rock fall?	Fault zone obscured, possibly by ancient rock-fall deposit derived from the Hurricane Cliffs
FS2-2	2	" "	43S,13W,NE1/410	Fault scarp?	Possible fault scarp ~5 meters high, very coarse colluvium, no evidence of fault in stream channel that has incised through this feature
FS2-3	2	" "	43S,13W,NW1/43	Fault exposure	Bedrock in fault contact with older colluvium, faulted units overlain by ~2 meters of unfaulted younger colluvium, no scarp
FS2-4	2	" "	42S,13W,NW1/422	Gravel pit	Gravel pit near base of Hurricane Cliffs - no fault exposure
FS2-5	2	Hurricane	42S,13W,NE1/415	Canyon mouth	Alluvial fan at canyon mouth heavily modified by man, no sign of scarps; smaller alluvial fans in the area do not appear displaced

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FS3-1	3	"	42S,13W,SE1410	Fault exposure	Fault exposure in bedrock, fault dips steeply to the west, 86° rake to the north (right lateral)
FS3-2	3	"	42S,13W,SE1/410	Lot excavation	Rough graded lot for home construction just west of Hurricane fault, final grading may expose fault
FS3-3	3	"	42S,13W,NW1/410	Fault exposure	Bedrock and older colluvium in fault contact, faulted units overlain by unfaulted younger colluvium, no scarp, fault dips 70° SW
FS3-4	3	"	42S,13W,NW1/410	Fault exposure	Bedrock and older colluvium in fault contact; large cut that requires extensive cleaning to determine geologic relations
FS3-5	3	"	42S,13W,NE1/424	La Verkin water tank cut	Poorly exposed bedrock faults in small draws; possible bedrock-cored scarp, but indistinct and possibly due to other causes
FS3-6	3	"	41S,13W,SE1/413	Fault exposure	Bedrock and older colluvium in fault contact overlain by younger alluvium, no scarp, fault dips 71° SW; (see Stewart and Taylor, 1996)
FS4-1	4	Pintura	40S,13W,SE1/423	Basalt flow	Basalt flow remnant on the footwall of the Hurricane fault, possibly correlative flow on hanging wall ~450 meters lower at base of Black Ridge
FS4-2	4	"	40S,13W,NE1/424	Basalt flow	Basalt flow remnant on footwall of the Hurricane fault, correlated geochemically by Stewart and Taylor (1996) with basalt on fault hanging wall ~ 450 meters lower at base of Black Ridge
FS4-3	4	"	40S,13W,center23	Fault scarp	Four short, steep, colluvium-mantled, bedrock-cored scarps ~200 meters from the base of the Hurricane Cliffs (cliff retreat); height 15-20 meters; ancestral Ash Creek stream alluvium caps and/or mantles

APPENDIX 1. HURRICANE FAULT RECONNAISSANCE OBSERVATIONS - UTAH

					these scarps in places (see Stewart and Taylor, 1996)
FS4-4	4	"	40S,13W,NE1/423	Fault exposure	Bedrock fault exposure overlain by unfaulted colluvium, no scarp; colluvium at base of Hurricane Cliffs observed in several incised drainages near this location, colluvium is not faulted and no scarps
FS4-5	4	"	40S,13W,SE1/414	Fault exposure?	Sharp contact (fault?) between basalt and Paleozoic bedrock at the base of the Hurricane Cliffs; Ash Creek has eroded a 50-75-meter-deep canyon in the basalt to the west, ancestral Ash Creek gravel rests on Paleozoic bedrock almost 100 meters above the present stream
FS4-6	4	"	40S,13W,SE1/414	Fault exposure	Hurricane fault, buff Paleozoic rock in fault contact with red Mesozoic rock; FS4-5 basalt is a few meters to the west and is not faulted, Ash Creek has incised basalt flow +50 meters
FS4-7	4	"	40S,13W,SW1/41	Fault exposure	Bedrock in fault contact with alluvium, fault dips 66° NW, alluvium is tilted to west (normal drag?), no scarp, location needs cleaning to work out sequence of faulting; bedrock exposure of fault to east dips 52° NW and slickenlines rake 88° to the north (right lateral)
FS4-8	4	"	40S,13W,W1/21	Alluvial fans	Walked alluvial fans and talus slopes along lower 1/3 slope of Black Ridge looking for scarps or other evidence of faulting - found none
FS4-9	4	"	40S,13W,NE1/41	Anomalous hill	Basalt rubble covered hill at base of Hurricane Cliffs, mapped by Cook (1960) as displaced basalt, no evidence of in place basalt, appears to be talus from basalt exposures high on Black Ridge
FS4-10	4	"	39S,13W,SE1/436	Anomalous draw	Linear, NW-trending drainage near alluvial-fan apex, no fault exposure but rock in cliff face exhibit weathered fault slick surfaces

APPENDIX 1. HURRICANE FAULT RECONNAISSANCE OBSERVATIONS - UTAH					
FS4-11	4	"	39S,12W,NW1/431	Fault scarps	Three short, steep, high, bedrock-cored scarps mantled with colluvium, slope angle 30°; fault exposed in wash between north and middle scarps, N10°W, 61° SW, is overlain by unfaulted colluvium
FS4-12	4	Kolob Arch	39S,12W,SE1/418	Landslide scarp?	Large (~20-m-high), generally north-trending scarp in basalt talus at north end of Black Ridge, underlain by Moenkopi and Chinle Fms; scarp origin uncertain but appears landslide related
FS4-13	4	" "	39S,12W,SW1/48	Landslide scarp?	Large (~30-m-high), north-trending scarp in basalt talus at north end of Black Ridge, underlain by Moenkopi and Chinle (?) Fms; scarp origin uncertain but appears landslide related
FS4-14	4	" "	39S,12W, NW1/48	Fault exposure	Two drainages converge to create Deadman Wash; Hurricane fault is exposed in both as a contact between Mesozoic and Paleozoic rock; both drainages have pronounced nick points at the fault
FS4-15	4	" "	39S,12W,SW1/45	Fault exposure	Bedrock fault exposure in wash incised into Hurricane Cliffs, faulted bedrock is overlain by unfaulted alluvium and colluvium
FS4-16	4	" "	39S,12W,SE1/432	Fault scarps	Two, short, parallel scarps; ~20-meter-high eastern scarp likely bedrock cored, slope angle 30°; ~5-meter-high western scarp formed on alluvium, slope angle 13°; western scarp is eroded and partially buried - Water Tank site
FS5-1	5	" "	38S,12W,NE1/416	Fault scarp?	Very steep alluvial-fan/talus slope at base of Hurricane Cliffs has a less steep inflection point about midway up the fan - fault scarp?
FS5-2	5	" "	38S,12W,NE1/416	Fault scarp?	At least two, possibly three ages of alluvial fans developed at base of Hurricane Cliffs; older, higher fan appears truncated and displaced;

APPENDIX 1. HURRICANE FAULT RECONNAISSANCE OBSERVATIONS - UTAH

					slope inflections on intermediate and younger fans may be scarps
FS5-3	5	Kanarraville	38S,12W,NW1/410	Fault exposure	Road to water tank crosses Hurricane fault, fault plane exposed in footwall, dips steeply to the northwest
FS5-4	5	"	38S,12W,SE1/43	Fault scarp	Short, likely bedrock-cored fault scarp, ~20 meters high, 30°+ slope
FS5-5	5	"	37S,12W,SE1/426	Fault scarp	Fault scarp on an older alluvial fan at a small draw, scarp is incised and a younger alluvial fan has formed downslope, toe of scarp has been removed by gullying - Kanarraville site
FS5-6	5	"	37S,12W,SW1/424	Fault scarp	Possible single-event scarp, ~3 meters high formed on young (Holocene - latest Pleistocene) alluvial fan at the mouth of a small drainage - Murie Creek site (Coyote Draw)
FS5-7	5	"	37S,12W,SW1/424	Fault scarp	Fault scarp formed on colluvial deposits at base of Hurricane Cliffs, ~200 meters long and mostly 10 meters or more high, beveled slope implies multiple surface-faulting earthquakes - Murie Creek site
FS6-1	6	Cedar Mountain	37S,11W,SW1/417	Fault scarps	Alluvial-fan surface is displaced across three parallel fault scarps, scarps range from ~3-7meters high and are ~50 meters long, fan surface is inactive - Bauer site
FS6-2	6	" "	37S,11W,NE1/417	Fault scarp?	At mouth of drainage incised into Hurricane Cliffs there is a ~10-meter-long, 1-meter-high possible scarp remnant; area has been chained and is highly disturbed, scarp identification uncertain
FS6-3	6	" "	37S,11W,NE1/417	Fault scarp?	Possible small scarp displaces alluvial-fan deposits at the mouth of a small drainage, area has been chained and is highly disturbed

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FS6-4	6	" "	37S,R11W,SE1/48	Fault scarp	Bedrock fault scarp formed on Moenkopi Fm. at the mouth of a small drainage; alluvium does not appear displaced, but area has been chained and is highly disturbed.
FS6-5	6	" "	37S,11W,SW1/49	Fault scarp	Small remnant of what may be a fault scarp in alluvium preserved against a bedrock scarp on the Moenkopi Fm. at Hicks Creek
FS6-6	6	" "	37S,11W,NW1/49	Fault scarp	High (~15 m) scarp formed on pediment deposit (Averitt, 1962), scarp is incised and younger alluvial fan(s) have formed on the hanging wall; fault is on trend with and connects directly with faults in bedrock to the south - Shurtz Creek site
FS6-7	6	" "	37S,11W,NW1/49	Alluvial terraces	Strong terrace along both sides of lower Shurtz Creek upstream from Hurricane fault - possibly tectonically related
FS6-8	6	" "	37S,11W,SE1/44	Alluvial terraces	Drainage incised into pediment on Hurricane fault footwall has two alluvial terraces locally along it, terraces are ~1.5 and ~3.5 meters above active stream channel - possibly tectonically related
FS6-9	6	" "	37S,11W,NE1/44	Fault scarps	Three subparallel scarps, two formed on alluvium and one on bedrock, scarps range from ~5-10 meters high and are ~50 meters long; displaced alluvial surface may be Shurtz Creek pediment or an older inactive alluvial-fan surface - Middleton site
FS6-10	6	" "	37S,11W,NE1/44	Fault scarp	Bedrock fault scarp formed on Moenkopi Fm., scarp trends into and is buried by landslide complex, no evidence of fault scarp in the landslide deposits
FS6-11	6	Cedar Mountain	37S,11W,sections	Landslide	Aerial photograph interpretation and a reconnaissance of landslide

APPENDIX 1. HURRICANE FAULT RECONNAISSANCE OBSERVATIONS - UTAH

			2,3,&4	complex	complex revealed no scarps unequivocally related to the Hurricane fault, scarps that are present appear related to landslide movement
FS6-12	6	Cedar City	36S,11W,sections 25, 26, 27, 34, 35, 36	Landslide complex	Aerial photograph interpretation and a reconnaissance of landslide complex revealed no scarps unequivocally related to the Hurricane fault, scarps that are present appear related to landslide movement
FS6-13	6	Cedar City	36S,11W,SE1/414	Stream morphology	Squaw Creek flows westward until issuing from the Hurricane Cliffs east of Cedar City, it then turns sharply north and flows to Coal Creek along the base of the cliffs; where north flowing, the stream may parallel a graben along the Hurricane fault; area is now developed and geologic relations are obscured.

APPENDIX 2A. SHURTZ CREEK SOIL MORPHOLOGY DATA										Prepared by Utah State University
Horizon	**Depth (cm)**	**Boundary (lower)**	**Munsell Color** dry moist	**Texture**	**Structure**	**Consistence**	**HCl Reaction**	**Roots**	**>2 mm % volume**	**Other**
Shurtz Creek West - Alluvial Fan										
A	0-8	a,s	nd 5YR 3/3	g sil	3 f gr	ss,ps	too wet	2f	15	frozen
BAt	8-24	c,s	nd 5YR 3/4	vg sicl	1 f&m sbk	ss,p	too wet	vf,3f,2m, 1c	60	2k po
Bt	24-31	c,w	nd 5YR 4/4	g sicl	m	ss,ps	too wet	1f,2m,1c	74	too wet
Bk1	31-56	g,s	7.5YR 6/4 7.5YR 4/6	nd	m	20% cw	ev	1f,1m	90	d, 2n coat
Bk2	56-80	g,s	nd 7.5YR 4/6	nd	m	nd	ev	1f,1m	85	d, 2n coat
Bk3	80-91	g,s	nd 7.5YR 4/6	nd	m	nd	ev	1vf,1f,1m	90	d, 2n coat
Bk4	91-100	-	nd 7.5YR 6/4	nd	m	nd	ev	1vf	90	d, 2n coat

Shurtz Creek East - Pediment										
A	0-11	c,s	nd 7.5YR 2.5/2	sil	2 f gr	nd	eo	2vf,3f,1m	10	frozen
BAt	11-18	a,w	nd 7.5YR 3/3	g sil	1 c sbk	nd	e-em	3vf,3f,2m	25	1 n po,d
Bt	18-26	c,i	nd 7.5YR 3/4	g sicl	1 m sbk	nd	e-em	3vf,3f,2m	50	2n po,d
Btk1	26-45	c,w	7.5YR 5/4 7.5YR 5/6	nd	1 m&c sbk	nd	es-ev	2vf,1f,2m	65	1n pf,d
Btk2	45-66	c,w	7.5YR 6/4 7.5YR 4/6	nd	m	20% cw	es-ev	1vf,1f,2m	75	2n po,d*
Btk3	66-100	g,s	7.5YR 7/4 7.5YR 6/4	nd	m	50% cw	ev	1f	50	3n po,d*
Btkm	100-110	-	7.5YR 7/4 7.5YR 6/4	nd	m	100% cw	es	-	65	2n po,d*
Although not described in detail, $CaCO_3$ coatings more extensive and thicker than in the west pit.										

Abbreviations:

Boundary: a = abrupt; c = clear; g = gradual; s = smooth; w = wavy; I = irregular.

Texture: sil = silt loam; sicl = silty clay loam; g = gravelly

Structure: 1 = weak; 2 = moderate; ma = massive; f = fine; m = medium; c = coarse; gr = granular; sbk = subangular blocky.

Consistence: ss = slightly sticky; ps = slightly plastic; p = plastic; % cw = percent volume weakly cemented.

Reaction: effervescence with 10% HCl: eo = none; e = slight; em = moderate; es = strong; ev = violent.

Roots: 1 = few; 2 = common; 3 = many; vf = very fine; f = fine; m = medium; c = coarse.

Other: d = disseminated carbonates;1 = few; 2 = common; 3 = many; n = thin; k = thick; pf = clay films on ped faces; po = clay films lining pores.

nd = not determined

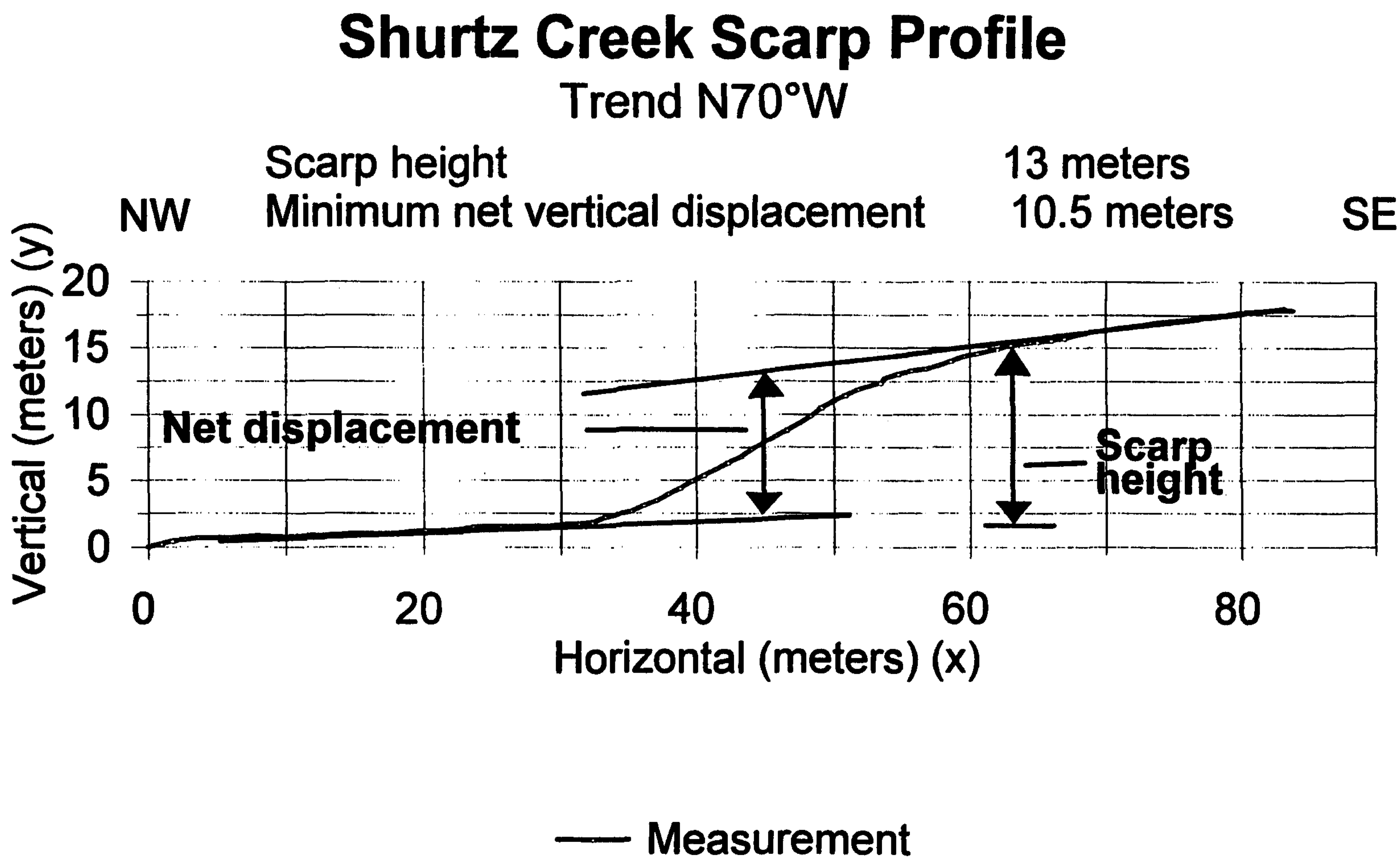
APPENDIX 2B. SHURTZ CREEK SITE - SOIL LABORATORY RESULTS						
Location	**Depth cm**	**Thickness cm**	**pH**	**Electrical Conductance**	**Percent Gypsum**	**Percent $CaCO_3$**
Shurtz Ck East	0					
	11	11	7.75	60.2	0.00	0.1
	18	7	7.94	55.5	0.00	1.1
	26	8	7.91	75	0.02	3.1
	45	19	8.5	57.3	0.00	24.9
	66	21	8.6	53.5	0.01	33.8
	100	34	8.83	51.8	0.01	43.4
	110	10	8.99		0.01	39.4
Shurtz Ck West	0					
	8	8	7.38	52.8	0.00	0.4
	24	16	8.32	62.3	0.00	6.4
	31	7	8.37	70.2	0.00	10.7
	56	25	8.63	55.6	0.00	14.1
	80	24	8.52	56.8	0.00	12.9
	91	11	8.51	54	0.00	23.2
	110	19	8.33	50.6	0.00	12.6

APPENDIX 2C. MURIE CREEK SOIL MORPHOLOGY DATA										Prepared by the Utah Geological Survey
Horizon	**Depth (cm)**	**Bound-ary**	**Munsell Color dry/moist**	**Texture**	**Structure**	**Consistence dry/moist/wet**	**HCl Reaction**	**Roots**	**>2 mm % vol.**	**Other**
Base Hurricane Cliffs - Colluvium, clasts are predominately resistant limestone from the Permian Kaibab Formation										
A1	0-5	c,w	5YR 4/1 5YR3/2	sil	sg vf gr	lo vfr s	eo	3f	10*	-
A2	5-17	g,w	7.5YR 4/2 5YR 3/2	sil	sg vf	so vfr s	eo	3f	10	-
Bt	17-27	g,s	5YR 4/3 5YR 3/3	sicl	1 f sbk	so vfr s	es	2f	20	pf
2Btk	27-56	g,w	5YR 5/3 5YR 3/3	sicl	1 m sbk	sh vfr ss	ev	1f	50	d
2Bk	56-85	-	5YR 4/2 5YR 3/4	sil	2 m sbk	sh fr ss	ev	1f	50	d, 2n coat

Coyote Draw - Alluvial Fan; parent material for this soil is alluvium derived from the Lower Red Member of the Moenkopi Formation, the alluvium contains considerable primary clay.										
A	0-7	c,s	5YR 4/3 5YR 4/4	sicl	m	sh fr s	eo	3f	10	-
Bw1	7-17	g,w	2.5YR 4/4 2.5YR 3/4	sicl	m	sh fr s	eo	3f	10	-
Bw2	17-44	g,w	2.5YR 4/6 2.5YR 4/4	sicl	2 m sbk	sh fr s	eo	2f	25	-
Bk	44-80	-	2.5 YR 5/4 2.5YR 3/4	sicl	2 m sbk	sh fr s	es	1f	25	d, 1n coat

Abbreviations: Same as Appendix 2A.

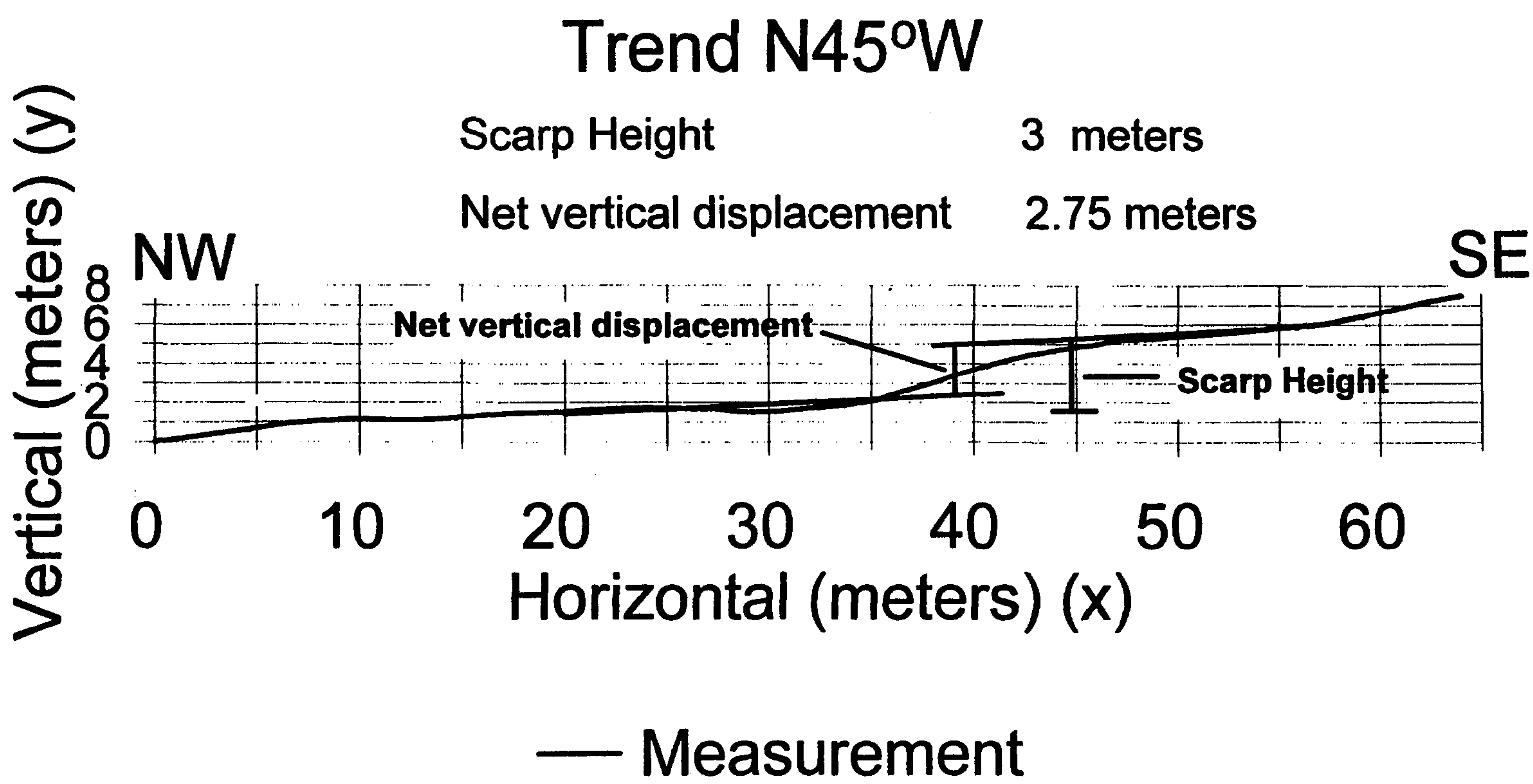
Appendix 3A



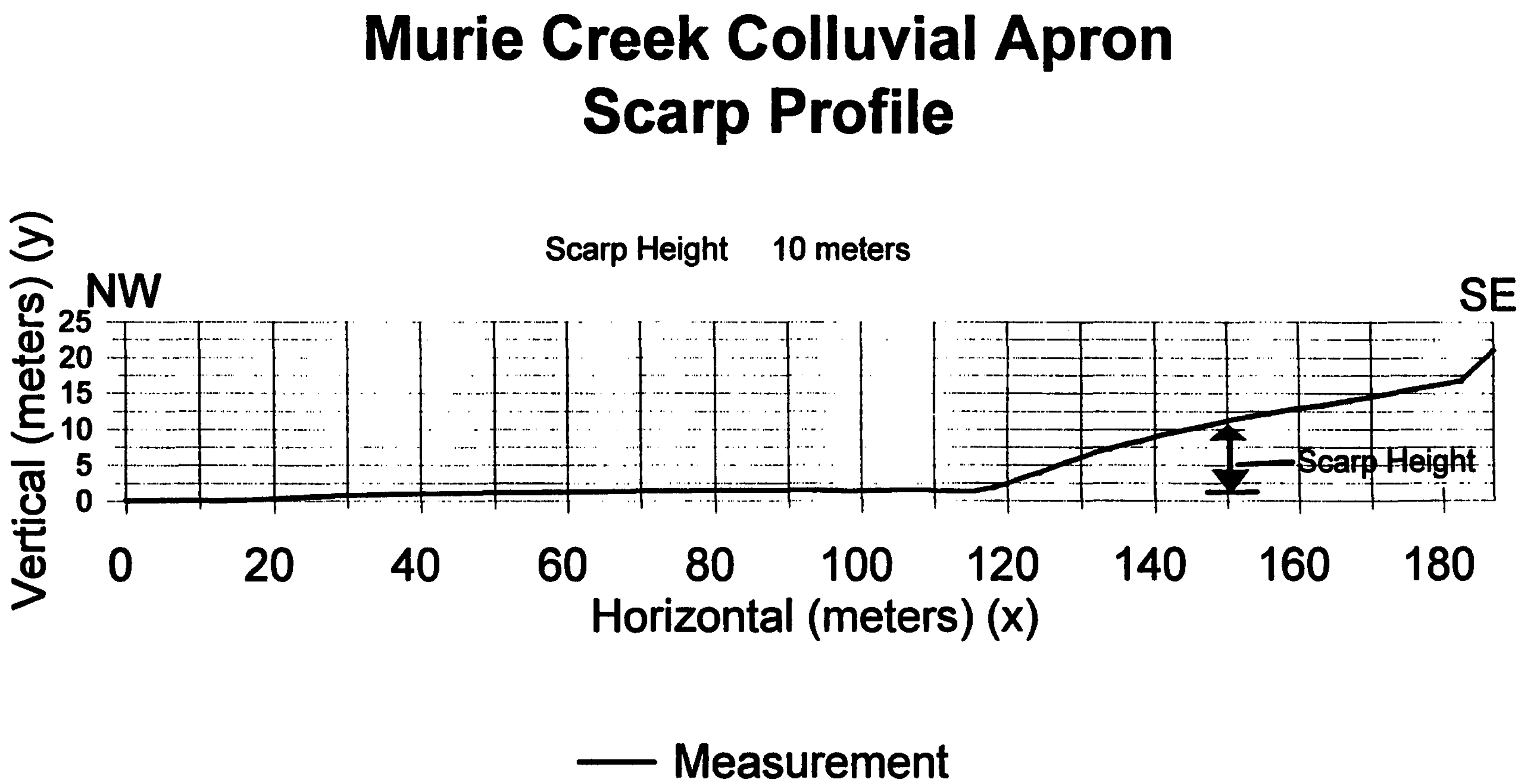
Shurtz Creek Scarp Profile
Trend N70°W
Scarp height 13 meters
Minimum net vertical displacement 10.5 meters
NW
SE
Vertical (meters) (y)
20
15
10
5
0
Net displacement
Scarp height
0
20
40
60
80
Horizontal (meters) (x)
Measurement

Appendix 3B

Coyote Draw Scarp Profile



Appendix 3C



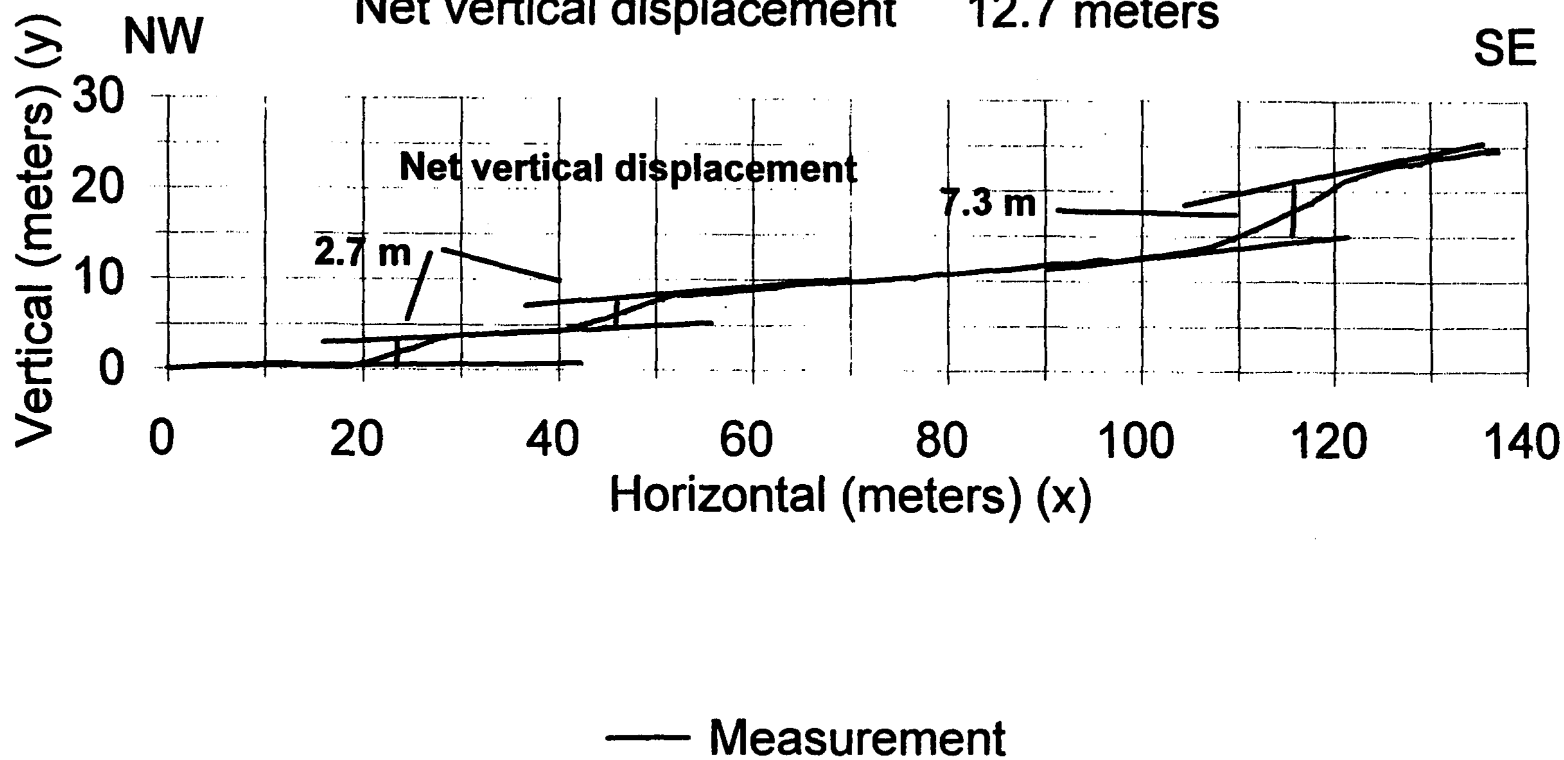
Murie Creek Colluvial Apron
Scarp Profile
Scarp Height 10 meters
NW
SE
Vertical (meters) (y)
25
20
15
10
5
0
Scarp Height
0
20
40
60
80
100
120
140
160
180
Horizontal (meters) (x)
Measurement

Appendix 3D

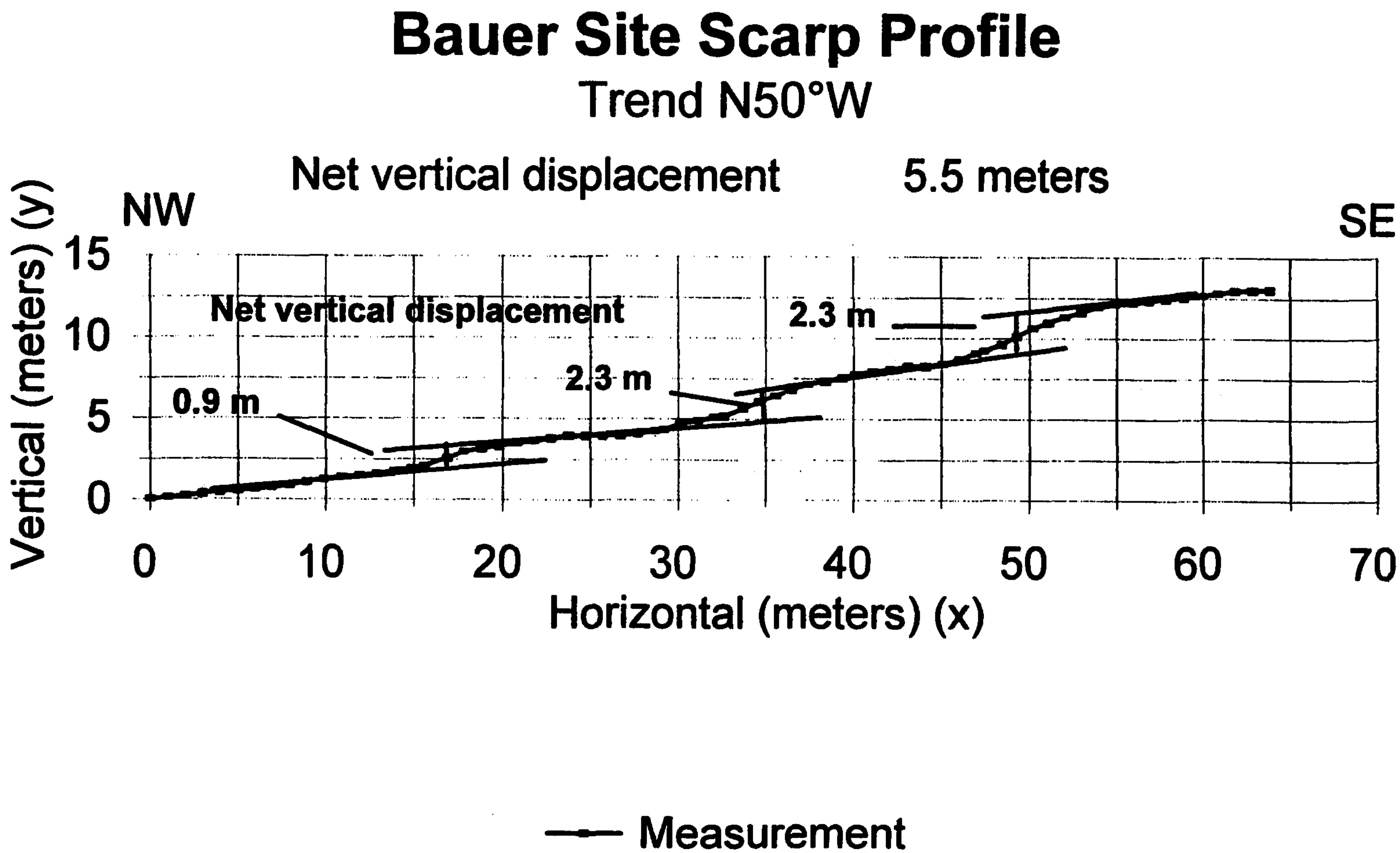
Middleton Site Scarp Profile

Trend N85°W

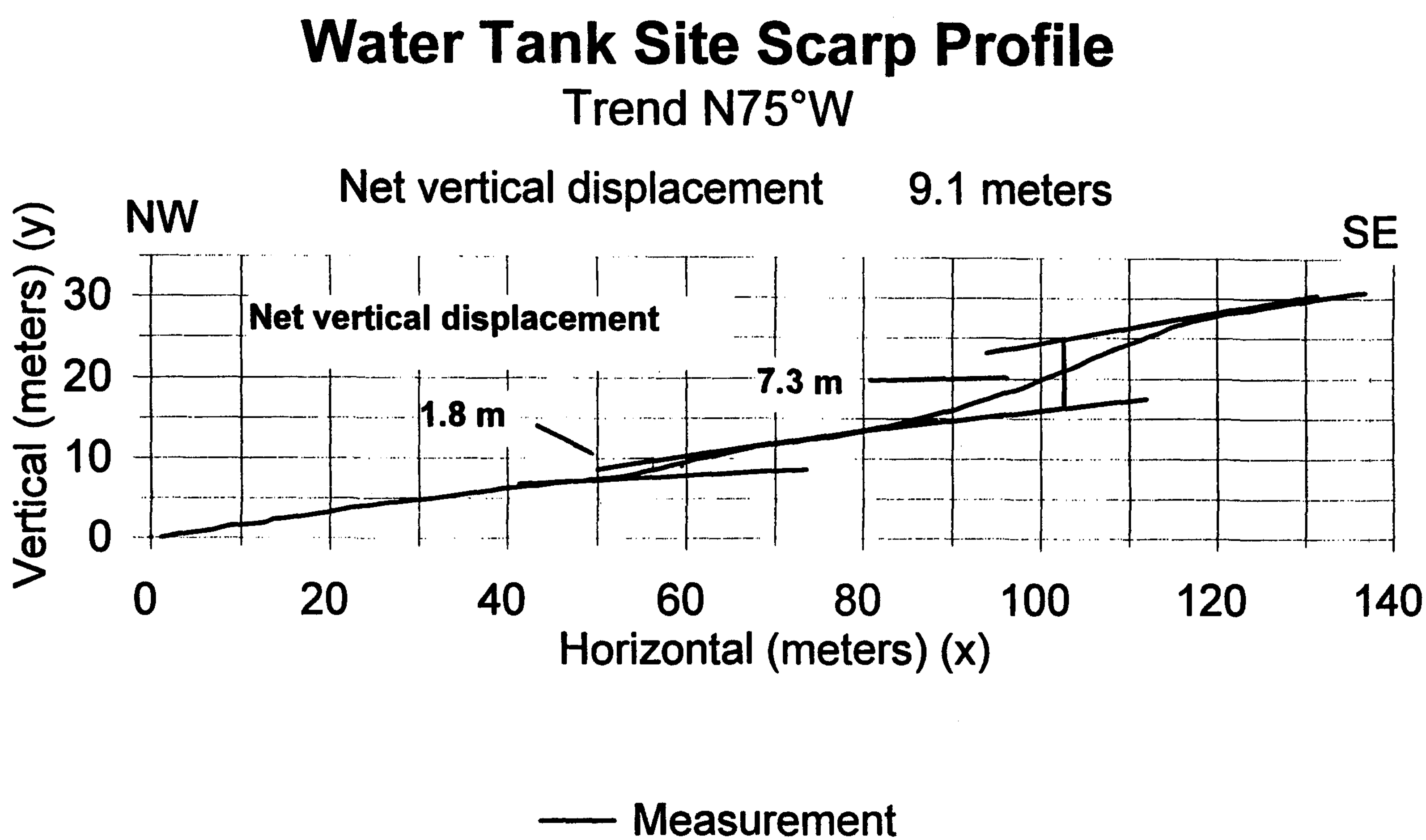
Net vertical displacement 12.7 meters



Appendix 3E


Bauer Site Scarp Profile
Trend N50°W
Net vertical displacement 5.5 meters
NW
SE
Net vertical displacement
0.9 m
2.3 m
2.3 m
Vertical (meters) (y)
15
10
5
0
0
10
20
30
40
50
60
70
Horizontal (meters) (x)
Measurement

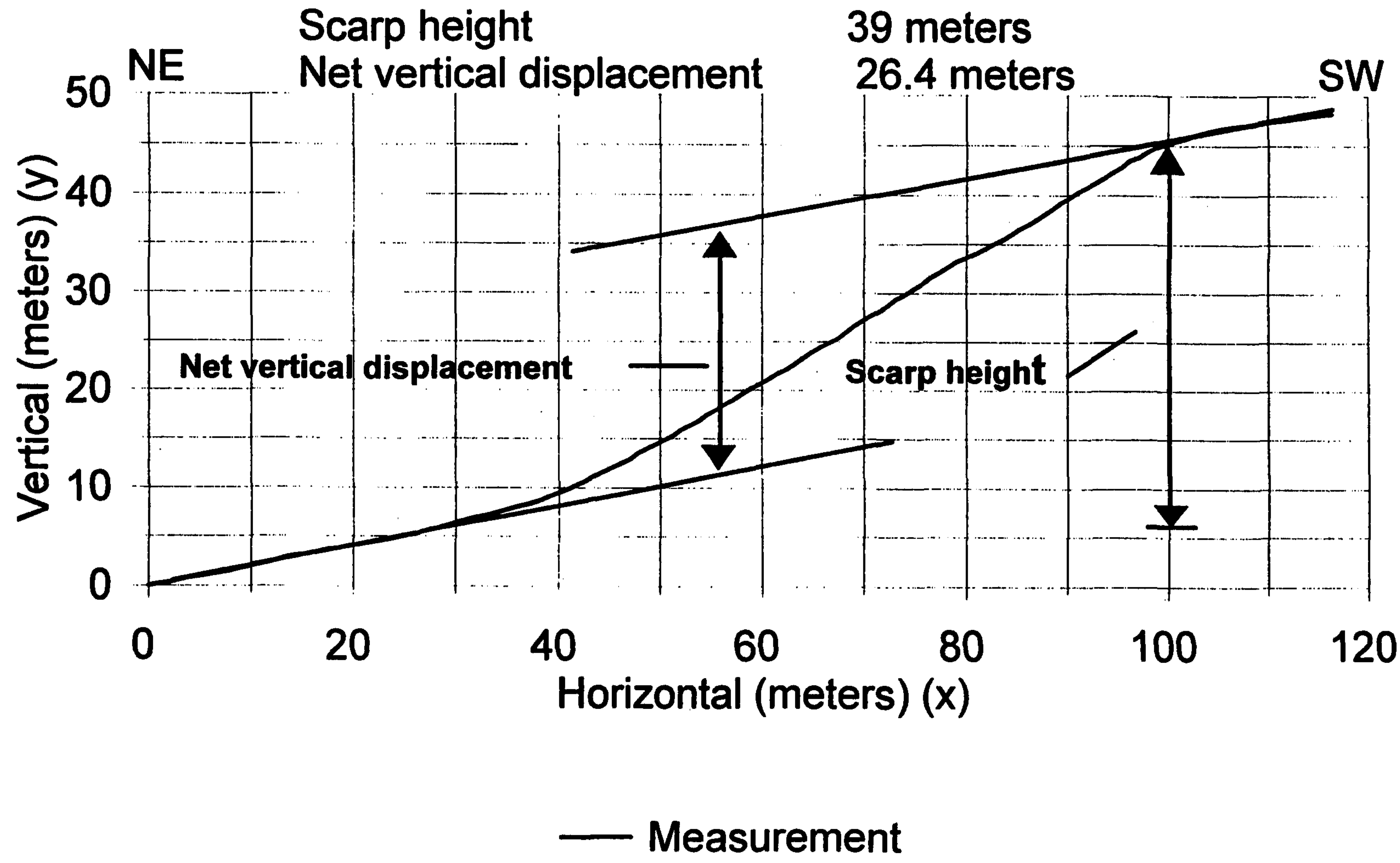
Appendix 3F


Water Tank Site Scarp Profile
Trend N75°W
Net vertical displacement 9.1 meters
NW
SE
Net vertical displacement
1.8 m
7.3 m
Vertical (meters) (y)
0
10
20
30
0
20
40
60
80
100
120
140
Horizontal (meters) (x)
Measurement

Appendix 3G

Bedrock Scarp Profile Near Pintura

Trend N75°E



Appendix 4. Soil descriptions along the southern Anderson Junction, Hurricane fault.

Soils of the Cottonwood Canyon site (CCQ0,CCQ1, CCQ2U, CCQ2-wedge, CCQ3U, and CCQ3D) were described by J. Boettinger and the Utah State graduate pedology class, spring, 1998. See Figures 3.2 and 3.3 for site locations and text for discussion. See Appendix 1 for abbreviations.

Horizon	Depth (cm)	Boundary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
CCQ0: Unfaulted, abandoned alluvial fan/fluvial terrace with northwest aspect.											
A	0-7	c,s	10YR 6/4	10YR 5/4	lfs	1 f sbk-1 f gr	so,vfr, so/po	es	1f	5	d
Bw	7-20	c,s	10YR 5/4	10YR 4/6	g lfs	1 f sbk	so,vfr,so/po	em	2f,1m	30	d
Bk1	20-36	c,s	10YR 5/4	10YR 5/6	vg lfs	1 f-m sbk	so,vfr,so/po	es	2f,1m	60	d
Bk2	36-47	c,s	10YR 6/4	10YR 5/4	xg ls	sg	lo,lo,so/po	ev	1f	60	d
Bk3	47-63	c,s	10YR 6/4	10YR 5/4	xcob lfs	1 f-m sbk	so-sh,vfr,so/po	ev	1vf	65	d, pockets of fine gravel
BCk	63-89	c,s	10YR 6/4	10YR 5/4	xcob ls	ma	lo,lo,so/po	es	1f,1m	75	d
BCky	89-100		10YR 7/4	10YR 5/4	xg ls	ma	lo,lo,so/po	es		80	d, gyp, CaCO3 pend

CCQ1: Faulted, abandoned alluvial fan/fluvial terrace with northwest aspect, from trench.

Vegetation: ~15% total cover (excluding grass) with 85% creosote, 10% low shrub (<1m), 5% cholla, rare prickly pear and yucca.

Horizon	Depth (cm)	Boundary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
A	0-8	c,s		7.5YR 5/4	ls	2 f gr		em	3f,3vf	6	d
Bw	8-15	c,s		7.5YR 4/6	s	2 f-m sbk		es	3f	6	d
2Bk1	15-57	a,s	7.5YR 6/6	7.5YR 5/6	xcob sl	1 f-m sbk		ev	2f	65	d, 3n CaCO3 coat
3Bk2	57-80	c,s	7.5YR 7/4	7.5YR 4/6	xg ?	1 f-m sbk, sg		ev	1m	65	d, 2n CaCO3 coat
3C	80-129	c,s	7.5YR 6/4	7.5YR 6/6	xg ?	sg		ev	1m	75	d
4Bkb	129-159	g,s	7.5YR 6/4	7.5YR 6/6	xg ?	sg		ev	1m	75	d, 3n CaCO3 pend
4Bkyb	159-170			7.5YR 6/6	xg?	v1 f-m sbk, sg		ev	1m	75	d,1n CaCO3, gyp pend

Horizon	Depth (cm)	Bound-ary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes

CCQ2-Wedge: Faulted, abandoned alluvial fan/ fluvial terrace with northwest aspect, from trench.

Horizon	Depth (cm)	Bound-ary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
A	0-8	a,s	10YR 5/4	10YR 4/3		1 f gr	so, vfr		2f, 2vf, 2c	15	d
AB	8-14	a,s	7.5YR 5/4	7.5YR 4/4		2 f sbk	sh		1vf, 1c	15	d
Bw	14-26	c,s	7.5YR 6/4	7.5YR 4/6		2 m sbk	sh-h		1vf, 1m, 1c	15	d
Bk1	26-47	c,s	7.5YR 6/4	7.5YR 4/4		1 c sbk	sh		1vf, 1m	15	d
Bk2	47-60	c,s	7.5YR 6/4	7.5YR 4/6		1 c sbk	sh-h		1f, 1m, 1c	15	d
BCk	60-78	c,s	7.5YR 6/4	7.5YR 4/6		vl vc sbk	so-sh		1vf	15	d
C1	78-105	c,s	7.5YR 6/4	7.5YR 4/6		ma	so-sh		1vf, 1f	20	d
C2	105-127	c,s	7.5YR 6/4	7.5YR 5/4		ma	so-sh		1vf, 1f, 1m	16	d
2C3	127-152	a,s	7.5YR 6/6	7.5YR 4/6		ma	so-sh		1vf, 1f, 1m	21	d
2C4	152-172	c,s	7.5YR 6/4	7.5YR 4/4		ma	sh		1f, 1m	20	d
2C5	172-193	c,s	7.5YR 6/4	7.5YR 4/4		ma	lo		1f, 1m	20	d
2C6	193-235		7.5YR 6/4	7.5YR 4/6		ma	lo		1f, 1m	25	d

Horizon	Depth (cm)	Bound-ary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
CCQ2U: Faulted, abandoned alluvial fan/fluvial terrace with northwest aspect, in footwall.											
Vegetation: ~40% total cover with 65% grass and low shrub, 25% creosote, 5% cholla, 5% yucca, occasional prickly pear											
A	0-13	c,s		10YR 5/4		1 m sbk - 2 f gr		em		20	d
Bw	13-39	g,s	7.5YR 6/6	7.5YR 5/6		1 m,f sbk		ev		55	d
Bk1	39-59	g,s	7.5YR 7/4	7.5YR 5/4		sg		ev		65	d, 3n,coat
Bk2	59-92	d,s?	7.5YR 7/4	7.5YR 5/4		sg		ev		75	d, 3n,coat
Bk3	92-116	g,s	7.5YR 7/4	7.5YR 5/4		sg		ev		75	d, 3n,coat, 2n pend
Bk4	116-145		7.5YR 7/4	7.5YR 5/6		sg		ev		80	d, 3n,coat and pend

Horizon	Depth (cm)	Boundary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes

CCQ3D: Faulted, abandoned alluvial fan with northwest aspect, hanging wall.

Horizon	Depth (cm)	Boundary	Munsell Color dry	Munsell Color moist	Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
A	0-1	c,s	7.5YR 5/4	7.5YR 3/4	fsl	1 f gr	vfr, so/po	es		5	d
Bw	7-19	c,s	7.5YR 5/4	7.5YR 4/4	fsl	2 m,c sbk	fr, so/po	es		8	d 1fsm
Bk1	19-27	c,s	7.5YR 5/4	7.5YR 4/6	g fsl	1 m,c sbk	fr, ss/ps	ev		20	d, 1f sm
Bk2	27-44	c,s	7.5YR 6/4	7.5YR 4/6		1 m,f sbk	lo-so, lo-fr	ev		65	d, 1n coat, pend
Bkm1	44-62	g,w	10YR 8/2	10YR 8/2		ma	cs	ev		75	
Bkm2	62-80	c,w	10YR 7/3	10YR 6/4		ma	cw to s	ev		75	
B'k1	80-110	g,w	10YR 7/4	10YR 5/6	xg fsl	1 m,f sbk, sg,m	lo-so,lo-vfr,so/po	ev		75	d, 3n coat, 1n pend
B'k2	110-132	g,w	10YR 7/3	10YR 5/4	xg sl	sg	fi,so/po	ev		65	d, 3n coat, 1n pend
B'k3	132-155		10YR 7/3	7.5YR 5/4	xg sl	sg	so/po	ev		65	d, 3n coat, 1n pend

Horizon	Depth (cm)	Bound-ary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
CCQ3U: Faulted, abandoned alluvial fan with northwest aspect, footwall.											
Vegetation: ~50% total cover with 45% blackbrush?, 40% yucca in large (<5 m) clusters, 10% creosote, 5% mormon tea, rare prickly pear, hedgehog cactus, and cholla.											
A	0-13	c,w		7.5YR 4/6	lfs	vl sbk - 2f gr		em	2m, 2f	5	d
Bw	13-35	g,i		7.5YR 4/6	g fsl	1f sbk - 2 f gr		ev	3m, 2co	30	d, 1 f sm
Bkm	35-69	g,i	7.5YR 6/6	7.5YR 4/6		ma		ev	1m	60	d, 2k pend, 3 k coat
B'k	69-145		7.5YR 7/3	7.5YR 5/6		sg		ev	2m	60	d, 1n pend, 1n coat

Soils of sites HTS, BRN, and BRM described by H. Stenner, J. Klawon, T. Biggs, 1998; see Figure 3.2 for site locations and text for discussion

HTS3: Faulted, abandoned alluvial fan/fluvial terrace with northwest aspect, in trench.

Vegetation: ~30% total cover (excluding grass) with 15% creosote, 10% cholla, 3% black brush?, and 2% yucca, prickly pear

Horizon	Depth (cm)	Boundary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
A	0-13	a,w	7.5YR6/4	7.5YR4/4	sl	1 f pl	so-sh	so,po	em	15	
Bw	13-22	c,w	5YR6/4	7.5YR4/6	sl	1 m sbk	so-sh	ss,ps	es	20	1v n dis
2Bk1	22-40	g,w	7.5YR6/4	7.5YR4/6	sl	1 m-c pl	so	so,po	es	50	n con
2Bk2	40-57	c,w	5YR7/4	7.5YR5/6	sl	1 f sbk	so	ss,ps	es	50	v n con
3Bk3	57-76	g,w	7.5YR7/4	7.5YR5/6	sl	1 f-m sbk	so	so,po	es	25	v n dis--clast bottoms
4Bk4	76-98	c,w	7.5YR7/4	7.5YR5/6	ls	sg	lo	so,po	es	25	1v n dis--clast bottoms
5Bk4	98-135		7.5YR7/4	7.5YR5/6	sl	sg	lo	ss,ps	es	20	1v n dis--clast bottoms

Horizon	Depth (cm)	Bound-ary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes

HTS1: Faulted, abandoned alluvial fan with northwest aspect, footwall.

Vegetation: ~30% total cover with 15% black brush?, 10% creosote, 5% cholla, occasional yucca, prickly pear

Horizon	Depth (cm)	Bound-ary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
A	0-10	a,w	7.5YR5/6	7.5YR4/6	sl	1 f pl	so	ss,ps	es	15	
Bw	10-24	c,w	5YR5/4	5YR4/6	vfsl	1 f-m pl	so	ss,ps	es	20	v n dis
2Bk1	24-49	c,w	7.5YR5/6	5YR5/6	sil with s	1 f-m gr	sh	ss,ps	es	50	n con
2Bk2	49-80	c,w	7.5YR6/4	5YR5/6	sl	1 f-m sbk to cw	sh	ss,ps	ev	50	patchy w cem
3Bkm	80-102	a,w	5YR7/3	7.5YR5/6	sl	cm	h	ss,ps	ev	40	m cem
3Bk3	102-127	a,w	5YR6/4	5YR5/6	sil with s	ma-1 f sbk to cm	sh	ss,ps	es	40	patchy m cem
4BC	127-149		5YR6/4	5YR5/6	sl	sg	lo	so,po	es	30	1n con

Horizon	Depth (cm)	Bound- ary	Munsell Color dry/moist		Texture	Structure	Consistence dry,moist,wet	React. To HCl	Roots	>2 mm % vol.	Carbonate notes
BRN7: Faulted, abandoned alluvial fan with west aspect.											
A	0-9	c,w	7.5YR5/6	7.5YR4/6	sl	2 m sbk	sh	so,po	es	20	v n--clast bottoms
Bw	9-22	a,w	7.5YR5/6	7.5YR4/6	fsl	1 f sbk	so	ss,ps	es	15	v n--clast bottoms
Bk1	22-52	c,w	5YR7/4	7.5YR5/6	sl	1 f sbk	so	so,po	es	60	v n con
Bk2	52-58		7.5YR6/4	7.5YR5/6	ls	sg	lo	so,po	es	50	v n dis
BRN3/4: Faulted, abandoned alluvial fan with west aspect.											
A	0-12	a,w	7.5YR5/4	7.5YR4/6	ls	1 vf-f gr	so	ss,po	es	25	v n dis--clast bottoms
Bw	12-30	c,w	7.5YR5/6	5YR4/6	fsl	1 f-m sbk	sh	ss,ps	es	25	n dis
Bk1	30-48	c,i	7.5YR7/4	7.5YR5/6	sl	sg	h	ss,po	ev	60	n con
Bk2	48-70		7.5YR7/4	7.5YR5/6	sl	sg	so	ss,ps	es	50	n dis

Appendix 5. Carbonate rind thickness data.
Rind thicknesses were measured to develop a soil chronosequence.

CCQ1

Pit depth (cm) to:	10	20	30	40	50	60	70	80	90	100
Rind thickness (mm):	0.6	0.36	0.64	0.46	0.27	0.78	0.18	0.08	0.02	0.14
	0.4	0.5	0.38	0.14	0.62	0.12	0.12	0.06	0.02	0.2
	0.24	0.34	1	0.64	0.18	0.22	0.18	0.16	1.98	0.02
	0.24	0.32	0.36	0.64	0.43	0.13	0.34	0.34	0.24	0.44
	0.64	0.24	0.32	0.28	0.32	0.14	0.14	0.12	0.09	0.58
	0.6	0.42	0.44	0.32	0.16	0.42	0.12	0.2	0.22	0.26
	0.2	0.24	0.38	0.5	0.22	0.14	0.28	0.14	0.05	0.04
	0.22	0.16	0.42	0.38	0.3	0.05	0.24	0.08	0.04	0.06
	0.18	0.4	0.48	0.46	0.55	0.04	0.12	0.18	0.06	0.04
	0.38	0.38	0.48	0.42	0.13	0.51	0.1	0.14	0.14	0.02
Mean thickness (mm):	0.37	0.336	0.49	0.424	0.318	0.255	0.182	0.15	0.286	0.18

CCQ2

Pit depth (cm) to:	10	20	30	40	50	60	70	80	90	100	110	120
Rind thickness (mm):	0.26	0.68	0.9	0.74	0.7	0.64	0.82	0.21	0.18	0.38	0.2	0.18
	0.98	0.68	0.52	0.58	0.64	0.19	0.84	0.04	0.28	0.12	0.14	0.02
	0.84	0.39	0.84	0.94	0.44	0.64	0.4	0.58	0.6	0.28	0.26	0.02
	0.14	0.64	0.44	0.72	0.98	0.6	0.34	0.54	0.2	0.2	0.18	0.14
	0.41	0.41	0.86	0.14	0.44	0.22	0.28	0.38	0.32	0.22	0.16	0.06
	0.72	0.22	0.44	0.59	0.48	0.26	0.24	0.37	0.5	0.06	0.18	0.22
	0.39	0.38	0.8	0.72	0.8	0.22	0.32	0.34	0.32	0.28	0.2	0.04
	0.54	0.42	0.62	1.02	0.58	0.52	0.26	0.62	0.18	0.26	0.2	0.04
	0.38	0.55	1.02	0.62	0.82	0.18	0.38	0.24	0.32	0.48	0.18	0.14
	0.12	0.58	0.81	0.5	0.54	0.58	0.68	0.38	0.7	0.24	0.1	0.02
Mean thickness (mm):	0.478	0.495	0.725	0.657	0.642	0.405	0.456	0.37	0.36	0.252	0.18	0.088

CCQ3D

Pit depth (cm) to:	10	20	30	40	50	60	70	80	90	100	110
Rind thickness (mm):	1.22	0.09	1.6	0.84	0.83	0.98	0.38	0.67	0.34	0.53	0.57
	0.22	1	0.86	0.84	0.08	1.47	1.23	0.33	0.38	0.48	0.11
	0.81	1.82	0.56	0.85	0.49	0.26	0.32	0.82	0.63	0.36	0.02
	0.24	0.51	2.5	0.58	0.89	0.55	0.18	0.86	0.31	0.12	0.21
	0.12	1.12	0.64	1.15	1.47	1.48	0.96	0.83	0.65	0.22	0.24
	0.68	1.64	1.04	0.91	1.37	0.7	0.47	0.22	0.62	0.66	0.3
	0.02	0.65	0.68	1.04	1.03	0.49	0.81	0.45	0.34	0.32	0.22
	0.02	0.08	0.76	1.37	1.39	0.71	0.44	0.08	0.35	0.49	0.18
	0.02	1.24	0.32	1.48	1.04	0.8	0.34	0.23	0.3	0.74	0.02
	0.02	0.19	1.75	1.3	0.23	1.02	0.79	0.96	0.45	0.37	0.08
Mean thickness (mm):	0.337	0.834	1.071	1.036	0.882	0.846	0.592	0.545	0.437	0.429	0.195

Appendix 6: Description of geologic units, Cottonwood Canyon trenches, Hurricane fault, Arizona.

Descriptions use the Unified Soil Classification System.

Q1 Trench:

Unit 5 DEBRIS FLOW (matrix supported)

Sandy silt: Brown (7.5YR 5/4); 5 percent cobbles, 5 percent gravel, 30 percent sand, 60 percent fines, maximum clast diameter 130 mm, angular to subrounded; low plasticity; nonstratified (massive bedding); noncemented; thin continuous carbonate coatings on larger clasts, probably inherited from previous deposit, smaller clasts have thin, discontinuous to no carbonate coatings; shear texture at faults; 20-50 cm thick, thicker on hanging wall.

Unit 4 DEBRIS FLOW (matrix supported)

Silty gravel with cobbles and sand: Light brown (7.5YR 6/4); 5 percent boulders, 15 percent cobbles, 35 percent gravel, 15 percent sand, 30 percent fines, maximum clast diameter 410 mm, subangular to subrounded; low plasticity; nonstratified (massive bedding), imbricated (particularly at base of unit); weakly cemented; thin continuous carbonate coatings; rotated clasts at faults; 40-50 cm thick.

Unit 3 FLUVIAL GRAVEL (low energy)

Silty gravel with sand: Light brown (7.5YR 6/4); 5 percent cobbles, 45 percent gravel, 35 percent sand, 15 percent fines, maximum clast diameter 170 mm, subangular to subrounded; nonplastic; stratified (5-10 cm), imbricated; weakly cemented; occasional very thin discontinuous carbonate coatings on clast bottoms; rotated clasts at faults; 30 cm thick.

Unit 2 DEBRIS FLOW (matrix supported)

Sandy silt: Light brown (7.5YR 6/4); 10 percent gravel, 30 percent sand, 65 percent fines, maximum clast diameter 90 mm, subangular to subrounded; low plasticity; nonstratified (massive bedding); weakly cemented; occasional very thin discontinuous carbonate coatings on clast bottoms; present only in footwall away from fault; 15-20 cm thick.

Unit 1 DEBRIS FLOW (matrix supported)

Silty gravel with cobbles and sand: Light brown (7.5YR 6/4); 5 percent boulders, 20 percent cobbles, 40 percent gravel, 15 percent sand, 20 percent fines, maximum clast diameter 630 mm, subangular to subrounded; low plasticity; nonstratified (massive bedding), imbricated; weakly cemented; common gypsum coatings on clast bottoms; lower portion of unit may be a more fluid phase of deposition; shear texture and rotated clasts at faults; base of unit not exposed.

Q2 Trench:

Unit 17 MODERN SOIL A HORIZON

Silt with gravel: Dark medium brown; 20 percent gravel, 5 percent sand, 75 percent fines, maximum clast diameter 800 mm, subangular to subrounded; thin, weakly developed soil A horizon, similar to unit 16 but darker in color and stratified (1 cm); weakly cemented; ~10-20 cm thick.

Unit 16 DEBRIS FLOW (matrix supported)

Gravelly silt: Light medium brown; 30 percent gravel, 5 percent sand, 65 percent fines, maximum clast diameter 60 mm, subangular to subrounded; nonstratified; weakly cemented; clasts dominantly limestone; 5-35 cm thick.

Unit 15 DEBRIS FLOW (matrix supported)

Gravelly silt with sand: Medium brown; 25 percent gravel, 20 percent sand, 55 percent fines, maximum clast diameter 65 mm, subangular to subrounded; nonstratified; weakly cemented; depositional flow may have been oblique to trench wall; 5-55 cm thick.

Unit 14 DEBRIS FLOW (matrix supported)

Sandy silt with gravel: Medium brown; 5 percent cobbles, 20 percent gravel, 25 percent sand, 50 percent fines, maximum clast diameter 180 mm, subangular to subrounded; nonstratified; weakly cemented; animal burrows present; variable thickness.

Unit 13 SLOPE COLLUVIUM

Sandy silt with gravel: Medium orange brown; 5 percent boulders, 5 percent cobbles, 20 percent gravel, 20 percent sand, 50 percent fines, maximum clast diameter 300 mm, subangular; nonstratified, alignment of elongate clasts parallel to slope; moderately cemented; arcuate fractures present; animal burrows present; variable thickness.

Unit 12c SLOPE COLLUVIUM

Gravelly silt with cobbles: Light pink tan; 20 percent cobbles, 20 percent gravel, 5 percent sand, 55 percent fines, maximum clast diameter 130 mm, subangular; nonstratified; weakly cemented; thin continuous carbonate coatings on clast bottom; clasts dominantly limestone; variable thickness.

Unit 12b FISSURE FILL

Sandy silt with gravel: Medium yellow brown; 20 percent gravel, 25 percent sand, 55 percent fines, maximum clast diameter 40 mm, subangular to subrounded; nonstratified; weakly cemented; separated from unit 12a by a block of unit 11; 20 cm thick.

Unit 12a FISSURE FILL

Silty sand with cobbles and gravel: Medium yellow brown; 15 percent cobbles, 20 percent gravel, 20 percent sand, 45 percent fines, maximum clast diameter 180 mm, subangular to subrounded; crudely stratified, alignment of elongate clasts suggests infilling from both fissure walls; weakly cemented; rare thin carbonate coatings on clasts; clasts dominantly limestone, possibly eroded unit 11; animal burrows present; bulk is 100 cm thick.

Unit 11 SLOPE COLLUVIUM

Gravelly elastic silt: Medium yellow brown; 5 percent boulders, 10 percent cobbles, 25 percent gravel, 10 percent sand, 50 percent fines, maximum clast diameter 400 mm, subangular; nonstratified, alignment of elongate clasts parallel to slope; moderately cemented; rare thin carbonate coatings on clasts; clasts dominantly limestone; shear fabric at minor fault; variable thickness.

Unit 10 DEBRIS FLOW (matrix supported)

Cobbley silty gravel: Light pink tan; 35 percent cobbles, 20 percent gravel, 5 percent sand, 40 percent fines, maximum clast diameter 200 mm, subangular; nonstratified; weakly cemented; thin to thick continuous carbonate coatings on clasts; clasts dominantly limestone; depositional flow oblique to trench wall; 30-40 cm thick.

Unit 9f FLUVIAL DEPOSIT (low to moderate energy)

Silty gravel: Light pink tan; 5 percent boulders, 10 percent cobbles, 60 percent gravel, 5 percent sand, 20 percent fines, maximum clast diameter 240 mm, subangular to subrounded; stratified; weakly cemented; thin to thick continuous carbonate coatings on clasts; depositional flow oblique to trench wall; 10-30 cm thick.

Unit 9e FLUVIAL DEPOSIT (moderate energy)

Cobbley silty gravel: Light pink tan; 30 percent cobbles, 45 percent gravel, 5 percent sand, 20 percent fines, maximum clast diameter 170 mm, subangular to subrounded; stratified; weakly cemented; thin to thick continuous carbonate coatings on clasts; depositional flow oblique to trench wall; 10-45 cm thick.

Unit 9d FLUVIAL DEPOSIT (low to moderate energy)

Silty gravel: Light pink tan; 5 percent cobbles, 60 percent gravel, 10 percent sand, 20 percent fines, maximum clast diameter 200 mm, subangular to subrounded; stratified; weakly cemented; thin continuous carbonate coatings on clasts; depositional flow oblique to trench wall; ~40 cm thick.

Unit 9c FLUVIAL DEPOSIT (very low energy)

Silty sand with gravel: Light pink tan; 5 percent cobbles, 25 percent gravel, 35 percent sand, 35 percent fines, maximum clast diameter 80 mm, subrounded; stratified; weakly cemented; depositional flow oblique to trench wall; 10-20 cm thick.

Unit 9b FLUVIAL DEPOSIT (low to moderate energy)

Silty gravel with cobbles: Light pink tan; 20 percent cobbles, 60 percent gravel, 5 percent sand, 15 percent fines, maximum clast diameter 180 mm, subangular to subrounded; stratified; weakly cemented; depositional flow oblique to trench wall; 20-60 cm thick.

Unit 9a FLUVIAL DEPOSIT (low to moderate energy)

Silty gravel: Light pink tan; 5 percent boulders, 5 percent cobbles, 60 percent gravel, 10 percent sand, 20 percent fines, maximum clast diameter 250 mm, subangular to subrounded; stratified; weakly cemented; thin discontinuous carbonate coatings on clasts; depositional flow oblique to trench wall; 10-50 cm thick.

Unit 8b SLOPE COLLUVIUM

Gravelly silt: Medium yellow tan; 20 percent gravel, 10 percent sand, 70 percent fines, maximum clast diameter 80 mm, subangular; nonstratified; moderately cemented; thin continuous carbonate coatings on clasts; clasts dominantly limestone; ~40 cm thick.

Unit 8a SLOPE COLLUVIUM

Silt with sand: Light yellow tan; 10 percent gravel, 15 percent sand, 75 percent fines, maximum clast diameter 20 mm, subangular to subrounded; nonstratified; moderately cemented; occasional very thin carbonate coatings on clasts; clasts are limestone and weathered yellow sandstone; ~30 cm thick.

Unit 7 SLOPE COLLUVIUM

Gravelly silt: Light yellow tan; 20 percent gravel, 10 percent sand, 70 percent fines, maximum clast diameter 40 mm, angular to subangular; nonstratified; moderately cemented; rare thin carbonate coatings on clasts; clasts are limestone and weathered yellow sandstone; animal burrows present; 5-30 cm thick.

Unit 6 SLOPE COLLUVIUM

Gravelly elastic silt: Light yellow tan; 5 percent cobbles, 30 percent gravel, 10 percent sand, 55 percent fines, maximum clast diameter 150 mm, subangular; nonstratified; moderately cemented; occasional thin carbonate coatings on clasts; clasts are limestone and weathered yellow sandstone; thickness unknown.

Unit 5 SLOPE COLLUVIUM

Gravelly silt with sand: Light yellow tan; 20 percent gravel, 15 percent sand, 65 percent fines, maximum clast diameter 30 mm, subangular; nonstratified; moderately cemented; rare very thin carbonate coatings on clasts; clasts are limestone and weathered yellow sandstone; animal burrows present; 20-40 cm thick.

Unit 4b DEBRIS FLOW (matrix supported)

Bouldery silty sand with cobbles: Medium orange brown; 30 percent boulders, 20 percent cobbles, 5 percent gravel, 5 percent sand, 40 percent fines, maximum clast diameter 800 mm, subangular;

nonstratified; weakly cemented; thin to thick continuous carbonate coatings on clasts; clasts are dominantly limestone; 30-100 cm thick.

Unit 4a DEBRIS FLOW (matrix supported)

Silty gravel: Light orange tan; 5 percent cobbles, 70 percent gravel, 5 percent sand, 20 percent fines, maximum clast diameter 150 mm, subangular; nonstratified; weakly cemented; thin continuous carbonate coatings on clasts; clasts are dominantly limestone; 12-20 cm thick.

Unit 3b FLUVIAL DEPOSIT (low energy)

Poorly graded gravel with silt: Medium pink brown; 5 percent boulders, 80 percent gravel, 5 percent sand, 10 percent fines, maximum clast diameter 400 mm, subangular to subrounded; nonstratified, elongate clasts oriented horizontal; weakly cemented; thin discontinuous carbonate coatings on clasts; clasts are dominantly limestone; 30-50 cm thick.

Unit 3a FLUVIAL DEPOSIT (moderate energy)

Silty gravel: Light pink tan; 70 percent gravel, 5 percent sand, 30 percent fines, maximum clast diameter 70 mm, subangular; nonstratified; moderately cemented; thin discontinuous carbonate coatings on clasts; clasts are dominantly limestone; 10-60 cm thick.

Unit 2 BEDROCK DERIVED COLLUVIUM

Silty gravel with sand: Brownish red; 40 percent gravel, 20 percent sand, 40 percent fines, maximum clast diameter 40 mm, subangular; nonstratified; moderately cemented; rare very thin carbonate coatings on clasts; clasts are limestone and sandstone; 20-40 cm thick.

Unit 1b SHEARED BEDROCK

Highly sheared shale and sandstone of the Hermit Shale: light tan yellow to dark brown red; alluvium is 10 percent gravel, 10 percent sand, 80 percent fines, maximum clast diameter 30 mm, subangular; nonstratified; moderately cemented; common block size of bedrock 5x10 cm, clasts are disintegrating yellow sandstone and limestone; bedrock thickness unknown, alluvium 20-50 cm thick.

Unit 1a FRACTURED BEDROCK

Fractured and sheared sandstone of the Hermit Shale or Esplanade Sandstone: tan to light yellow brown; common block size 15x20 cm, thickness unknown.

PUBLICATIONS

We submitted abstracts and gave presentations at the Seismological Society of America 1998 Annual Meeting and the 1998 Rocky Mountain Section of the Geological Society of America. We have submitted an abstract and will give a presentation at the American Geophysical Union Meeting in December, 1998. The abstracts are included below.

Seismological Society of America 1998

Lund, W.R., Stenner, H.D., and Pearthree, P.A., 1998, Preliminary results, paleoseismicity and seismic hazard investigation of the Hurricane fault, southwestern Utah and northwestern Arizona: Seismological Research Letters, v. 69, n. 2, p. 140.

The Utah Geological Survey and the Arizona Geological Survey are conducting a cooperative research project to evaluate the potential for large, damaging earthquakes on the Hurricane fault, an active normal-slip fault that extends for 250 km from Cedar City, Utah to south of the Grand Canyon in Arizona. Goals of the study include: 1) estimating fault slip rates over a variety of geologic time periods; 2) assessing how much of the fault has ruptured in individual large prehistoric earthquakes; and 3) estimating the size and timing of those earthquakes. Our study is focused on areas along the fault where Quaternary basalt flows or unconsolidated alluvium are displaced. We have submitted samples from several faulted basalt flows in southern Utah and from near the Grand Canyon in Arizona for Ar/Ar dating, which should provide fault slip-rate estimates for the mid- and late Quaternary and possibly for all of Quaternary time. Investigation of sites in Utah and Arizona with faulted alluvium provides evidence for recurrent late Quaternary movement and probable Holocene faulting. At the northern end of the fault near Cedar City, a late Quaternary alluvial surface (possible Bull Lake age, 80-120 kyr) at Shurtz Creek is displaced about 12 m and a probable early to mid-Holocene alluvial fan at Murie Creek is displaced 3 m. At Cottonwood Canyon in Arizona, late Quaternary alluvial surfaces are displaced about 5 and 20 m, respectively. A trench across a scarp formed on probable early to mid-Holocene alluvium revealed about 60 cm of displacement. At Whitmore Canyon near the Colorado River, late Quaternary alluvial surfaces record recurrent fault movement; older surfaces are displaced 5 to 7 m, and younger surfaces are displace about 1.5 to 3 m. With further work, we hope to better define the length of the young ruptures, integrate this information with long-term slip-rate data, evaluate rupture segmentation, and paleoearthquake magnitudes on the fault.

Rocky Mountain Section, Geological Society of America 1998

Stenner, H. D., Lund, W. R., Pearthree, P. A., and Everitt, B. L., 1998, Quaternary history and rupture characteristics of the Hurricane fault, southwestern Utah and northwestern Arizona: Geological Society of America Abstracts with Programs, v. 30, n. 6., p. 37-38.

We are investigating the Quaternary behavior of the Hurricane fault in southwestern Utah and northwestern Arizona to better characterize the seismic hazard associated with this fault. This major, 250-km-long normal fault extends from Cedar City, Utah to Peach Springs, Arizona, in the transition zone between the Colorado Plateau and the Basin and Range. We are collecting data along several sections of the fault to evaluate: 1) fault slip rates averaged over various intervals of the Quaternary, 2) the age of the most recent faulting, 3) the amount of slip during prehistoric faulting events, and 4) rupture segmentation of the fault.

We are focusing our study on areas along the Hurricane fault where Quaternary basalt flows or unconsolidated Quaternary alluvium are displaced. Samples from several faulted basalt flows in southern Utah and near the Grand Canyon in Arizona have been submitted for Ar/Ar dating and should yield fault slip-rate estimates for the late Quaternary and possibly most of the Quaternary. Investigations of localities in Utah and Arizona with faulted alluvium provide evidence for recurrent late Quaternary movements and probable Holocene faulting. Along the northern part of the fault near Cedar City, late Quaternary alluvial surfaces are displaced 10 to 12 m, and a probable early to mid-Holocene fan is displaced about 2 m. At the mouth of Cottonwood Canyon, 6 km south of the Utah border, late Quaternary alluvial surfaces are displaced by >5 m and about 20 m; based on trench interpretation, probable early to mid-Holocene deposits are displaced about 60 cm. In Whitmore Canyon near the Colorado River, late Quaternary alluvial surfaces record recurrent fault movement; older surfaces are displaced 5 to 7 m and younger surfaces are displaced about 1.5 to 3 m. The youngest surfaces are probably early Holocene to latest Pleistocene in age. With further research, we hope to better define the length of the young ruptures, integrate this information with longer term slip-rate data, and evaluate rupture segmentation and paleoearthquake magnitudes on the fault.

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Late Quaternary History and Rupture Characteristics of the Hurricane Fault, Southwestern Utah and Northwestern Arizona

H D Stenner (Arizona State University, Department of Geology, Tempe, AZ 85283; 602-965-5081; e-mail: heidi.stenner@asu.edu); W R Lund (Utah Geological Survey, SUU-Box 9053, Cedar City, UT 84720); P A Pearthree (Arizona Geological Survey, 416 W Congress, Tucson, AZ 85701); B L Everitt (Utah Dept of Water Resources, 1636 W N Temple, Suite 310, Salt Lake City, Utah 84116)

We have completed an initial investigation of the late Quaternary behavior of the Hurricane fault in southwestern Utah and northwestern Arizona to better characterize the seismic hazard associated with the fault. This major, 250-km-long normal fault extends from Cedar City, Utah to Peach Springs, Arizona, in the transition zone between the Colorado Plateau and the Basin and Range. Data evaluated from several sections of the fault give evidence of: 1) the age of the most recent faulting, 2) the amount of slip during the most recent event (MRE), 3) fault slip rates averaged over various intervals of the Quaternary, and 4) possible rupture segmentation of the fault.

Our study focused on areas along the Hurricane fault where unconsolidated Quaternary alluvium or Quaternary basalt flows are displaced. Along the northern part of the fault near Cedar City, recurrent movement is indicated by late Quaternary alluvial surfaces displaced 10 to 12 m, and a probable early to mid-Holocene fan is displaced about 2 m. At the mouth of Cottonwood Canyon, 6 km south of the Utah border, late Quaternary alluvial surfaces are displaced by >5 m and about 20 m. Based on trench interpretation, probable early to mid-Holocene deposits are displaced about 60 cm. The MRE recorded at Cottonwood Canyon probably ruptured a section of the fault 10-30 km in length. In Whitmore Canyon north of the Colorado River, late Quaternary basalt flows and alluvial surfaces record recurrent fault movement. Basalt flows are displaced 10-20 m, probable early Holocene-latest Pleistocene surfaces are displaced 2-3.5 m, and the length of the MRE was at least 15 km.