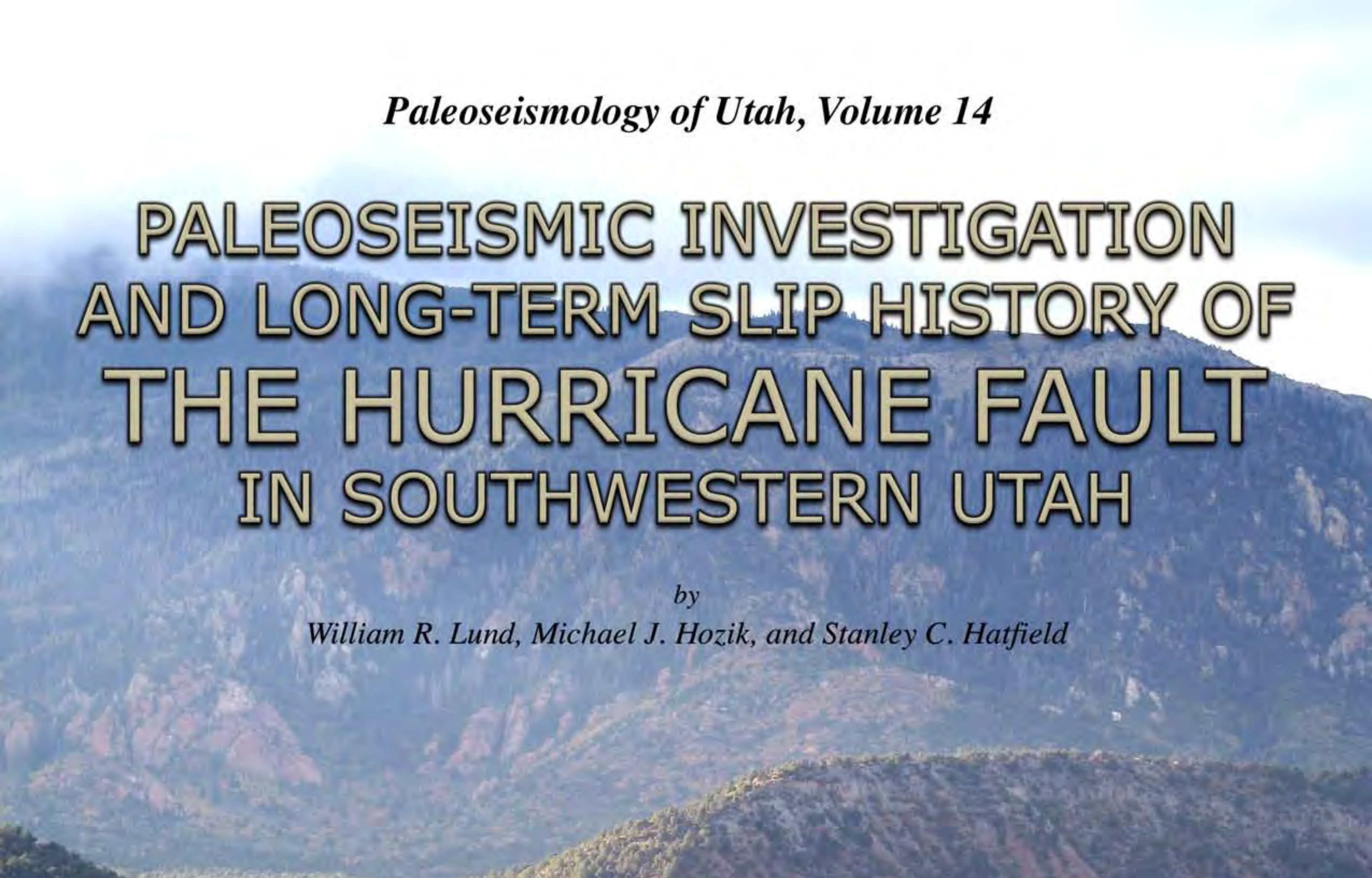

Paleoseismology of Utah, Volume 14

PALEOSEISMIC INVESTIGATION AND LONG-TERM SLIP HISTORY OF THE HURRICANE FAULT IN SOUTHWESTERN UTAH

by

William R. Lund, Michael J. Hozik, and Stanley C. Hatfield

SPECIAL STUDY 119

UTAH GEOLOGICAL SURVEY

a division of

Utah Department of Natural Resources

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by

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Cover Photo: Scarp formed on the Hurricane fault at Shurtz Creek about 8 km south of Cedar City.

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FOREWORD

This Utah Geological Survey Special Study, *Paleoseismic Investigation and Long-Term Slip History of the Hurricane Fault in Southwestern Utah*, is the fourteenth report in the Paleoseismology of Utah series. This series makes the results of paleoseismic investigations in Utah available to geoscientists, engineers, planners, public officials, and the general public. These studies provide critical information regarding paleoearthquake parameters such as earthquake timing, recurrence, displacement, slip rate, and fault geometry, which can be used to characterize potential seismic sources and evaluate the long-term seismic hazard presented by Utah's Quaternary faults.

This report presents the results of a study of the Hurricane fault in Utah, and is part of a more extensive National Earthquake Hazards Reduction Program-funded cooperative study by the Utah Geological Survey (UGS) and Arizona Geological Survey (AZGS) of the Hurricane fault in Utah and Arizona. The Hurricane fault is one of the longest and most active of several large, late Cenozoic, west-dipping normal faults within the structural and seismic transition between the Colorado Plateau and Basin and Range physiographic provinces. Assessing the seismic hazard of the Hurricane fault is important because southwestern Utah is experiencing a now decades-long construction and population boom. Results of the AZGS study of the Hurricane fault in Arizona are reported elsewhere.

This study shows that (1) the rate of slip on the Hurricane fault has slowed in more recent geologic time, (2) a previously identified structural segment boundary near Anderson Junction is likely a seismogenic segment boundary as well, (3) a third, previously unrecognized seismogenic segment likely exists at the north end of the fault, and (4) two of the three seismogenic segments recognized in Utah have experienced Holocene surface faulting. Based on these study results, the Hurricane fault in Utah is considered active and capable of generating earthquakes in excess of **M** 7.0.

William R. Lund, Editor
Paleoseismology of Utah Series

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PALEOSEISMIC INVESTIGATION AND LONG-TERM SLIP HISTORY OF THE HURRICANE FAULT IN SOUTHWESTERN UTAH

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ABSTRACT

The Utah Geological Survey (UGS) and Arizona Geological Survey (AZGS) cooperated on a study of the Hurricane fault in southwestern Utah and northwestern Arizona. The Hurricane fault is one of the longest and most active of several large, late Cenozoic, west-dipping normal faults within the structural and seismic transition between the Colorado Plateau and Basin and Range physiographic provinces. Assessing the seismic hazard of the Hurricane fault is important because southwestern Utah and nearby areas of northwestern Arizona and southeastern Nevada are experiencing a now decades-long construction and population boom. This report documents the UGS investigation of the paleoseismicity and long-term slip history of the northern part of the fault (proposed Ash Creek and Anderson Junction segments) in Utah. Results of the AZGS paleoseismic study of the proposed Anderson Junction, Shivwits, and Whitmore Canyon segments in Arizona are reported elsewhere.

Approximately 80 km of the Hurricane fault trend north-south through southwestern Utah. Displaced alluvial and colluvial deposits (meters to tens of meters) and Quaternary basalt flows (hundreds of meters) indicate a moderate rate of Quaternary fault activity. We made a reconnaissance along the Hurricane fault from the Utah-Arizona border to Cedar City, Utah, to identify potential sites for detailed paleoseismic investigation; measured scarp profiles and excavated soil test pits at several sites; attempted to excavate a trench across a fault scarp formed on unconsolidated deposits to characterize the size, timing, and rate of late Quaternary surface faulting; determined minimum constraints on the timing of the most recent surface faulting by investigating the age of faulted and unfaulted alluvial deposits along the fault; and determined the age of displaced basalt flows to calculate long-term slip rates at several locations along the fault.

Our reconnaissance identified five previously unrecognized fault scarps formed on unconsolidated deposits in addition to the large scarp already known at Shurtz Creek. At one site a probable single-event scarp cuts latest Holocene alluvial-fan deposits. The four remaining sites consist of large, multiple-event scarps formed on Pleistocene alluvial-fan and pediment deposits. The number, type, and preservation of scarps along the fault provide insight into possible seismogenic segmentation. The reconnaissance also identified a graben parallel to the Hurricane fault along Ash Creek Canyon that displaces geologic units in the hanging wall down-to-the-east, thus increasing apparent tectonic displacement across the main Hurricane fault. Displaced alluvial surfaces at Shurtz Creek, tentatively dated on the basis of soil-profile development and cosmogenic isotopes, provide a preliminary slip rate of 0.12-0.40 (0.18 preferred) mm/yr for approximately the past 30,000 to 100,000 years.

Our preferred trench site at Coyote Gulch is on private property and was unavailable for study. Trenching at Shurtz Creek, the best alternative site, encountered large boulders that prevented exposing the fault zone. The remaining sites had similar geologic or access constraints, so we refocused on dating geologically young alluvium that overlies the fault at three locations on the Ash Creek segment. Radiocarbon ages for unfaulted alluvium at the Middleton and Bauer sites were 1530-1710 cal yr B.P. (charcoal from a paleosol) and 330-525 cal yr B.P. (detrital charcoal), respectively. Faulted alluvium at Coyote Gulch yielded an age of 1055-1260 cal yr B.P. (detrital charcoal). The difference in ages of the alluvium at Coyote Gulch and Middleton sites, and the fact that the sediments at Coyote Gulch are faulted and those at Middleton are not, show that surface rupture associated with the most recent surface-faulting earthquake (MRE) at Coyote Gulch did not extend north to the Middleton site, indicating the possible presence of a seismogenic boundary between the two sites. The most likely location for a boundary is at a bend in the fault trace north of Coyote Gulch at Murie Creek. The proposed new northern fault segment is herein named the Cedar City segment and is approximately 20 km long. The redefined Ash Creek segment is about 33 km long. Based on those lengths and on limited displacement-per-event data, the Cedar City segment can produce a moment magnitude **M** 6.6 earthquake and the Ash Creek segment can produce an earthquake in excess of **M** 7.

The Hurricane fault displaces Quaternary basalt flows at several locations in Utah. Determining long-term slip rates for the fault using the displaced flows required correlating flows across the fault using trace-element geochemistry, dating flows using $^{40}Ar/^{39}Ar$ dating techniques, and evaluating near-fault deformation using a combination of paleomagnetic vector analysis and geologic mapping.

We identified four locations where displaced basalts are geochemically correlative across the Hurricane fault: two on the proposed Anderson Junction segment, one at the boundary between the proposed Anderson Junction and Ash Creek segments, and one on the proposed Ash Creek segment. A fifth site 12 km east of the fault in Cedar Canyon consists of a basalt remnant that occupies the ancestral channel of Coal Creek high on the north canyon wall. The basalt flow blocked Coal Creek and forced the stream to incise a new channel which left the basalt remnant stranded above the present stream channel. Coal Creek grades to Cedar Valley and crosses the Hurricane fault at the mouth of Cedar Canyon. Fault movement helps control stream base level and therefore stream-incision rate, which in turn provides a proxy for a minimum fault slip rate.

The new long-term slip rates range from 0.21 to 0.57 mm/yr and generally increase from south to north along the fault. Additionally, slip appears to increase incrementally

across the suspected Ash Creek/Anderson Junction segment boundary. Although little change in long-term slip rate is apparent across the proposed Ash Creek/Cedar City segment boundary, that does not preclude the existence of a seismogenic boundary there. A comparison of these new long-term slip rates with late Quaternary rates shows that slip has slowed on the Hurricane fault in the late Quaternary, and that the average recurrence for surface-faulting earthquakes is now several thousand to more than ten thousand years.

INTRODUCTION AND OVERVIEW

The Utah Geological Survey (UGS) and Arizona Geological Survey (AZGS) cooperated on a study of the Hurricane fault, one of the longest and most active of several large, late Cenozoic, west-dipping normal faults in southwestern Utah and northwestern Arizona (figure 1). The purpose of the study was to develop new paleoseismic information to help characterize the fault's late Quaternary behavior, test segmentation models, and provide information critical to earthquake-hazard assessment. The study was partially funded by the U.S. Geological Survey National Earthquake Hazards Reduction Program (NEHRP). Results of the Arizona investigation are presented in Pearthree and others (1998), Stenner and others (1999), Lund and others (2001), and Amoroso and others (2002, 2004). This report presents the results of the investigation in Utah.

Assessing seismic hazards in southwestern Utah is important because this region is experiencing a now decades-long population and construction boom. In terms of percent growth, the populations of Washington and Iron Counties

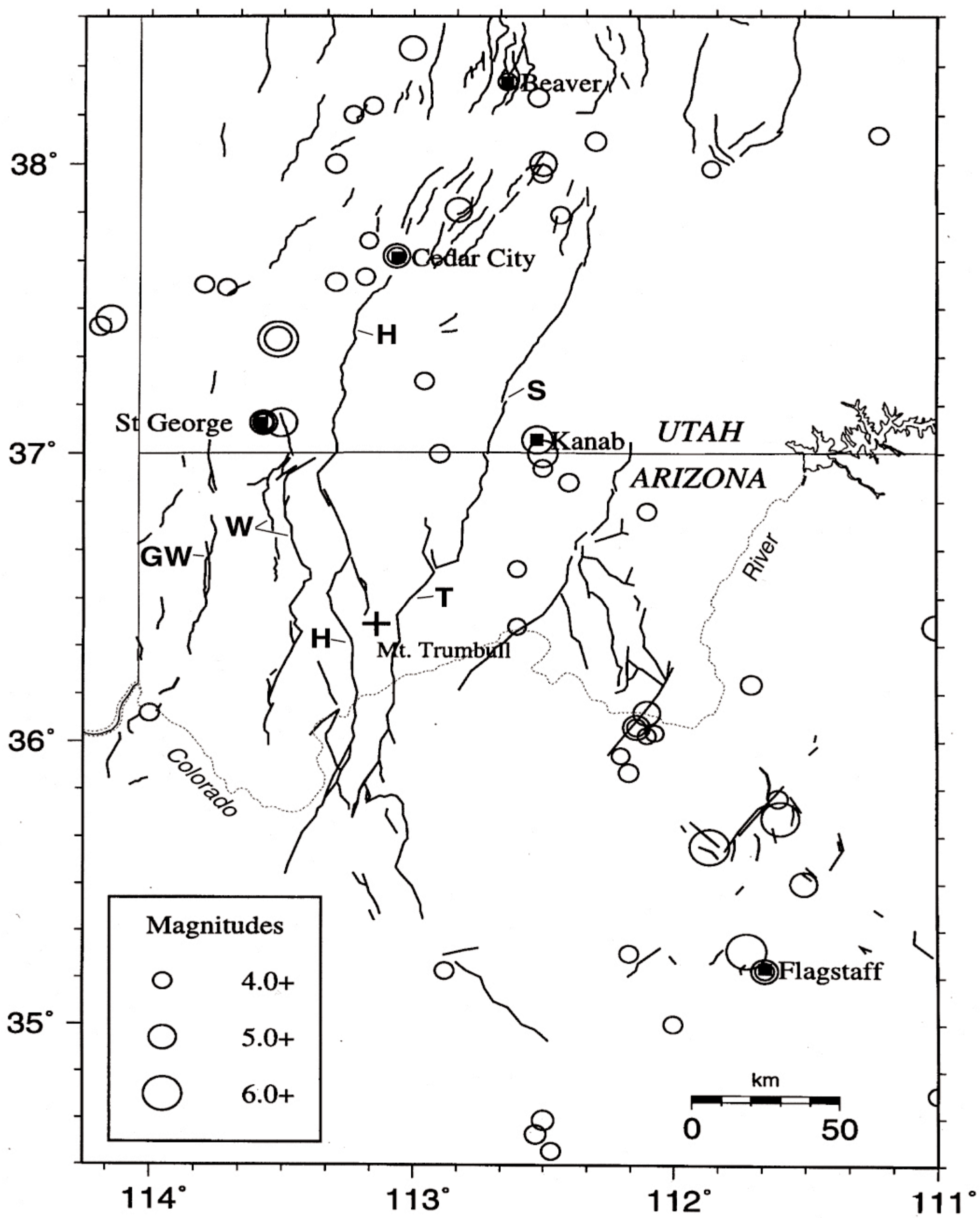


Figure 1. Quaternary faults and historical earthquakes in southwestern Utah and northwestern Arizona. H = Hurricane fault, W = Washington fault, GW = Grand Wash fault, S = Sevier fault, T = Toroweap fault (figure courtesy of the Arizona Geological Survey).

increased 86 and 64 percent, respectively, between 1990 and 2000 (Loomis, 2001). A proposed water pipeline from Lake Powell to Washington County would provide sufficient water for an estimated additional 300,000 residents. Adjacent areas of Arizona and Nevada are experiencing similar rapid growth. Zion National Park and Grand Canyon National Park are both near the Hurricane fault and each receives more than 2.5 million visitors annually.

Extending from Cedar City, Utah, to south of the Colorado River in Arizona (figure 2), the 250-km-long Hurricane fault has produced hundreds to thousands of meters of vertical displacement during late Cenozoic time (Huntington and Goldthwait, 1904, 1905; Gardner, 1941, 1952; Averitt,1964; Hamblin, 1965a, 1965b, 1984; Anderson and Mehnert, 1979; Hamblin and Best, 1980; Stewart and Taylor, 1996). In Utah, the Hurricane fault is mostly within the approximately 150-km-wide structural and seismic transition zone between the Colorado Plateau and Basin and Range Province (figure 3), where a series of north-trending normal faults displace generally subhorizontal Paleozoic and Mesozoic strata of the Colorado Plateau down-to-the-west. The spectacularly steep and linear Hurricane Cliffs represent a fault-line scarp that closely follows the trace of the Hurricane fault and records the displacement across that structure. Previous studies of the Hurricane fault documented displaced Quaternary basalt flows and alluvium (Hamblin, 1963, 1965b, 1970a, 1984; Anderson and Mehnert, 1979; Pearthree and others, 1983; Menges and Pearthree, 1983; Anderson and Christenson, 1989; Hecker, 1993; Stewart and Taylor, 1996; Pearthree and others, 1998; Amoroso and others, 2002; Black and others, 2003). Estimates of displacement across the Hurricane fault vary widely, ranging from a low of 1400-4000 feet (430-1200 m; Kurie, 1966) to a high of 12,000-13,000 feet (1800-4000 m; Dutton, 1880). Kurie (1966) attributed the wide range in estimates to the failure of many workers to recognize the significance of major fold structures that predate and parallel the trace of the Hurricane fault over much of its length in Utah. Anderson and Mehnert (1979) agreed and stated that the Hurricane fault in Utah appears to have block-normal displacement of about 2000-2800 feet (600-850 m). (Note: The metric system is used in this report except where numerical data quoted from other sources were originally published in the English system. In those instances, the metric conversion follows in parentheses).

Considering its long length, the Hurricane fault almost certainly ruptures in segments, as observed historically for long normal faults (Schwartz and Coppersmith, 1984; Schwartz and Crone, 1985; Machette and others, 1992). Previous workers (Stewart and Taylor, 1996; Stewart and others, 1997; Pearthree and others, 1998) have suggested that major convex fault bends and zones of structural complexity are likely candidates for boundaries between seismologically independent fault segments. Stewart and Taylor (1996) used fault trace complexity and geometry, shortening structures, and scarp morphology to define a geometric boundary between the proposed Ash Creek segment in Utah and the Anderson Junction segment in Utah and Arizona (figure 2). Stewart and others (1997) identify another potential boundary about 10 km south of the Utah-Arizona border, based on changing cumulative slip measurements and a large bend in the fault trace. South of the bend, the Hurricane fault defines the eastern margin of the Shivwits Plateau and is named the

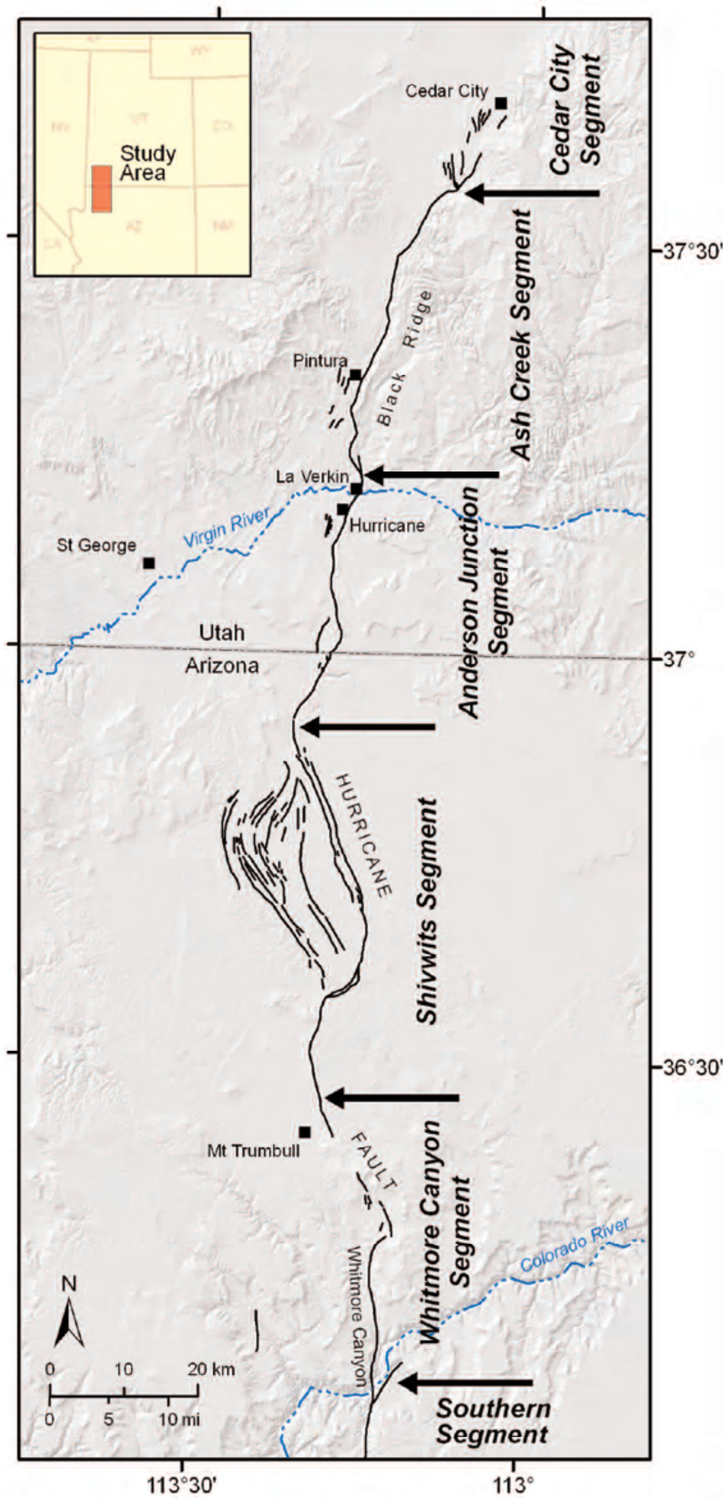


Figure 2. The Hurricane fault and proposed fault segments in Utah and Arizona. Bold arrows indicate segment boundaries (Stenner and others, 1999; Lund and others, 2001).

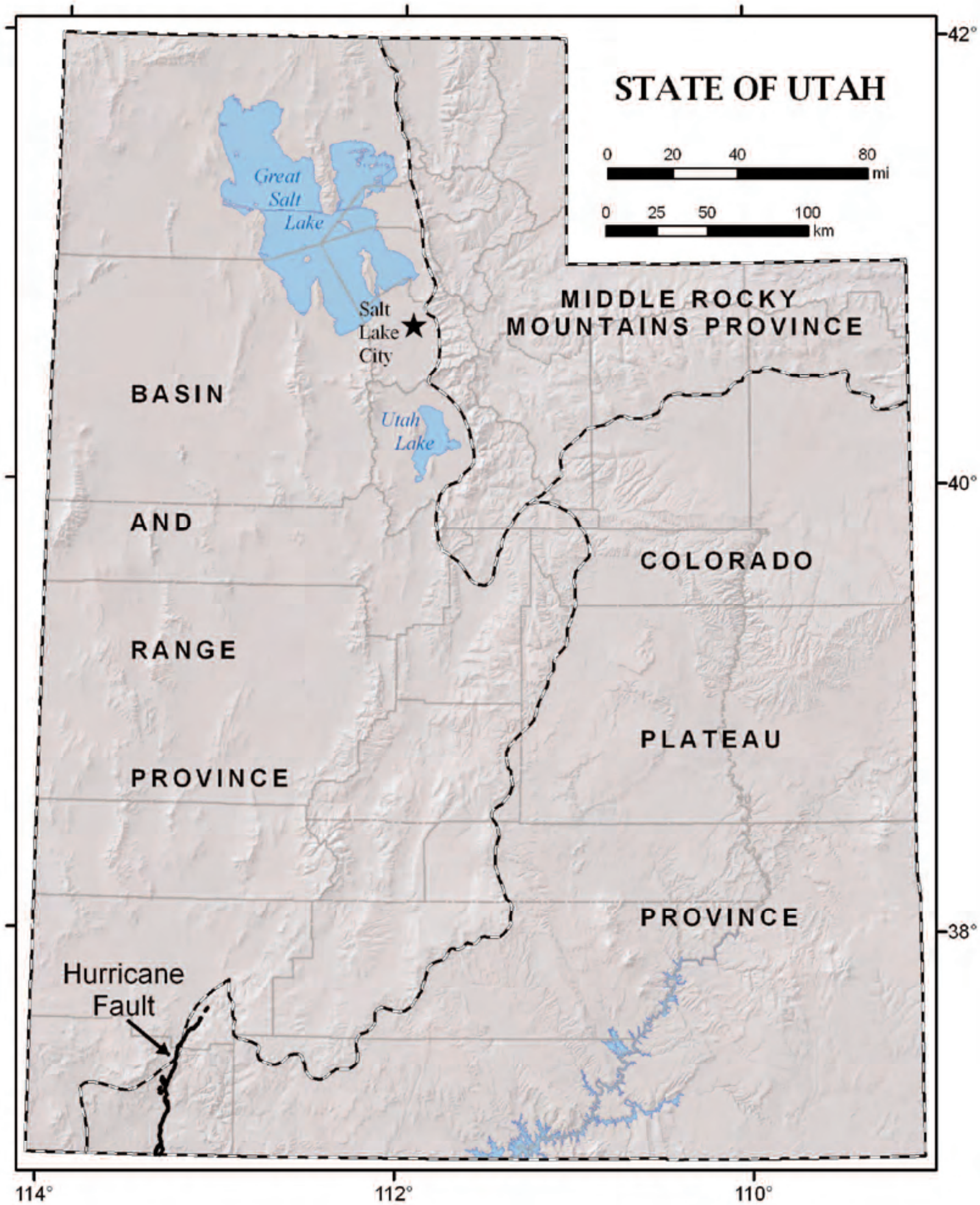


Figure 3. Relation of the Hurricane fault to physiographic provinces in Utah.

Shivwits segment (Pearthree, 1998). A major discontinuity in the fault trace near Mt. Trumbull south of the Shivwits segment defines another potential segment boundary between the Shivwits segment to the north and the Whitmore Canyon segment to the south (Menges and Pearthree, 1983; Pearthree and others, 1998). South of Mt. Trumbull, the Hurricane fault clearly displaces Quaternary basalt flows and late Quaternary alluvium in Whitmore Canyon. The lack of documented evidence of late Quaternary displacement on the fault south of the Colorado River indicates this part of the fault is another potential segment (Pearthree, 1998). For purposes of this report (see section on Field Reconnaissance below) we used similar, but generally smaller scale, changes in fault geometry to delineate shorter fault subdivisions, which we term "sections" to avoid the implication of seismogenic segmentation. However, some of these sections may be seismogenic segments as well.

Seismic hazard in southwestern Utah and northwestern Arizona is considered moderate, and probabilistic estimates of the 50-year 10-percent exceedance peak acceleration are less than 0.2 g (U.S. Geological Survey, 2002). The Colorado Plateau/Basin and Range transition is coincident with the Intermountain seismic belt (Smith and Sbar, 1974; Smith and Arabasz, 1991; figure 4), although this zone of seismicity becomes broader and more poorly defined from north to south in Utah. Surface rupture has not occurred along the Hurricane fault historically, but the area does have a pronounced record of seismicity. At least 20 earthquakes greater than M 4 have occurred in southwestern Utah over the past century (Christenson and Nava, 1992); the largest events were the approximate M 6 Pine Valley earthquake in 1902 (Williams and Trapper, 1953) and the M 5.8 St. George earthquake in 1992 (Christenson, 1995) (figure 4). The Pine Valley earthquake is pre-instrumental and poorly located,

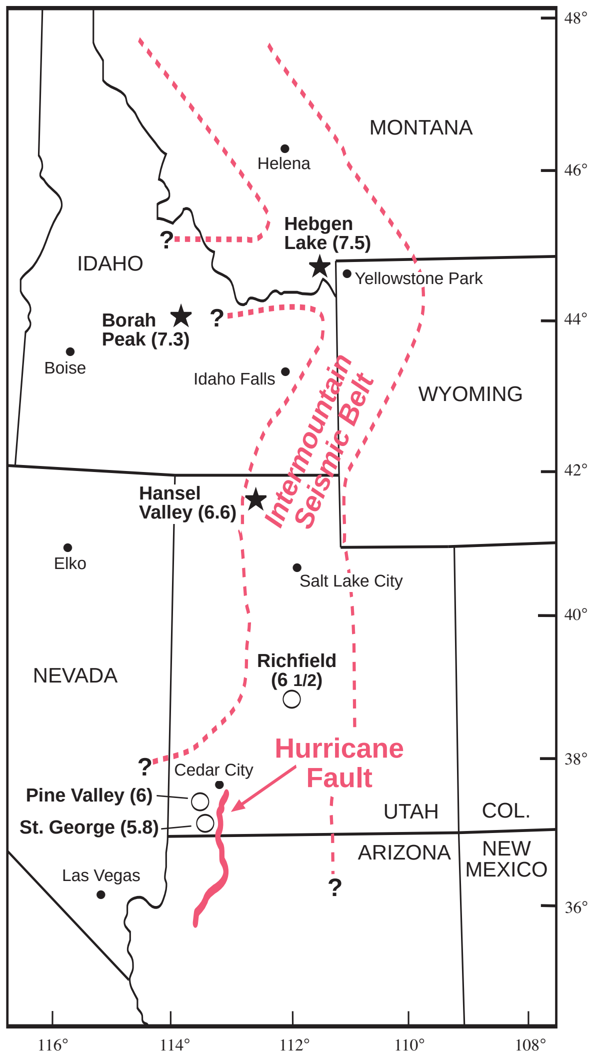


Figure 4. *The Intermountain seismic belt showing major historical earthquakes and the Hurricane fault. Earthquake magnitudes given in parentheses; stars indicate earthquakes that produced surface rupture.*

and therefore not definitively associated with a recognized fault. However, the epicenter is west of the surface trace of the Hurricane fault, so the earthquake may have occurred on that fault. Pechmann and others (1995) have tentatively assigned the St. George earthquake to the Hurricane fault. The largest historical earthquake in northwestern Arizona was the 1959 Fredonia earthquake (approximate M 5.7; DuBois and others, 1982). Since 1987 the northwest part of Arizona has been relatively seismically active (Pearthree and others, 1998), experiencing more than 40 earthquakes larger than M 2.5, including the 1993 M 5.4 Cataract Canyon earthquake between Flagstaff and the Grand Canyon. Despite the lack of a historical surface-faulting earthquake, available paleoseismic data indicate a fairly high rate of long-term Quaternary activity on the Hurricane fault (Pearthree and others, 1998). The fault displaces Quaternary basalt flows hundreds of meters at several locations, and displaced alluvial and colluvial landforms indicate that the fault has experienced tens of meters of displacement in late Quaternary time (past approximately 250,000 years) along its northern and central sections.

THE HURRICANE FAULT IN SOUTHWESTERN UTAH

The northernmost 80 km of the 250-km-long Hurricane fault trends roughly north-south through southwestern Utah (figures 1 and 2). A relatively high rate of Quaternary activity on the Utah portion of the fault is implied by the geomorphology of the high, steep Hurricane Cliffs, and by displaced alluvial and colluvial landforms (meters to tens of meters) and Quaternary basalt flows (hundreds of meters) at several locations along the fault. However, while recognized as a potential source of large earthquakes in southwestern Utah, the sparse evidence for latest Pleistocene or Holocene rupture makes assessing the seismic hazard of the Hurricane fault problematic.

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, and (4) displacement has been episodic through time. Gardner (1941, 1952) provides a general description of the fault in Utah. Averitt (1962, 1967) 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 km 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 publications on the tectonics of the Hurricane fault (Hamblin, 1965a, 1965b, 1970b, 1984; Hamblin and Best, 1980; 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 Sciences Associates (1982) mapped generalized surficial geology and photolineaments along the fault and trenched scarps and photolineaments that cross U.S. Soil Conservation Service (now National Resource Conservation Service) flood-retention structures. Based on historical seismicity and then 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° x 2° quadrangle based on existing data and reconnaissance fieldwork. The apparent absence of young fault scarps on unconsolidated deposits along the fault in Utah led them to conclude that a surface-faulting earthquake had probably not occurred during the Holocene. However, they noted that a lack of Holocene activity on the fault seemed inconsistent with the high Quaternary slip rate derived from displaced Quaternary basalts (Anderson and Mehnert, 1979; Hamblin and others, 1981). Black and others (2003) included the Hurricane fault in their 1:500,000-scale compilation of Quaternary tectonic features in Utah, and assigned a probable time of latest Pleistocene (<15 ka) to the most recent deformation. A structural analysis by Schramm (1994) of a complex part of the Hurricane fault near Anderson Junction showed that movement of 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 seismogenic (earthquake) boundary at a large geometric bend in the Hurricane fault at Anderson Junction (figure 2).

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 Trapper (1953) discussed the earthquake history of Utah including the 1902, estimated 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 discussion of seismicity and seismic hazards in southwestern Utah and northwestern Arizona in their review of the neotectonics of the Hurricane fault.

Hurlow (1998), in a report on the geology of the central Virgin River basin relative to ground-water conditions, provides a 1:100,000-scale compilation map of the region that includes the Hurricane fault as well as several geologic sections that cross the fault. Recent 1:24,000-scale geologic mapping by the Utah Geological Survey of the Divide (Hayden, 2004), Hurricane (Biek, 2003), and Pintura (Hurlow and Biek, 2003) quadrangles includes the trace of the Hurricane fault from the Utah/Arizona border northward to Pintura, a distance of about 42 km.

Lund and others (2002) summarize information on the tectonic development of the Hurricane fault and paleoseismic investigations conducted in both Utah and Arizona.

Physiography and General Geology

Beginning at the Utah-Arizona border, the Hurricane fault trends generally north and then northeast in Utah (figure 2). The change in trend is likely related to underlying crustal structure (Hamblin, 1970b; Best and Hamblin, 1970). The Hurricane fault is typically expressed as a narrow (seldom exceeding 1 km 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; Biek, 2003; Hurlow and Biek, 2003; Hayden, 2004). South of Anderson Junction, the fault cuts relatively undeformed, gently east-dipping Permian, Triassic, and Jurassic sedimentary rocks and Quaternary basalt (Biek, 2003; Hayden, 2004). At Anderson Junction, the north-trending Hurricane fault intersects the Kanarra anticline (Gregory and Williams, 1947; Hurlow and Biek, 2003), a northeast-trending Sevier-age (Armstrong, 1968) fold and associated thrust faults that deform Paleozoic and Mesozoic rocks. At that intersection, the Hurricane fault changes trend to the northeast and follows the fold and thrust belt to Cedar City (figure 2), displacing the deformed Paleozoic and Mesozoic rocks and the overlying undeformed Cenozoic rocks and Quaternary basalt flows across a narrow fault zone (Cook, 1960; Averitt, 1962, 1967; Kurie, 1966; Averitt and Threet, 1973; Hurlow, 1998; Biek, 2003; Hurlow and Biek, 2003).

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 m (Anderson, 1980). Anderson and Christenson (1989) believe the 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 km 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 three-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 to 1500 m near St. George and Anderson Junction, respectively, and expressed doubt that tectonic displacement or throw exceeds 2 km anywhere on the Hurricane fault in Utah.

A detailed structural analysis of the Hurricane fault near Anderson Junction (Stewart and Taylor, 1996) documented 450 m of stratigraphic separation on Quaternary basalt and a total stratigraphic separation of up to 2520 m 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 that movement likely began as early as the late Miocene or early Pliocene. Some workers assign a time of onset of motion on the Hurricane fault to the Miocene (Gardner, 1941; Averitt, 1964; Hamblin, 1970b), or contemporaneously with intrusion of the Pine Valley laccolith west of the fault (Cook, 1960). Others believe motion began in the late Pliocene or Pleistocene (Anderson and Mehnert, 1979; Anderson and Christenson, 1989).

Stewart and Taylor (1996) used hanging-wall and footwall shortening structures, fault geometry, increased complexity of faulting, and scarp morphology to define a geometric segment boundary near Anderson Junction (figure 5) where the fault bends upon intersecting the Kanarra anticline. They named the fault section north of the boundary the Ash Creek segment and the section south of the boundary the Anderson Junction segment. Stewart and Taylor (1996) did not identify additional geometric segment boundaries to the north. However, Stewart and others (1997) proposed a geometric segment boundary between the Anderson Junction and Shivwits segments about 10 km south of the Utah-Arizona border based on structural complexities and differences in stratigraphic separation across the proposed boundary.

Anderson and Christenson (1989) made a reconnaissance of Quaternary tectonic features in the Cedar City 1° x 2° quadrangle that included the Utah portion of the Hurricane

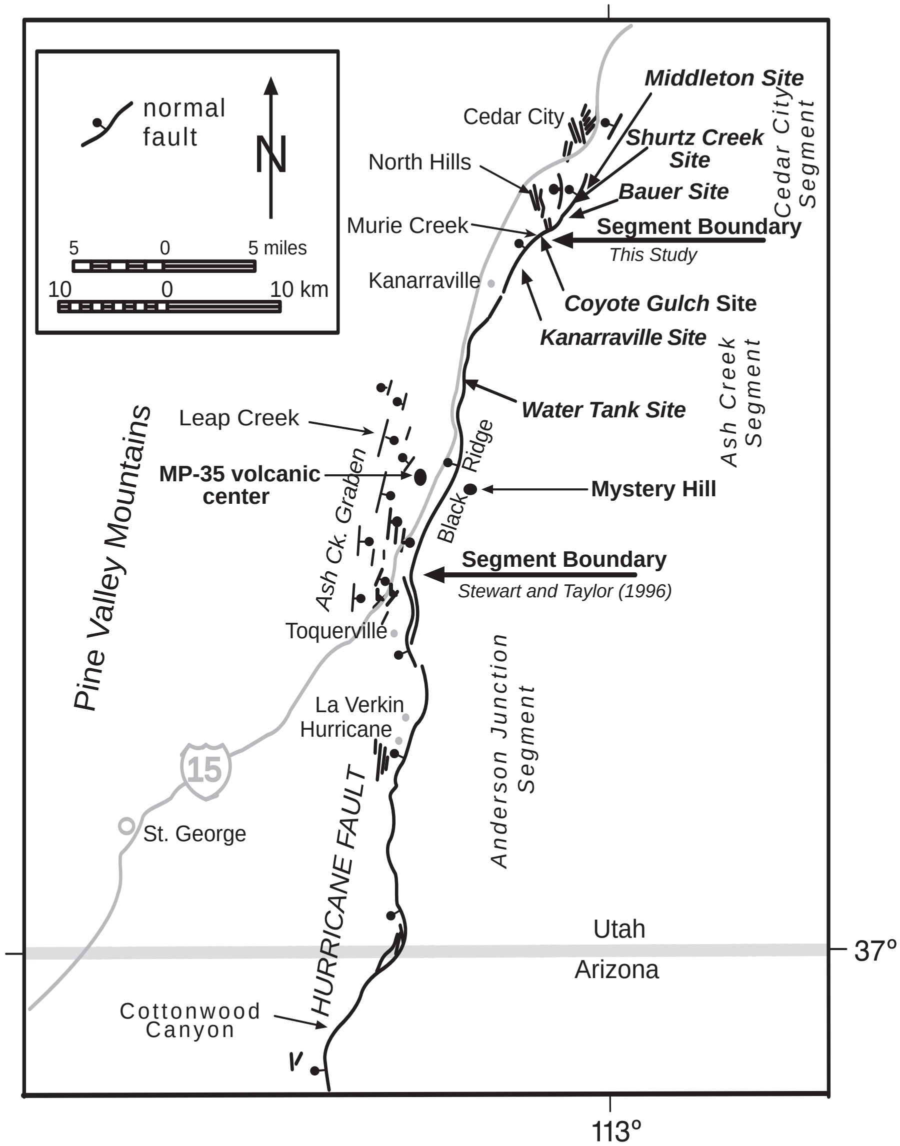


Figure 5. Hurricane fault in southwestern Utah showing sites with scarps on unconsolidated deposits. Ash Creek graben and MP-35 and Mystery Hill cinder cones are also shown.

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 km south of Cedar City (figure 5). 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: (1) several locations along the fault between Cedar City and Ash Creek Reservoir where short, steep, sections of the Hurricane Cliffs are formed on claystone and evaporite-bearing siltstone of the relatively non-resistant Triassic 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 nickpoints where small and intermediate ephemeral drainages formed in resistant Paleozoic rocks cross the Hurricane Cliffs. Anderson and Christenson (1989) interpret these three kinds of features along with the scarp at Shurtz Creek as evidence of a substantial rate of late Pleistocene surface displacement on the Utah part of the Hurricane fault, but were unable to document Holocene displacement. While not precluding the possibility of Holocene displacement, they speculated that the time since the most recent surface-faulting earthquake on the Utah part of the fault is probably greater than 10,000 years.

PALEOSEISMIC INVESTIGATIONS

The goal of this study was to develop paleoseismic information (earthquake timing, per-event and cumulative net vertical displacement, earthquake recurrence, and vertical slip rates) necessary to characterize the seismic hazard presented by the Hurricane fault to southwestern Utah. The investigation included (1) a field reconnaissance along the Utah part of the fault to identify potential sites for detailed paleoseismic study, (2) scarp profiling to determine cumulative net vertical displacement across scarps, (3) trenching to develop information on earthquake timing and recurrence, displacement, and late Quaternary vertical slip rates, and (4) correlation and dating of basalt flows displaced by the fault to determine vertical slip rates since the early to middle Quaternary.

Field Reconnaissance

To document possible geologically recent faulting on the Utah part 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 section." Each fault section represents a part of the fault 10 to 22.5 km long that extends between significant changes in fault strike (bends) and has generally similar geomorphic characteristics along its length (figure 6). The term "fault section" is used here in a purely descriptive manner for ease of discussion. Lengths of the fault sections reported below are measured along strike. Details of the reconnaissance are presented in appendix A.

Fault Section 1: Utah-Arizona Border to Large Unnamed Drainage

From the Utah-Arizona border, the Hurricane fault strikes N. 30° E. for 1.5 km to a large, unnamed, ephemeral drainage incised in the Hurricane Cliffs (section 26, T. 43 S., R. 13 W.). At the drainage, the fault changes strike abruptly to N. 5° W., creating a sharp bend in the fault trace (figure 6). Southward into Arizona, the fault continues on a trend of about N. 30° E. for approximately 10 km to another prominent bend in the fault just south of Cottonwood Canyon. The 10 km of the fault in Arizona and the contiguous 1.5 km in Utah form a single fault section as defined above. Along this fault section, 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 border and the unnamed ephemeral drainage, short, colluvium-mantled bedrock scarps are present at isolated locations typically several tens of meters west of the base of the Hurricane Cliffs (FS1-1, FS1-2; appendix A). The colluvial apron between the cliffs and the fault scarps is thin and mantles a bedrock surface, indicating retreat of the Hurricane Cliffs from the main fault trace. The scarps are as much as 6 m high, indicating recurrent surface faulting 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 trace of the Hurricane fault and are not displaced (FS1-3; appendix A), indicating an absence of middle to late Holocene faulting.

Fault Section 2: Large Unnamed Drainage to Frog Hollow

The Hurricane fault trends generally north-south for 12.5 km from the large, unnamed drainage to Frog Hollow (section 15, T. 42 S., R. 13 W.) where the fault bends to the northeast (figure 6). Along this fault section, the fault forms a narrow zone marked by a high, steep cliff with resistant, buff and yellow-tan Paleozoic limestone 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 cliffs.

Along this section of the fault, evidence of late Quaternary faulting is poorly preserved if present at all. A possible scarp about 5 m high (FS2-2; appendix A) is present at the mouth of a small wash at the base of the Hurricane Cliffs about 5 km north of the southern end of this fault section. The scarp is formed on very coarse, bouldery alluvium, and the ephemeral stream from the small wash has incised

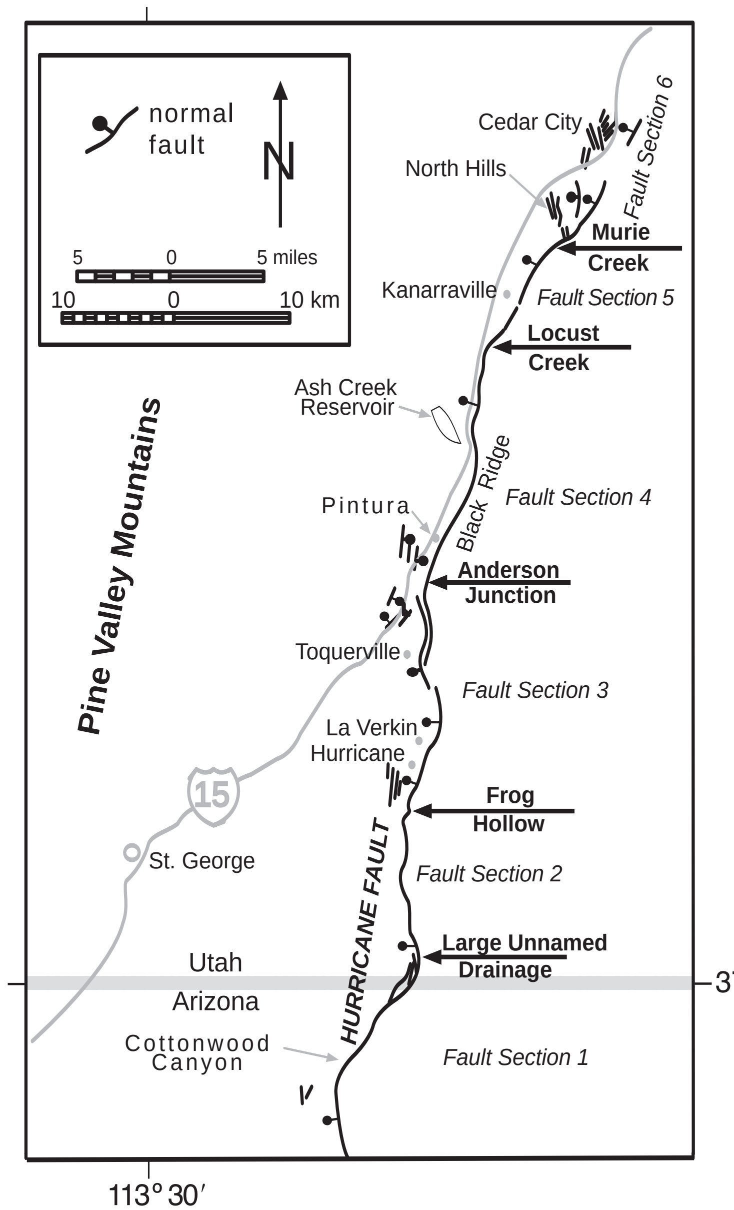


Figure 6. Hurricane fault, section boundaries as defined for field reconnaissance.

through it. Examination of the stream cut 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 wash about 7.5 km south of the Hurricane City airport exposes a steeply dipping fault contact between bedrock and older colluvium (FS2-3; appendix A). About 2 m of unfaulted younger colluvium overlies the faulted deposits. The near absence of scarps on this section 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 most recent surface-faulting earthquake, or that the active fault trace is in bedrock in the cliffs above the colluvium and alluvial fans.

Fault Section 3: Frog Hollow to Anderson Junction

At Frog Hollow, the Hurricane fault begins a broad, 18-km-long, Z-bend that extends to near Anderson Junction (SW¼ section 23, T. 40 S., R. 13 W.). The strike of the fault changes through the bend and varies from about N. 35° E. to N. 10° W. The communities of Hurricane, La Verkin, and Toquerville are on this section of the fault (figure 6), making it the most urbanized part of the Hurricane fault in either Utah or Arizona. In several places, urban development now extends into the fault zone.

We could not positively identify any scarps along this fault section; 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 A) slickenlines rake 86° 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 A; 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 A). There, older colluvium is in fault contact with bedrock, but the faulted units are overlain by younger, unfaulted deposits with no scarp at the surface.

From near La Verkin to Anderson Junction, the Hurricane fault forms a wide zone (up to 1.5 km) with several subparallel, west- and smaller east-dipping faults that displace the Triassic Moenkopi Formation incrementally down-to-the-west (Stewart and Taylor, 1996; Biek, 2003). Unconsolidated deposits are generally absent along this part of the fault, but fault exposures in bedrock are common.

Fault Section 4: Anderson Junction to Locust Creek

At Anderson Junction, the Hurricane fault bends to the east and trends generally N. 15° E. for 22.5 km to Locust Creek (section 16, T. 38 S., R. 12 W.), about 6 km south of Kanarraville (figure 6). This section of the fault follows the west limb of the Kanarra anticline. 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 A) 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 location of the scarps west of the base of the Hurricane Cliffs indicates cliff retreat prior to the onset of most recent surface faulting. Stewart and Taylor (1996) described these scarps as being on "unconsolidated Quaternary gravel or alluvium," and cite them as evidence for geologically recent 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 (approximately 30°) and height (nearly 40 m in some places) of the scarps. Exposures in stream cuts incised through the scarps show that the fault is overlain by unfaulted colluvium (FS4-4, appendix A), indicating an absence of geologically recent (Holocene) surface faulting.

Northward along the base of Black Ridge, 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 A). 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 A). 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; appendix A). The fault dips 66° and the alluvium is tilted toward the west. A second exposure in the same drainage shows the fault dipping 52° NW and slickenlines raking 88° to the north (FS4-7; appendix A).

Anderson and Christenson (1989) recognized and mapped scarps antithetic to the Hurricane fault formed on Quaternary–Tertiary alluvium (Hurlow, 1998) 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 are greater than 60 m high, and commonly greater than 10 m high, (3) formed on basalt as well as alluvium, and (4) in many places are accompanied by smaller, west-facing scarps sympathetic to the Hurricane fault, resulting in the creation of smaller subsidiary grabens. 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 highway and along the west side of Ash Creek Canyon at the base of the Pine Valley Mountains for a minimum distance of 17 km (figure 5). The graben encompasses the whole of Ash Creek Canyon between Black Ridge and the Pine Valley Mountains, and is herein 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 5) displaces a Quaternary basalt flow several meters down-to-the-east.

From Ash Creek Reservoir to Locust Creek, the fault is 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 section of the fault and have pronounced nickpoints at or near the fault trace. Scarps are mostly absent except for a pair of short, subparallel scarps about 1 km south of the Kolob entrance to Zion National Park (FS4-16; appendix A). The eastern scarp is almost 13 m high (appendix B) and appears similar to the large, colluvium-mantled bedrock scarps observed elsewhere on this section of the fault. The smaller, western scarp is 4.5 m high (appendix B) and is formed on alluvium. It is eroded in several places and buried or partially buried in others. This is the first scarp on the main Hurricane fault recognized north of the Arizona-Utah border that is unequivocally formed exclusively on unconsolidated deposits. The two scarps are 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 small ephemeral drainage that incises the Hurricane Cliffs near Ash Creek Reservoir (FS4-15; appendix A) exposes a bedrock fault. 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 wall of the drainage, several meters of apparently unfaulted colluvium overlies the faulted bedrock. This fault is likely subsidiary to the main Hurricane fault to the west, and may no longer be active, or may not be active during every surface-faulting earthquake on the main fault.

Fault Section 5: Locust Creek to Murie Creek

At Locust Creek, the Hurricane fault bends to the east and trends N. 30° E. for about 10 km to Murie Creek (section 24, T. 37 S., R. 12 W.). The Hurricane Cliffs along this section of the fault are straight and steep and are crossed by several ephemeral and three perennial streams. The ephemeral streams generally have pronounced nickpoints at the fault, whereas the perennial streams have incised through the cliffs and are graded to 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 A). These features are short and generally much modified by erosion, and may owe their origin to geomorphic processes 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 km north of Kanarraville, a short scarp about 5 m high is formed on an alluvial fan at the mouth of a small ephemeral drainage at the base of the Hurricane Cliffs (figure 5; FS5-5, appendix A). The stream has incised through the scarp, and only about 10 m of scarp are preserved along strike. A younger fan has formed where the ephemeral stream issues from the scarp. A seldom-used, two-wheel, dirt track at the base of the scarp has diverted the stream, creating a gully at the toe of the scarp. The faulted alluvial fan remains as a remnant above the present drainage, and is probably late Pleistocene in age. Because of its proximity to Kanarraville, this location is hereafter referred to as the Kanarraville site.

The longest and best preserved scarps formed on unconsolidated deposits on the Utah part of the Hurricane fault are near Murie Creek (figure 6). The scarps are at the northern terminus of fault section 5 where the fault bends to the east. A 3-m-high scarp (appendix B) displaces geologically young alluvial-fan deposits at the mouth of a small ephemeral drainage (herein named Coyote Gulch) about 0.5 km south of where Murie Creek enters Cedar Valley (FS5-6; appendix A). North of the young scarp, a higher scarp is formed on colluvium at the base of the Hurricane Cliffs (FS5-7; appendix A). This scarp is more than 200 m long, generally 10 m or more high (appendix B), and has a pronounced bevel, indicating multiple surface-faulting earthquakes. These two adjacent scarps are hereafter referred to as the Coyote Gulch site.

Fault Section 6: Murie Creek to Cedar City

At Murie Creek, the Hurricane fault begins a pronounced 16.5-km-long bend to the east and north, trending as much as N. 45° E., before turning back to the north near Shurtz Creek (section 9, T. 37 S., R. 11 W.), and finally trending nearly due north at Cedar City (figure 6). For this report, this part of the fault is considered a single fault section, 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 section 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 6), 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 section of the fault, giving the cliffs a less steep and rugged character. Both perennial and ephemeral streams drain 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 this deposit at the base of the Hurricane Cliffs both at Shurtz Creek (FS6-6; appendix A) and where the smaller ephemeral stream issues from the cliffs about a kilometer north of Shurtz Creek (FS6-8; appendix A). Both streams have incised 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 A) and the small drainage to the north (FS6-8; appendix A) may have formed following surface faulting. The site north of Shurtz Creek, which consists of three subparallel scarps, is hereafter referred to as the Middleton site (figure 5), after the owner of the property on which the scarps are located.

About 2.5 km south of Shurtz Creek, the Hurricane fault displaces an alluvial-fan deposit at the mouth of a small, ephemeral drainage. The alluvial-fan surface is displaced across three subparallel fault scarps (FS6-1; appendix A). This location is herein named the Bauer site, after the owner of the property on which the scarps are located. 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 A). However, the area has been chained and rough graded for agricultural purposes, making scarp identification uncertain.

The landslide complex begins a few tens of meters north of the Middleton site, and obscures the trace of the fault for a distance of about 4 km. Examination of aerial photographs revealed numerous scarp-like lineaments within the landslide complex (FS6-11, FS6-12; appendix A); 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 be obscured by the trees and not be visible on 1:24,000-scale aerial photographs. Therefore, the relation between the age of the landslide complex and the age of most recent surface faulting on the Hurricane fault remains unknown.

North of the landslide complex, basin-fill deposits conceal the Hurricane fault (Averitt and Threet, 1973). Squaw Creek flows west to where it issues from the Hurricane Cliffs just east of Cedar City (FS6-13; appendix A). 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, obscuring geologic relations. 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. Initially striking north and dipping east, they change to a northwest strike and a northeast dip to form the east limb and partial nose 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 (left) beneath Cedar Valley 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 and other studies show that the Wasatch fault has experienced numerous Holocene surface-faulting earthquakes, and can be divided into seismogenic segments based on differences in earthquake timing. The seismogenic segment boundaries are also in general accord with recognized geometric and structural discontinuities along the fault.

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 deposits, 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 Coyote Gulch, a probable latest Holocene alluvial-fan deposit is displaced across what we interpret to be a single-event scarp. Additionally, we identified a number of previously unrecognized, likely bedrock-cored scarps at other locations (appendix A). This new information on scarp abundance, location, and type shows that (1) the northernmost part of the Hurricane fault likely experienced a surface-faulting earthquake during the Holocene, and (2) the height, and at some locations the beveled nature, of other scarps indicates that multiple surface faulting has occurred on the Utah part of the fault during the late Quaternary. Clearly, the Hurricane fault has not been as active during the late Quaternary as the Wasatch fault to the north. However, some parts of the Hurricane fault likely have been active more recently than previously thought (Anderson and Christenson, 1989), and multiple, large, surface-faulting earthquakes 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 5). Because they used slip rate as one criterion for their boundary, it is implicit that they were defining a seismogenic boundary separating fault segments each independently capable of producing surface-faulting earthquakes. Based largely on fault-bend geometry, they speculated that the adjoining Ash Creek segment to the north is 24 km long, and the Anderson Junction segment to the south is 19-45 km long, but noted 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 km, 17-23 km, and 30-39 km (dePolo and others, 1991). In several of those historical earthquakes, 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 faulting may extend 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 as 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 formed on basin-fill deposits are absent south of Anderson Junction where bedrock consists chiefly of the Triassic Moenkopi Formation, units of which are described by Anderson and Christenson (1989) as being less resistant to scarp degradation than some coarse-grained Quaternary 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 timing.

In Utah, lengths between major geometric bends in the Hurricane fault range from about 10 to 22.5 km, 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 sections 1 and 2, 3 and 4, 4 and 5, and 5 and 6 (figure 6). However, as noted previously, 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 section 1 are more abundant and better preserved than on section 2, particularly as section 1 is followed south into Arizona. Poorly preserved scarps on section 2 give way to no recognizable scarps on section 3, although some small or indistinct scarps may have been obscured by urbanization. The boundary between sections 3 and 4 is at the bend in the fault at Anderson Junction; as previously discussed, no scarps were observed south of the bend, but scarps are present to the north. Fault section 4 includes the first scarp recognized on unconsolidated deposits north of the Utah-Arizona border at the Water Tank site. Section 5 has comparatively abundant scarps and includes two locations, Kanarraville and Coyote Gulch that have scarps on unconsolidated deposits. The fact that both fault sections 4 and 5 have scarps on unconsolidated deposits may indicate the two sections represent a single seismogenic fault segment. However, the scarps at Coyote Gulch and Kanarraville are much better preserved than the alluvial scarp at the Water Tank site, suggesting a difference in earthquake timing between those locations.

The scarps at Coyote Gulch are immediately south of the fault bend that separates fault sections 5 and 6. Based on location, the Coyote Gulch scarps are part of section 5; however, fault section 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 Coyote Gulch. As has been demonstrated by historical Basin and Range Province 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 section 6 and the scarps at Coyote Gulch. However, the scarps at Coyote Gulch appear younger, in one instance considerably younger, than the scarps on fault section 6, indicating that two adjacent fault segments at the north end of the Hurricane fault have both experienced relatively recent, but different surface-faulting histories.

Scarcity of fault scarps: Results of this reconnaissance show that although fault scarps are scarce along much of the Hurricane fault in Utah, some parts of the fault have likely experienced at least one surface-faulting earthquake during the Holocene, and other parts of the fault have experienced multiple surface-faulting earthquakes in the late Quaternary. Possible reasons for the poorly preserved record of surface faulting include the following: (1) individual surface-faulting earthquakes in the late Quaternary have been small (< M 7), resulting in fault scarps that are 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, (4) erosion rates are high and active deposition at the base of the Hurricane Cliffs rapidly buries scarps, or (5) surface faulting may occur within the rugged bedrock higher up in the Hurricane Cliffs, thus bypassing unconsolidated basin-fill deposits altogether and leaving little or no recognizable 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.

Sites Identified for Possible Detailed Paleoseismic Study

The six sites in Utah having scarps on unconsolidated deposits (from north to south Middleton, Shurtz Creek, Bauer, Coyote Gulch, Kanarraville, and Water Tank) represent the best locations for developing detailed paleoseismic information on the size and timing of past surface-faulting earthquakes on the Utah part of the Hurricane fault. The type, amount, and quality of information that can be obtained from a particular site depends on the geologic relations at that location. All six sites are on the northern 50 km of the fault. The scarps are short, the longest being about 200 m long, and are widely separated (one to several km apart) with little or no evidence of geologically young displacement between them. Differences in net vertical displacement and scarp morphology determined by scarp profiling (appendix B) indicate that some sites likely have different surface-faulting histories. Other scarps identified during the field reconnaissance are formed on bedrock and are mantled with colluvium. However, geologic relations for a few scarps remain equivocal, and while most are probably formed on bedrock, some may be on unconsolidated deposits (appendix A).

We performed a preliminary evaluation of the six sites where scarps are formed on unconsolidated deposits, based chiefly on geologic relations and scarp profiling. Two sites, Shurtz Creek and Coyote Gulch, have the greatest potential for providing paleoseismic information for the northern Hurricane fault; consequently, we focused our efforts on those locations and discuss them in the greatest detail.

Although scarps are formed on unconsolidated Quaternary/Tertiary deposits on the west side of the Ash Creek graben (see description of fault section 4 above), no attempt was made during this study to profile them because of their generally remote location, uncertain association with the Hurricane fault, extremely coarse texture (boulder alluvium), and in some instances great height (>60 m).

Shurtz Creek Site

Site geology: At the Shurtz Creek site (NW¼ section 9, T. 37 S., R. 11 W.; figure 5), Mesozoic sedimentary rocks crop out in the Hurricane Cliffs east of the mouth of Shurtz Creek. 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 [Kanarra anticline of Gregory and Williams, 1947, and Hurlow and Biek, 2003]) is just east of and parallels the Hurricane fault at Shurtz Creek. Above these deformed units lie relatively undeformed Cretaceous and Cenozoic rocks including Quaternary basalt at the top of the drainage basin. Averitt (1962) mapped the Shurtz Creek pediment in the Shurtz Creek amphitheater, an area of relatively low elevation formed in the Hurricane Cliffs on the softer Mesozoic rock units in the Shurtz Creek drainage basin.

The Shurtz Creek scarp is formed on both alluvium and bedrock. The coarse-grained alluvial deposit previously mapped as a pediment by Averitt (1962) is displaced across a single ~15.5-m-high scarp (appendix B). Careful examination of the high, steep walls of the stream bank where Shurtz Creek incises the fault scarp revealed no evidence of bedrock in the upper ~15 m of the deposits underlying the upper surface. To the north, the same fault is expressed as a sharp, linear contact between Mesozoic sedimentary rock and valley-fill alluvium. Southward, the fault bifurcates, forming western and eastern strands. Beyond the pediment deposit, the western strand follows the base of the Hurricane Cliffs, separating Mesozoic bedrock from valley-fill alluvium. The soft, easily eroded bedrock forms a distinct, but dissected and rounded scarp. Pinyon and juniper trees growing in alluvium on the hanging wall have been chained (cleared by dragging a heavy ship's anchor chain between two bulldozers) and as a consequence that area is greatly disturbed; if any scarps were formed on alluvium there, they have been destroyed. 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 Member of the same formation, repeating part of the stratigraphic section.

The coarse-grained alluvial surface on the upthrown side of the fault is heavily forested and covered with basalt boulders, many more than 2 m in diameter. Other rock types present are chiefly limestone and minor sandstone derived from Mesozoic and Cenozoic rock units that crop out in the Shurtz Creek drainage basin. Few of those clasts are more than 10 cm in diameter. The abundance and size of the boulders on this surface reflect the greater resistance of basalt to erosion compared to the sedimentary rocks that crop out in the drainage basin. Most boulders show evidence of long exposure at the ground surface. Many have split into two or more pieces; some have spalled repeatedly so that multiple degrees of patina (desert varnish) development are evident on the same boulder, and most support growths of lichen and moss. Shurtz Creek has eroded at least one post-faulting stream terrace into the coarse alluvial deposit along both sides of its channel upstream from the fault scarp.

There are two ages of alluvial deposits 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 runoff, this surface receives active deposition. An older alluvial deposit lies immediately south and approximately a meter higher than the young alluvial fan. Like the surface 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.

Surface age estimates from soil development: The alluvial surface on the upthrown side of the fault and the older of the two alluvial surfaces on the downthrown side of the fault are similar in appearance. Both are covered with large basalt boulders that show evidence of long exposure (desert varnish, spalling, split boulders) 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 lag gravel deposits that resemble desert pavement.

Based on surface morphology, we initially hypothesized that the two boulder-covered surfaces on either side of the fault scarp were correlative. If so, and if the age of the displaced surface could be determined, a vertical 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) independently examined the soils formed on each surface. Soil morphology data and USU laboratory results are in appendix C. The soils on both surfaces have moderate to well-developed argillic and calcic horizons, and gypsum is leached from both soil profiles confirming both surfaces are older than Holocene (Dr. Janis Boettinger, USU, written communication, 1998; Sidney Davis, Davis Consulting Earth Scientists, verbal 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 a depth of 26 cm on the upthrown side, but <8 only to a depth of 8 cm on the downthrown side. 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 cm 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 cm 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 cm on the upthrown block and reaches a maximum of 43 percent between 66 and 100 cm. A drop in $CaCO_3$ content at the base of the test pit on the downthrown side of the fault (appendix C) also argues for a younger soil there.

The well-developed argillic B and Stage II (lower surface) and Stage III (upper surface) Bk horizons in the soils at Shurtz Creek argue for different ages for the two 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 having similar $CaCO_3$ accumulations in the Beaver Basin 90 km north of Shurtz Creek. Therefore, based on differences in soil-profile development, the surfaces across the scarp at Shurtz Creek are not considered 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). Additions of younger material to the downthrown surface could explain the differences in the two soils. The surface on the downthrown block is considered a younger alluvial fan that substantially post-dates deposition of the coarse alluvial deposits that form the alluvial surface on the upthrown block.

Surface age estimates from cosmogenic isotopes: Concurrent with the soils investigation, we undertook a study to determine the ages of the upper and lower Shurtz Creek surfaces by analyzing cosmogenic isotope abundances in rock clasts on those surfaces. The U.S. Geological Survey (USGS) 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. The USGS also analyzed a sample from a basalt boulder on the upthrown surface for ^{36}Cl isotope abundance. Lawrence Livermore National Laboratory performed the laboratory analyses.

Age estimates determined from ^{26}Al abundance in sandstone samples from both surfaces range from 12,000 to 22,000 years, clustering around 15,000 to 18,000 years (Dr. Thomas Hanks, USGS, written communication, 1998). These ages are unexpectedly young considering the age of the surfaces predicted from soil development data (see above). The result was similar with the ^{36}Cl isotope analysis of the basalt boulder, which resulted in an exposure age of about 30,000 years (Dr. Thomas Hanks, USGS, written communication, 2001). The University of Utah (U of U) sampled two basalt boulders on the upthrown surface at Shurtz Creek for ^{3}H isotope abundance, and calculated ages of about 30,000 and 60,000 years (Cassandra Fenton, U of U, written communication, 2001).

The difference between the estimated surface ages obtained from soil-profile development and cosmogenic isotope abundances at Shurtz Creek is puzzling. Although basalt bedrock comprises less than 10 percent of the Shurtz Creek drainage basin, basalt boulders dominate the morphology of both Shurtz Creek surfaces, reflecting the more resistant nature of basalt compared to sandstone. The young cosmogenic ages for the sandstone likely reflect the sandstone's greater susceptibility to weathering when exposed at the ground surface. We hypothesize that most of the large sandstone boulders and cobbles originally deposited on the surface have disintegrated, leaving behind small remnants of their cores, which have been exposed to atmospheric radiation for a comparatively short time. Other sandstone clasts may have been transported upward to the surface by freeze-thaw action, and therefore also have been exposed at the surface for a comparatively short time. However, the ^{36}Cl and ^{3}H cosmogenic ages obtained from basalt boulders also indicate a comparatively young age for the upthrown Shurtz Creek surface of between 30,000 and 60,000 years, compared to the 80,000 to 100,000 years minimum age indicated by soil-profile development. The difference between the soil-profile and cosmogenic age estimates may be the result of spalling of the boulder surfaces. The boulders exhibit multiple patches of different degrees of desert varnish ranging from slightly darker than the color of fresh rock to a deep shiny black patina, indicating that spalling of the boulder surfaces is an ongoing incremental process. Over time spalling progressively removes rock from the boulder surfaces, which may result in cosmogenic exposure ages for the boulders that are too young, even for the most darkly patinated surfaces.

Net vertical displacement and vertical slip-rate estimate: We profiled the Shurtz Creek scarp using a meter stick and Abney hand level (appendix B). The scarp is 15.5 m high, has a maximum slope angle of 28°, and a net vertical displacement of 12 m (table 1). Calculating a vertical slip rate at Shurtz Creek is complicated by the following considerations: (1) the alluvial surfaces on either side of the Hurricane fault are not the same age (see discussion above); younger deposits have accumulated on the downthrown side of the fault and therefore the net vertical displacement obtained from the scarp profile is a minimum value, (2) the ages of the surfaces predicted from soil-profile development, and those obtained from cosmogenic isotope abundances are inconsistent, (3) the time interval between the formation of the displaced surface and the first surface-faulting earthquake is unknown, and (4) the elapsed time since the most recent surface-faulting earthquake at Shurtz Creek is unknown. Calculating a well-constrained vertical slip rate requires that the net vertical displacement be known over one or more closed seismic cycles (a time interval bracketed by two surface-faulting earthquakes). This is not the case at Shurtz Creek where neither the net vertical displacement nor the time interval over which the displacement occurred are accurately known. The two open time intervals could be considerable, and may represent thousands of years. For large cumulative displacements and long time periods, for example hundreds of meters over many hundreds of thousands of years as represented by displaced basalt flows elsewhere along the Hurricane fault (see discussion below), the effect of these time considerations is small, as are reasonable uncertainties in cumulative net vertical displacement. However, at Shurtz Creek, the pre- and post-faulting time intervals may account for a significant part of the age of the displaced surface, and the underestimation of net vertical displacement across the scarp may be considerable. Because the two time intervals tend to cancel each other when calculating slip rates, their effect may be minimal if they are roughly equivalent. However, using a too-small value of net vertical diplace-ment will result in an underestimation of the actual slip rate.

Using the Shurtz Creek scarp-profile data, and estimating that the surface on the upthrown side of the fault is between 30,000 and 100,000 years old based on a combination of cosmogenic and soil-profile data, and further assuming that the pre- and post-faulting time intervals largely cancel each other, we obtained a late Quaternary slip rate at Shurtz Creek of between 0.12 to 0.40 mm/yr. Our preferred vertical slip rate is 0.18 mm/yr, which incorporates the median age (65,000 yrs) of the upthrown surface. The slip rate at Shurtz Creek is likely a minimum because the surface on the downthrown side of the fault has been buried by an unknown thickness of post-faulting alluvium, thus making the net vertical displacement measured from the scarp profile less than the total net displacement at this site. Our preferred late Quaternary vertical slip rate is less than one-half the vertical slip rate calculated from displaced basalt flows for this study (see below),and is roughly half the average vertical slip rate calculated for the past million years by Hamblin and others (1981) using displaced basalt flows near the town of Hurricane. Our preferred rate is also about one-fifth to one-seventh the average slip rate for the most active segments of the Wasatch fault during the Holocene (Machette and others, 1992; Lund, 2005). Interestingly, it is about the average (determined from limited data) for the Wasatch fault between 100,000 to 200,000 years ago (Machette and others, 1992).

Coyote Gulch Site

Site geology: At the Coyote Gulch site (SE¼SW¼ section

Table 1. *Scarp-profile data.*

Location	Scarp Height	Net Vertical Tectonic Displacement	Maximum Slope Angle	Remarks
Shurtz Creek	15.5 m	12 m	28°	Coarse alluvium - bedrock cored?
Murie Creek				
Coyote Gulch	3 m	2.5 m	14°	Possible single-event scarp
Colluvial apron	10 m	—	21.5°, 14°	Beveled, multiple-event scarp
Middleton Site				
East Scarp	9.5 m	7.3 m	27.5°	Bedrock
Middle Scarp	4 m	2.7 m	18°	Alluvial fan
West Scarp	4 m	2.7 m	19°	Alluvial fan
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

24, T. 37 S., R. 12 W.), the Hurricane fault displaces a young (mid- to late Holocene) alluvial-fan deposit across a 3-m-high scarp at the mouth of Coyote Gulch, a small drainage that emerges from the Hurricane Cliffs south of Murie Creek (figure 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. The scarp is partially buried by post-faulting alluvium deposited before the ephemeral stream issuing from Coyote Gulch fully incised the scarp. Red siltstone, claystone, and yellow-buff limestone of the Triassic Moenkopi Formation crop out in the Coyote Gulch drainage basin, resulting in a correspondingly fine-grained alluvial-fan deposit. Based on the young age of the alluvial fan (see below), this is the youngest fault scarp recognized along the Utah portion of the Hurricane fault, and we interpret it to represent a single surface-faulting earthquake.

A few tens of meters north of the Coyote Gulch scarp, a colluvial deposit at the base of the Hurricane Cliffs is displaced across a scarp that diverges to the northwest from the cliff front for a distance of about 200 m. The colluvium is derived chiefly from limestone of the Permian Kaibab Formation (Kurie, 1966; Hintze, 1988), which crops out in the cliffs immediately east of the scarp The scarp is generally 10 m or more high and has a pronounced bevel (table 1; appendix B), indicating that the scarp is the result of multiple surface-faulting earthquakes. The trace of the scarp is gently sinuous, reflecting post-faulting erosion. The hanging wall slopes a few degrees eastward toward the fault and has received post-faulting sedimentation that obscures any antithetic faults that may have formed on the downthrown block. The scarp ends abruptly to the north at the contact between the colluvium and the Murie Creek alluvial fan. Although likely older than the young alluvial fan at Coyote Gulch, little evidence exists 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, and indicates a possible continuation of faulting, but no discernable scarp or other evidence of displacement is present. The age relation between the Murie Creek alluvium and the faulted colluvium is unknown; however, based on the absence of scarps on the fan, the fan alluvium is likely younger than the most recent surface faulting at this site.

Surface age estimates from soil development: We excavated two soil test pits at Murie Creek, one in the young alluvial-fan deposit at Coyote Gulch and the other in the colluvium at the base of the Hurricane Cliffs. Both soil pits were on the upthrown side of the fault. Soil morphology data for the two soils are shown in appendix C. No laboratory analyses were performed on the soils.

Due to its red, clay-rich parent material derived from the Moenkopi Formation, the soil on the Coyote Gulch alluvial fan is red in color and clayey throughout. The 80-cm-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 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 interpret the age of the Coyote Gulch alluvial-fan deposit as less than 10,000 years old.

The soil on the colluvium at the base of the Hurricane Cliffs has an A horizon more than twice as thick (17 cm) as the soil on the Coyote Gulch alluvial fan; a 39-cm-thick, clay-enriched Bt horizon; and below a depth of 27 cm the soil exhibits Stage II carbonate morphology. Both the Bt horizon and the Stage II carbonate morphology indicate an older 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 about 90 km to the north.

Net vertical displacement and vertical slip-rate estimate: Scarp profiles surveyed with a total station show a height of 3 m and a net vertical displacement of 2.5 m for the scarp at Coyote Gulch, and a height of 10 m for the scarp on colluvium to the north (table 1, appendix B). Maximum net vertical displacement 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 displacement along strike, effects of near-fault deformation (for example, backtilting and graben formation), erosion, sedimentation at the scarp base (fault hanging wall), and differences in colluvium age.

The small scarp at Coyote Gulch likely represents a single surface-faulting earthquake, and is unlikely to represent more than two such earthquakes. Because the number of surface-faulting earthquakes is both small and unknown, calculating a vertical 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 earthquakes that created the scarp. Assuming that the age of faulting is Holocene (<10,000 yrs), the vertical slip rate at Coyote Gulch would be ≤ 0.25 mm/yr, which is about one-quarter to one-fifth 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. However, this is an open slip rate, and since both the number of earthquakes and their timing is unknown, it may represent a maximum, a minimum, or an intermediate slip value.

The slopes of the surfaces on either side of the large scarp at Murie Creek are widely divergent (appendix B), indicating the downthrown block is buried by younger alluvium, and that not even a tenuous correlation exists between the surfaces across the fault. Therefore, we were unable to obtain a meaningful measurement of net vertical displacement across the large scarp, and consequently could not make a reasonable vertical slip-rate estimate.

Middleton Site

The Middleton site is about 1 km north of Shurtz Creek (NW¼SE¼ section 4, T. 37 S., R. 11 W.; figure 5), where bedrock and Averitt's (1962) Shurtz Creek amphitheater pediment deposit are displaced down-to-the-west across three subparallel scarps. The investigation at this site consisted of profiling the scarps with an Abney level and meter stick; we did not excavate soil test pits. The eastern scarp is about 9.5 m high and has a maximum slope angle of 27.5° (table 1; appendix B). It separates bedrock of the Moenkopi Formation in the footwall from pediment deposits in the hanging wall. The middle and western scarps are both formed on the pediment deposit. These scarps are each about 4 m high and have maximum slope angles of 18° and 19°, respectively (appendix B, table 1). From east to west, the net vertical displacements across the scarps are 7.3, 2.7, and 2.7 m, respectively. The 12.7 m of total displacement across the three scarps is about 0.7 m more than recorded at Shurtz Creek (12 m), in what are likely deposits of the same age. The somewhat larger displacement likely reflects along-strike variations in slip, although the Shurtz Creek measurement is a minimum due to deposition of younger sediment on the downthrown side of the fault.

The Middleton surface is isolated above the present stream channel and is inactive. The surface is covered with basalt cobbles and small boulders that exhibit strong patina development, indicating long exposure times. Further evidence of age is the near absence of sandstone clasts on the surface, even though sandstone crops out extensively in the adjacent drainage basin. Averitt (1962) mapped this deposit as the Shurtz Creek pediment; however, it has many affinities with the displaced deposits at the Bauer site (see below), which Averitt (1962) mapped as an alluvial fan. 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 surfaces at the Middleton and Bauer sites are similar in age to the Shurtz Creek pediment.

Bauer Site

The Bauer site is about 2.5 km south of Shurtz Creek (NE¼SW¼ section 17, T. 37 S., R. 11 W.; figure 5). Three subparallel fault scarps displace an alluvial-fan deposit (Averitt, 1962) down-to-the-west in a manner similar to the Middleton site. Also similar to the Middleton site, the investigation at this site consisted of measuring a scarp profile with an Abney level and meter stick; we did not excavate soil test pits. The eastern and middle scarps are each about 5 m high and have maximum slope angles of 22° and 20°, respectively (table 1; appendix B). The western scarp is more eroded than the two eastern scarps, is about 2 m high, and has a maximum slope angle of 16°. From east to west, the net vertical displacements measured across the scarps are 2.3, 2.3, and 0.9 m, respectively. The 5.5 m of displacement recorded by the three scarps is about half the net displacement at Shurtz Creek (12 m) and 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 in surfaces of the same age. Therefore, we conclude that the displaced alluvial-fan deposits at the Bauer site are younger than the displaced alluvial surfaces at the Shurtz Creek and Middleton sites.

Kanarraville Site

At the Kanarraville site (SE¼ section 26, T. 37 S., R. 12 W. ; figure 5), a remnant of an older alluvial fan at the mouth of a small ephemeral drainage is truncated by faulting. The scarp is about 5 m high and is incised by the ephemeral stream. A young alluvial fan has formed on the downthrown side of the fault 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, two-wheeled dirt track runs parallel to the base of the scarp and has diverted the ephemeral stream along the base of the scarp and eroded a gully nearly a meter deep. The faulted fan is estimated to be late Pleistocene in age, but because of the scarp's highly modified state, no further work was done at this location.

Water Tank Site

The Water Tank site (SE¼ section 32, T. 39 S., R. 12 W.; figure 5) consists of two short (<100 m) subparallel scarps: a large, likely bedrock-cored eastern scarp, and a smaller, eroded and partially buried western scarp formed on alluvium. The Water Tank site is the southernmost location on the Utah part of the Hurricane fault with scarps formed on unconsolidated deposits. We used an Abney level and meter stick to measure a scarp profile where the western scarp is relatively unaffected by erosion or deposition. The western scarp is 4.5 m high and has a maximum slope angle of 13° (table 1; appendix B). The eastern scarp is 12.7 m high and has a maximum slope angle of 20°. Net vertical displacements measured across the western and eastern scarps are 1.8 and 7.3 m, respectively, for a total net vertical displacement of 9.1 m. We did not excavate soil test pits at the Water Tank site.

Trenching

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 intended to determine the size and timing of past surface-faulting earthquakes. Bedrock-cored scarps have been trenched with some success (Jackson, 1991), but generally prove problematic and are less likely to produce useful results (McCalpin, 1996; Olig and others, 1996). Therefore, the six sites with scarps on unconsolidated deposits now recognized on the Utah part of the Hurricane fault offer the best opportunity for evaluating the fault's late Quaternary surface-faulting history.

We considered all six sites for trenching and selected Coyote Gulch, with its approximately 3-m-high, likely single-event scarp formed on a late Pleistocene/Holocene-age alluvial fan and 10-m-high, multiple-event scarp formed on colluvium at the base of the Hurricane Cliffs, as our preferred trench site. However, the Coyote Gulch site is on private property, and the landowner was unwilling to allow trenching either mechanically or by hand. Following a re-evaluation of the remaining five sites, we selected the large, single scarp at Shurtz Creek for trenching (figure 7).

At Shurtz Creek, all of the late Quaternary displacement on the Hurricane fault is confined to a single, 15.5-m-high (12 m net vertical displacement) scarp formed on alluvium (appendix B, figure 7). We originally rejected the Shurtz Creek site because the ground surface on both the up- and downthrown sides of the fault is covered with large basalt boulders, some up to 2 m in diameter. We were concerned that similar boulders in the subsurface might impede trenching. However, the Middleton and Bauer sites are also rocky and those sites have multiple fault scarps that would require multiple trenches, presenting potential dating and correlation problems between excavations. Road building and other human activities have modified the scarps at the Kanarraville and Water Tank sites, and at least one of the scarps at the Water Tank site is likely bedrock cored.

Trenching commenced at Shurtz Creek using a trackhoe with a 48-inch bucket. The trackhoe immediately encountered several very large boulders in the subsurface, which limited the trench depth to less than 1.5 m and prevented exposing the fault zone. The Shurtz Creek site is in a dense pine and juniper forest (figure 7) that contains numerous pre-Columbian Native American sites. Both our access path to the trench site and the trench location itself were determined by the Bureau of Land Management (BLM) through a lengthy permitting process. Moving to another location on the Shurtz Creek scarp would have required reapplying to the BLM for a new permit, performing a second archeological survey, and additional extensive tree removal to access the new site. Because large basalt boulders are ubiquitous along the scarp, we believed the chances of completing a successful trench anywhere on the Shurtz Creek scarp were low and decided against further excavation there. Trenching at one of the four remaining scarp locations mentioned above was likewise rejected because we had already attempted a trench at the most geologically favorable site, and the other sites either have similar large boulders associated with multiple fault scarps, access restrictions, or have been modified in one manner or another.

Dating Stream and Alluvial-Fan Deposits

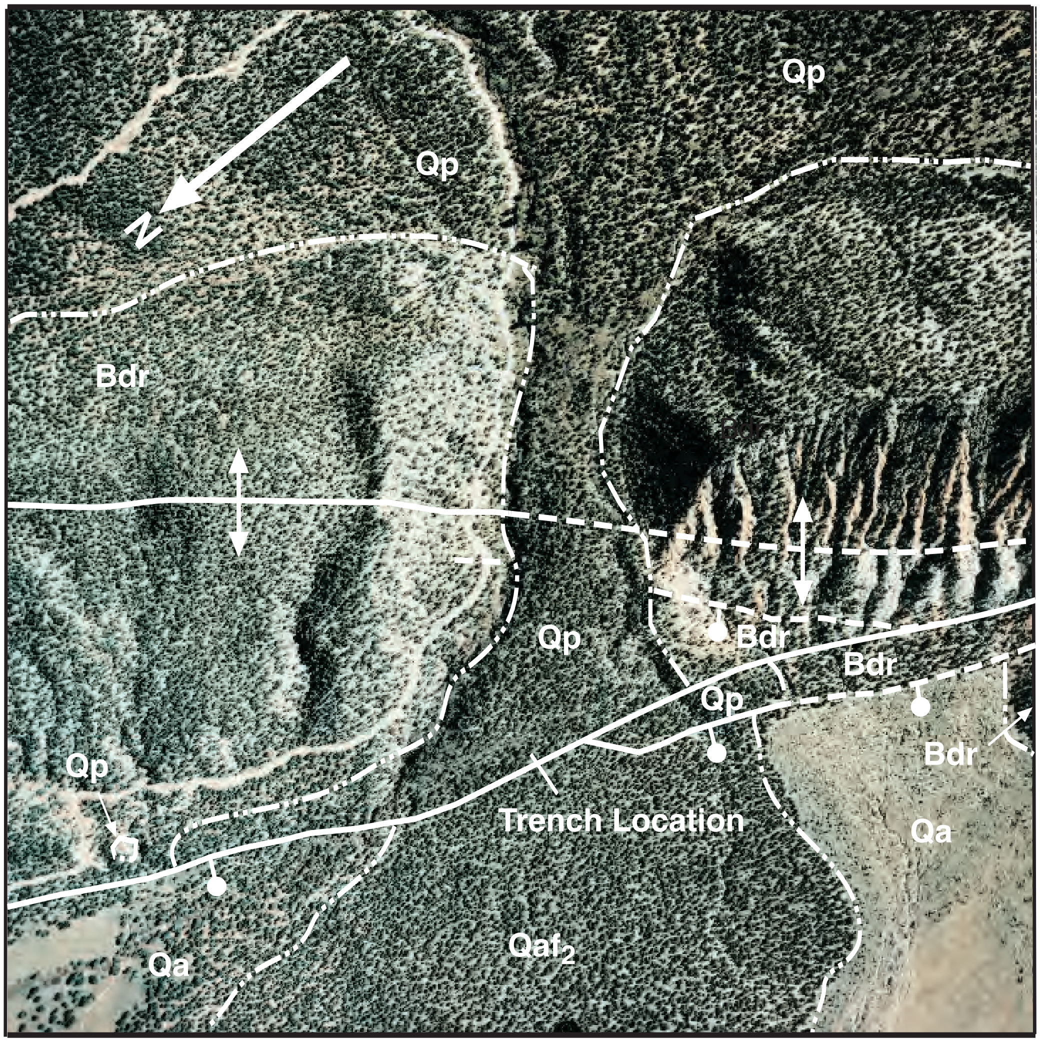
Lacking a viable trench site on the Utah part of the Hurricane fault, we focused our efforts on dating geologically young alluvial-fan and stream-terrace deposits where they overlie the fault zone at the Middleton, Bauer, and Coyote Gulch sites (figure 5).

The deposits at the Middleton and Bauer sites are unfaulted and therefore postdate the most recent surface faulting at those locations. The alluvial fan at Coyote Gulch is faulted and therefore predates the most recent surface faulting there. Dating these deposits would provide broad limiting ages on the timing of the most recent surface faulting at the north end of the Hurricane fault.

Near-vertical stream banks along incised drainages expose the sediments of interest at all three sites. We made detailed descriptions of the soils formed on the fan and terrace surfaces to determine if the relative age of the deposits could be differentiated on the basis of soil-profile development (appendix C). Utah State University analyzed bulk samples from soil horizons for grain-size distribution and total carbonate content. Paleo Research Institute (PRI) processed bulk samples collected from selected stratigraphic intervals within the deposits and identified charcoal suitable for accelerator mass spectrometry (AMS) radiocarbon dating.

Middleton Site

Just before issuing from the Hurricane Cliffs, the un-



EXPLANATION

GEOLOGIC UNITS

Qa	Valley-fill alluvium
Qaf_1	Young alluvial-fan deposit
Qaf_2	Older alluvial-fan deposit
Qp	Pediment-mantle deposit
Bdr	Bedrock, undifferentiated

400 meters

SYMBOLS

Geologic contact

Shurtz Creek anticline

Normal fault, bar and ball on downthrown side, dashed where approximately located

Figure 7. *Photogeologic map of the Shurtz Creek site, Hurricane fault, Utah, showing trench location (after Averitt, 1962).*

named drainage at the Middleton site (figures 5 and 8) dissects a late Quaternary alluvial surface mapped by Averitt (1962) as "pediment deposits in the Shurtz Creek amphitheater." This surface is displaced 12.7 m down-to-the-west across three strands of the Hurricane fault. The stream has deposited a geologically young alluvial fan at the base of the cliffs where it enters the valley. The alluvial fan and an alluvial terrace that extends up the drainage from the fan apex combine to bury all three fault strands where they cross the stream.

We made detailed descriptions of three soil profiles (figure 9, appendix C) at the Middleton site in the steep banks of the incised stream at and a short distance upstream from the modern alluvial-fan apex. Profiles MS-1 and MS-2 are on alluvial-fan deposits consisting chiefly of coarse-grained debris-flow and debris-flood sediment. Profile MS-3 is formed on a stream-terrace deposit consisting chiefly of coarse fluvial and debris-flow material. The MS-2 and MS-3 surfaces overlie the Hurricane fault and are not displaced. The relation between the alluvial fan on which the MS-1 soil has formed and the Hurricane fault is unclear. The MS-1 surface is immediately south of the drainage mouth and is juxtaposed against a bedrock scarp of the Hurricane fault. The nature of the contact between the fan deposit and the scarp is problematical. The contact is most likely depositional, but the possibility that the fan and bedrock are in fault contact cannot be discounted.

Paleo Research Institute isolated charcoal suitable for AMS ^{14}C dating from five bulk soil samples collected from selected horizons within the three Middleton soil profiles. We submitted 0.024 g of charcoal identified by PRI as the genus Rosaceae (rose family) from soil profile MS-3 for AMS ^{14}C dating. The charcoal came from the A horizon of a buried paleosol at a depth of 117-139 cm (horizon 4Ab2, figure 9). The paleosol is formed on a debris-flow/flood deposit that remained at the ground surface for sufficient time for a soil to form. The soil was then buried by subsequent debris-flow and fluvial sediments. We selected this charcoal sample for dating because (1) charcoal obtained from a soil A horizon is likely primary, accumulating during the soil-forming process, rather than detrital, having been entrained within a debris flow or flood and carried to the site from another location, and (2) the rose family consists of relatively short-lived species, so the age of the charcoal likely closely approximates the age of the soil. The charcoal from the paleosol A horizon yielded an AMS ^{14}C age of 1710±40 ^{14}C yr B.P. (Beta-140470), which calendar calibrates to cal A.D. 240 to 420 (1710 to 1530 cal yr B.P.). This calibrated age provides a minimum limit for the timing of most recent surface faulting at Middleton; the most recent event occurred sometime before 1530-1710 cal yr B.P., but how much before is unknown.

Bauer Site

At the Bauer site two small, unnamed ephemeral drainages issue from the Hurricane Cliffs (figure 10). Just before exiting the cliffs, the drainages dissect a late Quaternary alluvial fan (Averitt, 1962). The fan surface is displaced 5.5 m down-to-the- west across three strands of the Hurricane fault. The unnamed ephemeral drainages have combined to deposit a geologically young alluvial fan at the base of the Hurricane Cliffs; the fan apex extends up the northernmost drainage and buries the western fault strand where it crosses the drainage.

We described the soil (figure 9, appendix C) formed on the alluvial fan where it is exposed in a stream bank. The soil is poorly developed, exhibiting some rubification in a thin Btw horizon, a weak Bk horizon expressed as Stage I or Stage I-minus carbonate development, and weak soil structure.

Paleo Research Institute processed a bulk sediment sample collected from 13 to 60 cm below the ground surface. This interval corresponds to the Bk horizon (horizons Bk1 and Bk2; figure 9) of the soil formed on the fan. The processing isolated several small fragments of detrital charcoal and other organic matter. Only one charcoal fragment, weighing 0.008 g, was large enough to permit AMS ^{14}C dating. The plant genus of the charcoal could not be identified (PRI, written communication, 2000). The charcoal fragment yielded an AMS ^{14}C age of 420±40 ^{14}C yr B.P. (Beta-140469), which calendar calibrates to both cal A.D. 1425 to 1515 (525 to 435 cal yr B.P.) and cal A.D. 1590 to 1620 (360 to 330 cal yr B.P.). The two age ranges result from irregularities in the correlation curve for this time period (Darden Hood, Beta Analytic Inc., written communication, 2000). The calibrated age estimate represents a minimum limit on the timing of surface faulting at the Bauer site. The most recent surface faulting occurred sometime before ~360 to 525 cal yr B.P., but how much before is unknown, and because the charcoal was detrital, the deposit is younger than the AMS age estimate.

Coyote Gulch Site

At the Coyote Gulch site a small ephemeral drainage issuing from the Hurricane Cliffs has deposited a geologically young alluvial fan at the base of the cliffs (figure 11). The alluvial-fan surface is displaced down-to-the-west across a partially buried 3-m-high, probable single-event fault scarp.

The alluvial fan at Coyote Gulch (Qaf_1, figure 11) is incised about 1.5 m by the intermittent stream. We described the soil formed on the fan surface (figure 9; appendix C) on the footwall side of the fault where the stream bank exposes the soil profile. The rock units that crop out in the Coyote Gulch drainage are chiefly the fine-grained lower and middle red members of the Moenkopi Formation, so the alluvial-fan sediment has a high initial clay content and strong primary red color, making subtle changes in clay content and rubification associated with soil development difficult to identify. The soil exhibits minor rubification in a thin Btw horizon, a weak Bk horizon showing incipient Stage I carbonate development, and weak or absent soil structure.

Fan sediments exposed in the stream cut exhibited laterally continuous thin bedding (individual continuous beds 2 to 5-cm-wide) and showed no evidence of bioturbation. Examination of the fan sediments showed no visible evidence of organic material. Paleo Research Institute processed a bulk sediment sample from an interval 15 to 128 cm below the fan surface, and identified three small fragments of detrital charcoal. This interval corresponds to the soil Bk horizon (horizons Bk1 and Bk2, figure 9). Care was taken during sampling of the fan sediments to avoid contamination by organic material from outside the sampled area, and the continuous

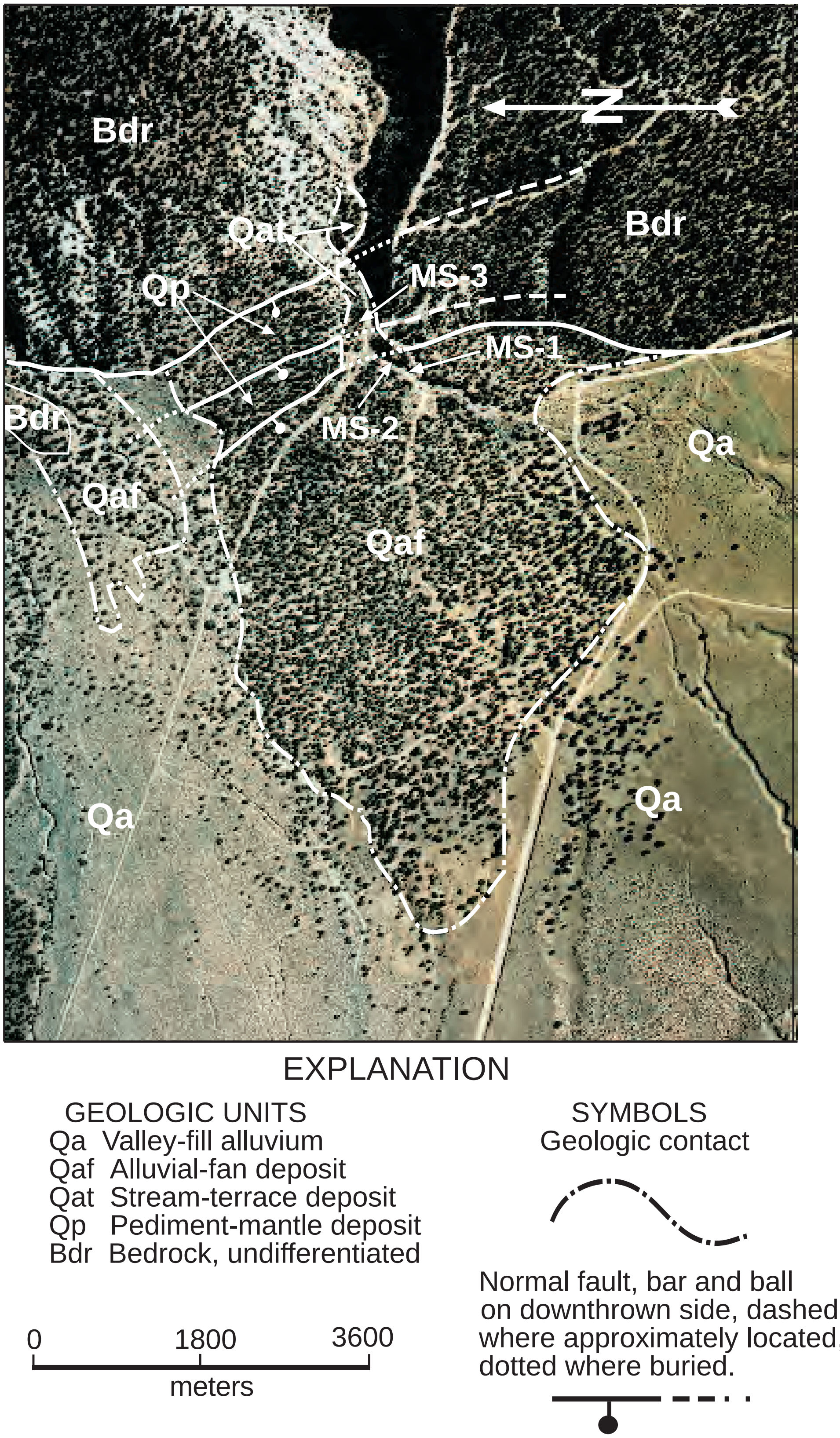


Figure 8. *Photogeologic map of the Middleton site, Hurricane fault, Utah, showing the locations of soil profiles MS-1, MS-2, and MS-3 (after Averitt, 1962).*

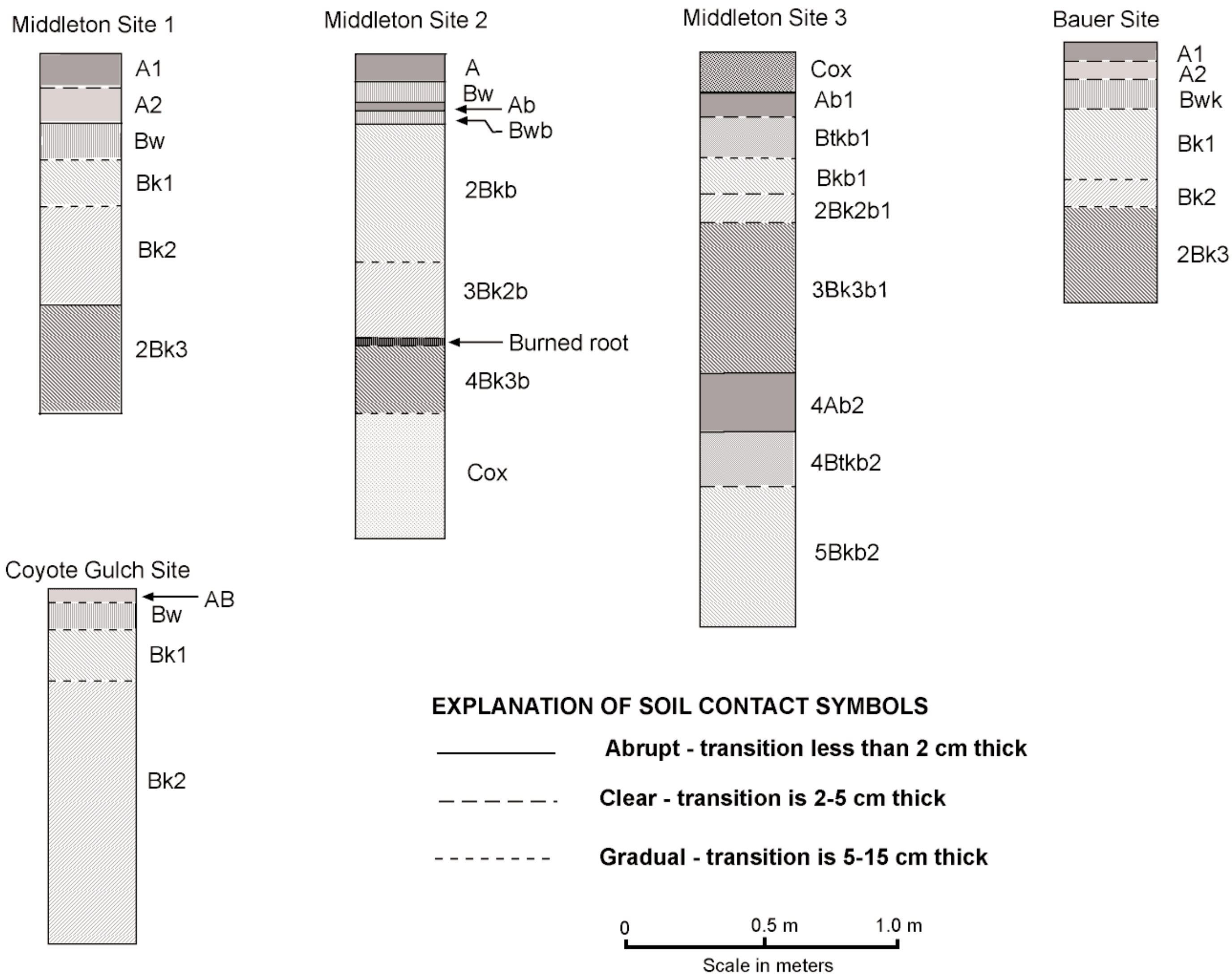


Figure 9. *Soil profiles measured at the Middleton, Bauer, and Coyote Gulch sites, Hurricane fault, Utah (soil profile nomenclature after Birkeland and others, 1991).*

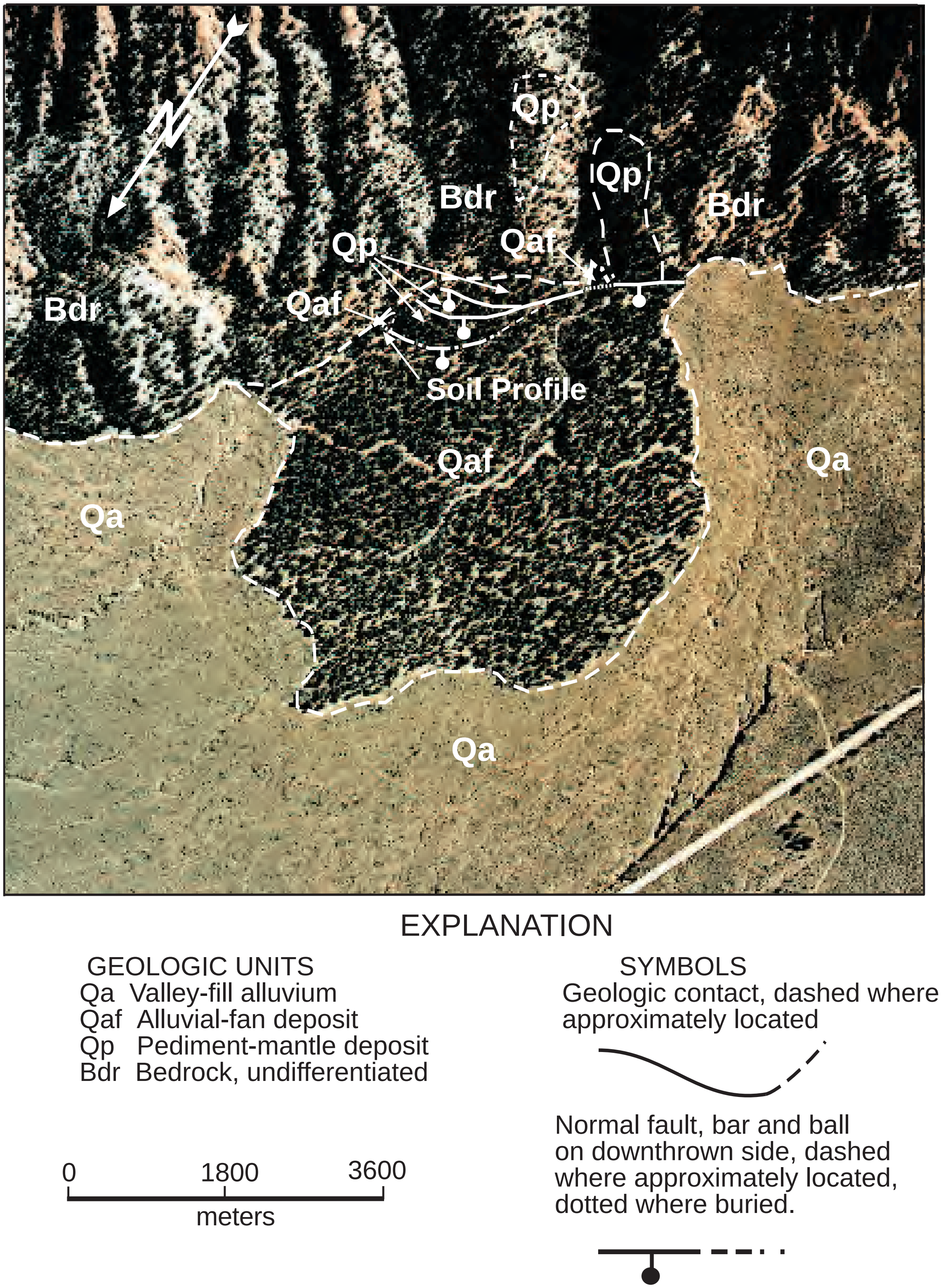
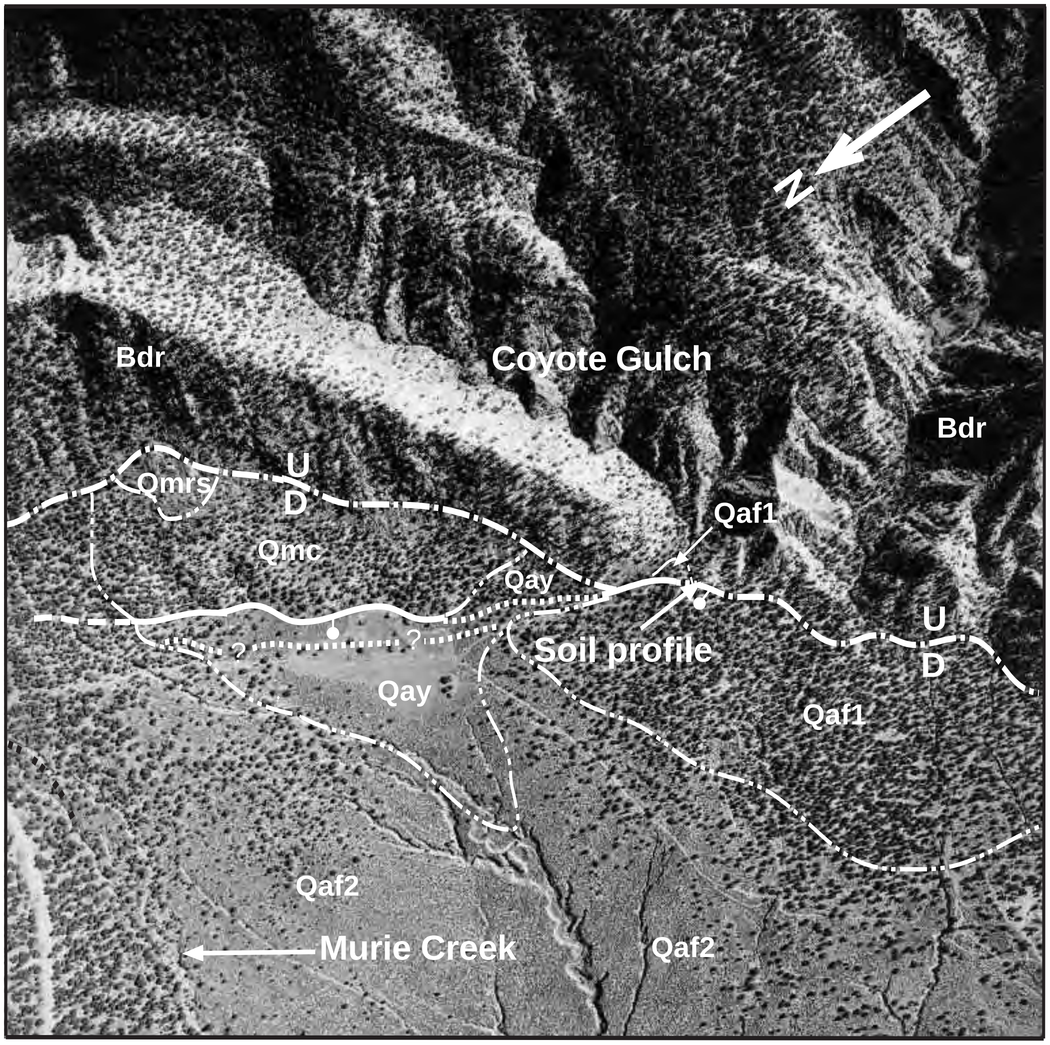


Figure 10. *Photogeologic map of the Bauer site, Hurricane fault, Utah, showing soil profile location (after Averitt, 1962).*



EXPLANATION

GEOLOGIC UNITS

Qay Young alluvium
Qaf1 Young alluvial-fan deposits
Qaf2 Older alluvial-fan deposits
Qmc Slope colluvium
Qmrs Rock slide deposit (?)
Bdr Bedrock, undifferentiated

400 meters

SYMBOLS

Geologic contact

U D **Main trace Hurricane fault, approximately located ; U = upthrown side, D = downthrown side of fault.**

Normal fault, bar and ball on downthrown side, dashed where approximately located, dotted where buried or inferred

Figure 11. *Photogeologic map of the Coyote Gulch site, Hurricane fault, Utah, showing soil profile location.*

thin bedding of the sediments demonstrated that the sediment was not bioturbated. The recovered charcoal fragments consisted of juniper, sagebrush, and an unidentified plant genus. None of the fragments were individually large enough for AMS ^{14}C dating, so we combined them into a single composite sample for dating. The combined sample yielded an AMS ^{14}C age of 1220±40 ^{14}C yr B.P. (Beta-140468), which calendar calibrates to cal A.D. 690 to 895 (1260 to 1055 cal yr B.P.). The calibrated age estimate represents a maximum average limiting age for surface faulting at the Coyote Gulch site. The most recent surface faulting likely occurred sometime after 1055 to 1260 cal yr B.P., but how long after is unknown, nor is the actual age of the fan known, other than it is younger than the detrital charcoal contained within it.

The scarp profile at Coyote Gulch recorded a vertical net slip of 2.5 m. Data on surface-faulting displacement are limited for the Hurricane fault in Utah, but the 2.5 m measured at Coyote Gulch is the largest displacement observed on the proposed Ash Creek segment. If not a maximum displacement value, it is likely a close approximation.

Discussion

Soils formed on alluvial-fan and stream-terrace deposits at the Middleton, Bauer, and Coyote Gulch sites are weakly developed, indicating a young geologic age for those deposits. Charcoal recovered from the deposits yielded AMS ^{14}C age estimates ranging from 330 to 1710 cal yr B.P., establishing a late Holocene age for the deposits. The AMS age estimates at both the Bauer and Coyote Gulch sites came from detrital charcoal and therefore overestimate the age of those deposits. The extent to which those deposits are younger than the charcoal contained in them is not known.

At the Middleton and Bauer sites, the alluvial-fan and/or stream-terrace deposits that overlie the Hurricane fault are not displaced, indicating that the MRE at those sites is older than the age of the deposits. The AMS ages obtained from charcoal at the Middleton and Bauer sites,1530-1710 and 330-525 cal yr B.P., respectively, provide minimum limits on the timing of the MRE. Conversely, at Coyote Gulch, the alluvial fan is faulted, indicating that the MRE there is younger than the alluvial-fan deposit it displaces. A composite sample of detrital charcoal recovered from the alluvial-fan sediments yielded an average age of 1055 to 1260 cal yr B.P., which provides a maximum limit on the time of most recent surface faulting. As at the Bauer site, the charcoal at Coyote Gulch was detrital and therefore is older than the alluvial-fan sediments in which it was found.

The AMS ages from the Middleton, Bauer, and Coyote Gulch sites provide insight into the history of geologically recent surface faulting at the north end of the Hurricane fault. All three sites are on Stewart and Taylor's (1996) proposed Ash Creek segment. If their proposed segment is a single seismogenic segment, the timing of surface faulting should be the same everywhere along it provided that the entire segment ruptures during large surface-faulting earthquakes. This is apparently not the case, since the timing of the MRE at Coyote Gulch, as deduced from the age of the displaced alluvial-fan deposit there is younger than 1055 to 1260 cal yr B.P., while the ages of the unfaulted deposits at the Bauer and Middleton sites fewer than 10 km to the north range from 330-525 to 1530-1710 cal yr B.P. We may discount the results from the Bauer site, because the age of the unfaulted deposits obtained there is younger than the age of the alluvial fan at Coyote Gulch and therefore the young stream-terrace deposit at the Bauer site may not have existed at the time of the most recent surface faulting on the north end of the fault. However, the unfaulted stream terrace overlying the Hurricane fault at the Middleton site is older than the Coyote Gulch alluvial fan. The AMS age obtained for the terrace came from charcoal recovered from a paleosol A horizon, and closely approximates the age of the deposit at 1530-1710 cal yr B.P. The timing of most recent surface faulting at Coyote Gulch is a maximum of 1210 cal yr B.P. (likely younger). Consequently, the Coyote Gulch and Middleton sites do not appear to have experienced the same surface-faulting history, and therefore we believe the two sites likely are not on the same seismogenic fault segment.

Murie Creek is at a bend in the Hurricane fault (figures 1 and 5). Based on the difference in timing of the most recent surface faulting at the Coyote Gulch and Middleton sites, we believe that the fault bend may represent a seismogenic segment boundary. If so, Stewart and Taylor's (1996) Ash Creek segment would extend from their proposed segment boundary near the fault bend at Anderson Junction to the bend at Murie Creek, a distance of about 33 km; would include the fault scarps at the Water Tank, Kanarraville, and Coyote Gulch sites; and would be the location of a late Holocene surface-faulting earthquake that ruptured all or part of the segment. A previously unrecognized seismogenic segment that includes the Bauer, Shurtz Creek, and Middleton sites would extend from Murie Creek to the north end of the Hurricane fault near Cedar City, a minimum distance of 20 km. This northernmost segment is short when compared to segment lengths reported for many other large normal faults in the Basin and Range Province (Schwartz and Coppersmith, 1984; Schwartz and Crone, 1985; dePolo and others, 1991; Machette and others, 1992), but is within the range of lengths documented by Machette and others (1992) for segments near the ends of the Wasatch, East Cache, East Bear Lake, Lemhi, Lost River, and Rainbow Mountain faults. The possible new seismogenic segment at the north end of the Hurricane fault is herein named the Cedar City segment (figure 1). Pending future approval from the landowner, trenching of the single- and multiple-event scarps at Coyote Gulch may provide additional collaborative information on the timing of surface faulting on the Ash Creek segment of the Hurricane fault and provide further evidence for the existence of the proposed Cedar City segment.

Long-Term Slip Rates From Displaced Basalt Flows

Previous workers have long recognized that Quaternary basalt flows are displaced across the Hurricane fault at several locations in both Utah and Arizona (Huntington and Goldthwait,1904, 1905; Gardner, 1941, 1952; Cook, 1960; Hamblin, 1963, 1970a, 1970b, 1984, 1987; Anderson and Mehnert, 1979; Anderson and Christenson, 1989). Hamblin and others (1981) used a displaced basalt flow near La Verkin, Utah (Pah Tempe Hot Springs; figure 12) to estimate vertical strain rates on the Hurricane fault. Willis and Biek (2001) used displaced basalt flows in the St. George basin to determine long-term downcutting rates at the western margin

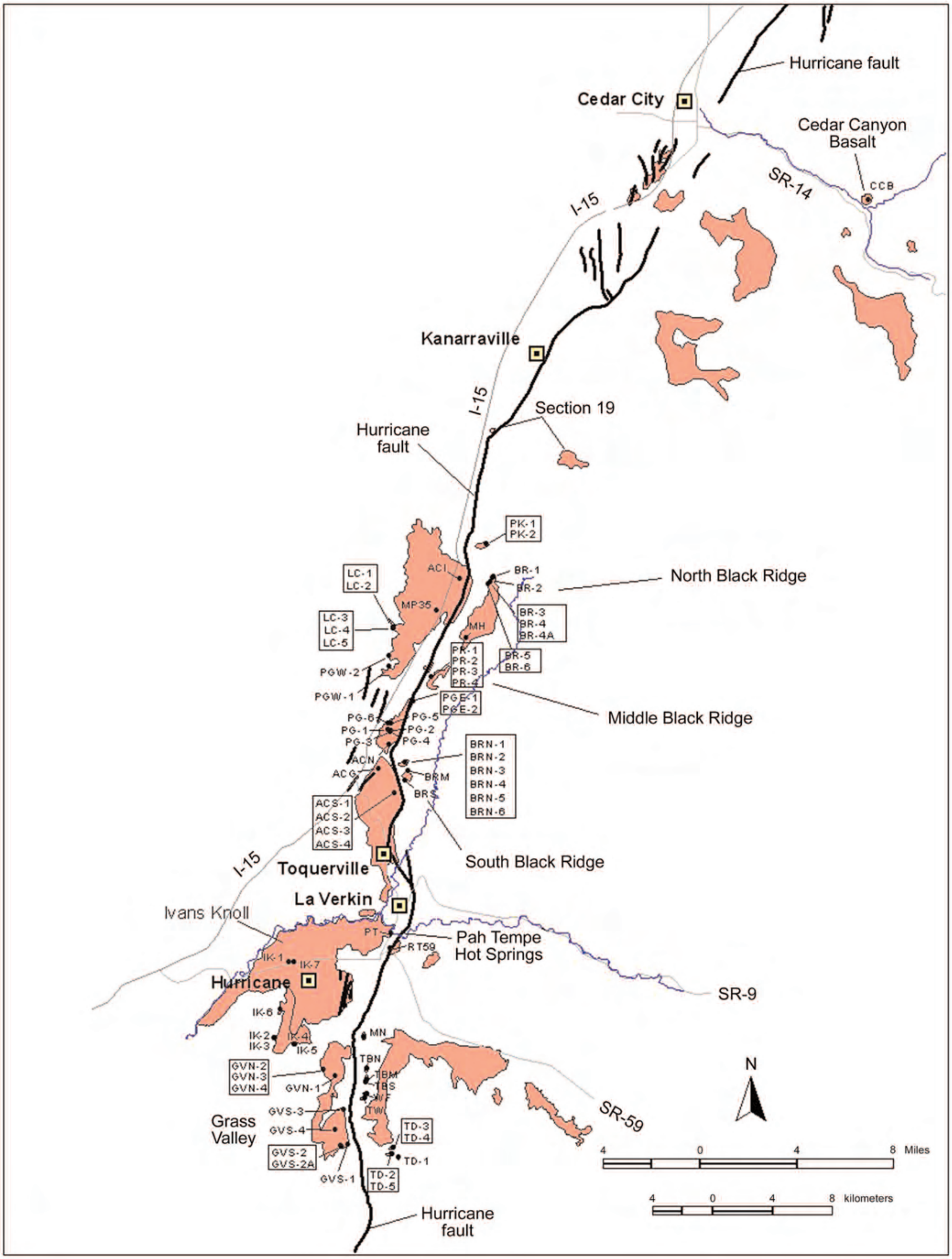


Figure 12. *Quaternary basalts (shaded areas) associated with the Hurricane fault in Utah and geochemical (appendix D), paleomagnetic (appendix E), and radiometric (table 2) sample sites.*

of the Colorado Plateau in southwestern Utah. Anderson and Mehnert (1979) calculated a preliminary slip rate for the fault just north of the Murie Creek bend (Section 19; figure 12) on the proposed Cedar City segment using a displaced flow for which they obtained K-Ar radiometric ages. At South Black Ridge near Anderson Junction (figure 12), Stewart and Taylor (1996) showed that basalt flows can be correlated across the Hurricane fault using basalt geochemistry. They did not date the basalt and thus did not calculate a vertical slip rate.

In Utah, the Hurricane fault has displaced basalt flows on the proposed Anderson Junction segment at Grass Valley near the Utah-Arizona border, between Mollies Nipple (footwall; MN on figure 12) and Ivans Knoll (hanging wall; IK on figure 12) south of the town of Hurricane (Biek, 2003), and at Pah Tempe Hot Springs between the towns of Hurricane and La Verkin (figures 1 and 12). Continuing north, the fault displaces flows at South Black Ridge at the proposed Anderson Junction-Ash Creek segment boundary (Stewart and Taylor, 1996), and on the proposed Ash Creek segment near Middle Black Ridge and at North Black Ridge (figures 1 and 12). A single displaced flow exists on the proposed Cedar City segment approximately 2 km north of Murie Creek in section 19, T. 37 S., R. 11 W. (figures 1 and 12). Finally, 12 km east of Cedar City, erosion on Coal Creek has isolated the remnant of a basalt flow high on a cliff above the stream on the north side of Cedar Canyon (figure 12). Coal Creek is graded to Cedar Valley and crosses the Hurricane fault at the mouth of Cedar Canyon. We believe that the rate of stream incision on Coal Creek is related to the rate of displacement on the Hurricane fault, which changes the base level of the stream following each surface-faulting earthquake. Therefore, the rate of stream incision provides a proxy slip rate for the Hurricane fault at Cedar City. This slip rate is considered approximate and likely a minimum value due to the contemporaneous filling of Cedar Valley as erosion proceeded, thereby lowering the stream gradient over time. The rate of incision is also affected by climate changes during the period of interest; the magnitude of the climate-controlled effects and their direction, enhancing or retarding downcutting, is not known, but we believe that they tend to generally cancel each other out over time.

We obtained long-term slip rates for the Hurricane fault using displaced basalt flows by (1) establishing definitive correlation of flows across the Hurricane fault using minor- and trace-element geochemistry and petrology (appendix D, figure 12); except in one case, we did not consider physical proximity across the fault as evidence that flows are correlative, (2) determining the age of correlative flows, and (3) evaluating the effects of near-fault deformation (backtilting and antithetic faulting) using a combination of paleomagnetic vector analysis (appendix E, figure 12) and geologic mapping to determine the net vertical displacement of the flows across the fault.

Basalt Correlation

We collected basalt samples from 59 locations along the Hurricane fault in Utah (figure 12) and submitted them to GeoAnalytical Laboratory at Washington State University for x-ray fluorescence identification of major, minor, and trace elements. We then constructed a series of variation diagrams using Ti02 , P_2O_5, Cr, Zr, Sr, and Ba (appendix D). Results of the variation analyses showed that correlative flows are present on either side of the Hurricane fault at Grass Valley North, South Black Ridge, Middle Black Ridge, and North Black Ridge (figure 12). Additionally, Biek (2003) has geochemically correlated displaced flows at Pah Tempe Hot Springs and Mollies Nipple/Ivans Knoll.

We also determined the geochemistry of two cinder cones considered potential sources for the basalt flows in the Black Ridge area (figures 5 and 12). The MP35 cinder cone is on the fault hanging wall, immediately west of Interstate 15 (I-15) at milepost 35. The Mystery Hill cone is on the fault footwall on top of Black Ridge (the Hurricane Cliffs) near Pintura. Surprisingly, the chemistries of the two cones do not correlate, nor do they correlate with any of the basalt flows in the area (appendix D). This result was unexpected and is puzzling considering that these cones are the only known volcanic sources associated with the Black Ridge basalts. Because the Mystery Hill cone is on the fault footwall at the top of the Hurricane Cliffs, flows from that source may have cascaded over the cliffs onto the fault hanging wall. If cascading occurred, but remained unrecognized due to subsequent erosion or burial, slip rates calculated using remnants of the cascaded flow on either side of the fault would overestimate the rate of past fault slip. The flows on the hanging wall along Black Ridge do not correlate geochemically with the Mystery Hill cone, precluding the possibility that we used cascaded flows from that source in our vertical slip-rate calculations. We could not identify a source for the correlative flows along Black Ridge, preserving the possibility that a volcanic cone on the fault footwall was the source of the flows. However, if that is the case, all evidence of that cone has either been removed by erosion or buried by subsequent eruptions.

We made thin sections of all of the basalt samples collected for geochemical analysis and examined them twice, once before and again after we had the geochemical results (appendix D). Following these careful examinations, we concluded that the petrographic characteristics of the basalt flows displaced by the Hurricane fault are so variable that they offered no aid or improvement to the correlations established using geochemical data.

Basalt Age Estimates

Age estimates for the basalts used in our slip-rate calculations (table 2) come from several sources (figure 12). As part of this study, we obtained $^{40}Ar/^{39}Ar$ whole-rock ages for basalts from Grass Valley North (GVN-2); South Black Ridge (ACG); the Mystery Hill volcanic cone (MH); two ages from North Black Ridge, one from the footwall (BR-1) and one from the hanging wall (ACI) of the fault (figure 12); and the flow remnant on the north side of Cedar Canyon (CCB). Hayden (2004) dated basalts in The Divide quadrangle and reported two $^{40}Ar/^{39}Ar$ whole-rock ages from the Remnants flow, one on the footwall and the other on the hanging wall of the Hurricane fault. Geochemical data (Hayden, 2004; this study) show that the Remnants flow is correlative across the fault and corresponds to our Grass Valley North basalt. Biek (2003) reported two $^{40}Ar/^{39}Ar$ whole-rock ages (VR123-11 and H11299-2) from the Ivans Knoll flow on the fault hanging wall. Sanchez (1995), as part of a study of mafic volcanism in the Colorado Plateau - Basin and

Table 2. *Radiometric ages of displaced basalt flows along the Hurricane fault in Utah (see figure 12).*

Field No.	Age	Type	Location	Section, Township, Range, SLB&M	Fault Relation	Segment	Source
GVN-2	1.47 ± 0.34 Ma	$^{40}Ar/^{39}Ar$	Grass Valley	NW1/4SW1/4NW1/4 Sec. 28, T. 42 S., R. 13 W.	Hanging Wall	Anderson Junction	This study
TD50699-1	0.94 ± 0.04 Ma	$^{40}Ar/^{39}Ar$	Grass Valley	SW1/4NE1/4SE1/4 Sec. 27, T. 42 S., R. 13 W.	Footwall	Anderson Junction	Hayden, 2004
TD11699-3	1.06 ± 0.03 Ma	$^{40}Ar/^{39}Ar$	Grass Valley	SW1/4SW1/4NW1/4 Sec. 28, T. 42 S., R. 13 W.	Hanging Wall	Anderson Junction	Hayden, 2004
VR123-11	1.03 ± 0.02 Ma	$^{40}Ar/^{39}Ar$	Ivans Knoll	NW1/4 Section 19, T. 42 S., R. 13 W.	Hanging Wall	Anderson Junction	Biek, 2003
H11299-2	0.97 ± 0.07 Ma	40Ar/39Ar	Ivans Knoll	SE1/4 Section 31, T. 41 S., R. 13 W.	Hanging Wall	Anderson Junction	Biek, 2003
Sample 6-15	353 ± 45 ka	$^{40}Ar/^{39}Ar$	Pah Tempe Hot Springs	Section 35, T. 41 S., R. 13 W.	Footwall	Anderson Junction	Sanchez, 1995
ACG	0.81 ± 0.10 Ma	^{40}Ar/39Ar	South end Black Ridge	SE1/4NW1/4NE1/4 Sec. 26, T. 40 S., R. 13 W.	Hanging Wall	Anderson Junction/ AshCreek	This study
MH	0.87 ± 0.04 Ma	$^{40}Ar/^{39}Ar$	Mystery Hill volcanic cone	NW1/4NE1/4SE1/4 Sec. 30, T. 39 S., R. 12 W.	Footwall	Ash Creek	This study
BR-1	0.84 ± 0.03 Ma	$^{40}Ar/^{39}Ar$	North end Black Ridge	NW1/4NW1/4NW1/4 Sec 16, T. 39 S., R. 12 W.	Footwall	Ash Creek	This study
ACI	0.88 ± 0.05 Ma	$^{40}Ar/^{39}Ar$	North end Black Ridge	SE1/4SE1/4SE1/4 Sec. 7, T. 39 S., R. 12 W.	Hanging Wall	Ash Creek	This study
IHH-273-1	1.09 ± 0.34 Ma	K-Ar	North Hills	NW1/4NE1/4SW1/4 Sec. 19, T. 37 S., R. 11 W.	Hanging Wall	Cedar City	Anderson and Mehnert, 1979
C-311-34	1.06 ± 0.28 Ma	K-Ar	Kolob Terrace	NE1/4SW1/4SW1/4 Sec. 21, T. 37 S., R. 11 W.	Footwall	Cedar City	Anderson and Mehnert, 1979
CCB	0.63 ± 0.10 Ma	$^{40}Ar/^{39}Ar$	Cedar Canyon	NW1/4SE1/4SW1/4 Sec. 25, T. 36 S., R. 10 W.	Footwall	Cedar City	This study

Range transition zone, reported an $^{40}Ar/^{39}Ar$ whole-rock age (sample 6-15) for basalt in the footwall of the fault near Pah Tempe Hot Springs. Anderson and Mehnert (1979) reported two K-Ar ages (IHH-273-1 and C-311-34) on apparently correlative basalt flows, one on either side of the fault at the south end of the North Hills about 2 km north of Murie Creek.

The New Mexico Geochronology Research Laboratory (NMGRL) at the New Mexico Institute of Mining and Technology performed the $^{40}Ar/^{39}Ar$ analyses for Biek (2003), Hayden (2004), and for this study. The U.S. Geological Survey Geochronology Laboratory in Denver performed the $^{40}Ar/^{39}Ar$ analysis for Sanchez (1995). No laboratory information is available for the Anderson and Mehnert (1979) K-Ar analyses.

Evaluating Near-Fault Deformation

Pronounced back-tilting of the hanging-wall block toward the footwall block is evident along the southern half of the proposed Ash Creek segment and on the Anderson Junction segment in Utah. Hamblin (1965a) referred to this phenomenon as "reverse drag" and attributed it to the listric nature of the fault plane at depth. He reported reverse drag of more than 30 degrees near the fault plane, but noted that normal drag is also common at many locations on both the hanging wall and footwall of the fault (Hamblin, 1970b). With the exception of the basalt remnant in Cedar Canyon and the displaced flow at Pah Tempe Hot Springs, the Quaternary basalt flows evaluated for this study are affected by drag folding and at some locations by antithetic faulting. The effect of the deformation typically enhances the apparent throw across the fault and must be accounted for to determine net vertical displacement.

We used two techniques to evaluate near-fault deformation where correlative basalts are displaced across the fault. The first consisted of interpretation of new 1:24,000-scale geologic mapping available for much of the Hurricane fault in Utah (Biek, 2003; Hurlow and Biek, 2003; Hayden, 2004) combined with aerial-photo analysis and field reconnaissance of critical areas. The second technique compared the orientation of magnetic vectors in correlative basalts to determine the extent to which the basalts have been affected by drag folding. Paleomagnetic analysis of basalt cores from both sides of the fault showed back-tilting ranging from <10 to 25 degrees in the hanging wall around an axis of rotation that in all cases was approximately parallel to the fault trace (appendix E).

Extrusion of lava may be accompanied by subsidence. Therefore, displacements across the Hurricane fault recorded by basalt flows may include a vertical component related to subsidence over an emptying magma chamber. We are unable to evaluate the magnitude, if any, of this component; however, if such subsidence did occur, it would result in an overestimation of net vertical displacement and ultimately in slip rates that are too high, by an unknown amount. However, considering the comparatively small volume of the basalt flows, we consider a significant affect due to subsidence over an emptying magma chamber unlikely.

Fault Slip Rates

Grass Valley: Hayden (2004) mapped the Remnants basalt flow on both the up- and downthrown sides of the Hurricane fault at the north end of Grass Valley about 7 km south of the town of Hurricane on the proposed Anderson Junction segment (figures 1 and 12). Both her geochemical data (Hayden, 2004) and ours (appendix D) confirm that the flows are correlative. She reported two $^{40}Ar/^{39}Ar$ ages for the Remnants basalt, one from the footwall and the other from the hanging wall. We obtained a third $^{40}Ar/^{39}Ar$ age from our geochemical and paleomagnetic sampling site on the hanging wall (GVN-2; figure 12). The three $^{40}Ar/^{39}Ar$ whole-rock ages are 0.94 ± 0.04 Ma, 1.06 ± 0.03 Ma, and 1.47 ± 0.34 Ma, respectively (table 2).

Paleomagnetic data from the Remnants basalt flow are highly erratic (appendix E), probably due to local remagnitization of the rock by lightning strikes, and therefore are of no use in evaluating back-tilting of the fault hanging wall. Visual examination showed that the hanging-wall basalt is tilted toward the fault, but dip measurements were difficult to obtain due to the jointed and rubbley nature of the basalt outcrops. On the hanging wall, the Remnants flow is buried by Quaternary alluvium and colluvium immediately west of the fault, further complicating our analysis of back-tilting. Hayden (2004) mapped the nearest Remnants flow outcrops in the hanging wall approximately 750 m west of the Hurricane fault. Given the above constraints, we used the elevation difference between the top of the Remnants flow on the upthrown side of the fault and the highest elevation (and least tilted basalt) on top of correlative flows on the downthrown side of the fault as a best approximation of vertical net slip. The elevation difference is 440 m.

The two-sigma confidence limits reported for the three $^{40}Ar/^{39}Ar$ ages at Grass Valley do not overlap, indicating that the three ages are discrete and non-correlative. Nevertheless, the two ages obtained by Hayden (2004) are relatively close in time (0.94 ± 0.04 Ma and 1.06 ± 0.03 Ma) and could represent a reasonable suite of ages coming from a single volcanic eruptive episode. Conversely, our age from the Remnants flow on the hanging wall (1.47 ± 0.34 Ma) is 400,000 to 500,000 years older than the Hayden (2004) ages from apparently geochemically correlative basalts. We cannot explain this difference; both the 1.06 ± 0.03 Ma and 1.47 ± 0.34 Ma ages came from the same basalt-capped hill (GVN-2; figure 12).

Because of the discrepancy in the radiometric ages, we calculated two slip rates for the Grass Valley site, the first using an average of the two Hayden (2004) ages and the second using our older age. The vertical slip rates at Grass Valley after converting net vertical displacement to millimeters are:

$$440{,}000 \text{ mm}/(0.94 + 1.06/2) \text{ Ma} = \mathbf{0.44 \text{ mm/yr}}$$

(based on the Hayden (2004) ages)

and

$$440{,}000 \text{ mm}/1.47 \text{ Ma} = \mathbf{0.30 \text{ mm/yr}}$$

(based on the age obtained from this study)

Because of the relatively close correspondence in time of the Hayden (2004) ages, we consider the slip rate calculated using her data to be the preferred rate at Grass Valley. However, due to the imprecise nature of the correlation of the Remnants flow across the Hurricane fault (see above), we consider the Grass Valley slip rate to contain a high degree of uncertainty, and therefore to only approximate the long-term vertical slip rate at this location.

Ivans Knoll - Mollies Nipple: Although Biek (2003) showed that the flows at Mollies Nipple on the fault footwall and at Ivans Knoll on the hanging wall are geochemically correlative and obtained two $^{40}Ar/^{39}Ar$ ages for the Ivans Knoll flow (see table 2), we were unable to reliably constrain the net vertical displacement across the fault at this location and therefore did not make a vertical slip-rate estimate.

Pah Tempe Hot Springs: Hot water rising along the Hurricane fault creates Pah Tempe Hot Springs at the mouth of Timpoweap Canyon where the Virgin River cuts through the Hurricane Cliffs between the towns of Hurricane and La Verkin, Utah (figure 12). This site is on the proposed Anderson Junction segment, and Biek (2003) mapped a basalt flow displaced by the Hurricane fault at the canyon mouth. The flow ponded in an embayment at the base of the Hurricane Cliffs and was later displaced by subsequent fault movement. In the fault footwall, the flow now occupies an intermediate position part way up the cliff. The flow is displaced 73 m down-to-the-west, and the geologic relation between the basalt on the cliff face and the basalt at the base of the cliffs is unequivocal. Additionally, Biek (2003) has demonstrated that the flow is geochemically correlative across the fault.

Paleomagnetic data collected from the Pah Tempe basalt flow on either side of the Hurricane fault (figure 12) show normal magnetization, and indicate that the hanging wall is tilted less than 10 degrees toward the fault, if it is tilted at all (appendix E). Visual examination confirms a lack of discernable back-tilting except in a very narrow zone immediately adjacent to the fault. The 73 m difference in elevation between the basalt in the footwall and in the hanging wall was measured outside of the deformation zone.

Sanchez (1995) obtained an $^{40}Ar/^{39}Ar$ whole-rock age of 353 ± 45 ka for the basalt in the fault footwall (table 2). This flow was previously dated by Best and others (1980) at 289 ± 86 ka using the K-Ar dating method. For our analysis, we used the Sanchez (1995) $^{40}Ar/^{39}Ar$ age, considering the newer dating technique both more accurate and more precise.

The vertical slip rate at Pah Tempe Hot Springs for the past 353,000 years after converting net vertical displacement to millimeters is:

$$73{,}000 \text{ mm}/353{,}000 \text{ yr} = \mathbf{0.21 \text{ mm/yr}}$$

The Pah Tempe vertical slip rate is approximately one-half of the preferred slip rate at Grass Valley. The difference between the two sites may represent a difference in long-term vertical slip rates on two independent fault segments, with a presently unrecognized segment boundary between them. However, based on new geologic mapping by Biek (2003), we consider the presence of an unrecognized seismogenic boundary along this part of the Hurricane fault unlikely. Slip along a seismogenic segment can vary both temporally and spatially (Wallace, 1985; Nelson and Personius, 1993). The fact that the displaced basalt flow at Pah Tempe Hot Springs is only about one-third the age of the basalt at Grass Valley, leads us to believe that the lower slip rate at Pah Tempe Hot Springs is chiefly the result of a slowing of slip on the Hurricane fault in more recent geologic time, rather than a difference in slip based on location along the fault.

South Black Ridge: The Hurricane fault makes a pronounced bend at the south end of Black Ridge near Toquerville (figure 12). Stewart and Taylor (1996) identified the bend as a structural segment boundary and also proposed it as a possible seismogenic segment boundary. The Hurricane fault displaces a stack of basalt cooling units (chemically similar flows that share a common cooling history, most likely a common source, and which were extruded rapidly enough that there are no weathering zones or sedimentary deposits between the individual units; G.C. Willis, Utah Geological Survey, verbal communication, 1999) more than 360 m down-to-the-west at the bend (Schramm, 1994; Hurlow and Biek, 2003; figure 12). Geochemical data (Schramm, 1994; this study appendix D) show that the basalts on the footwall and hanging wall are correlative.

The flows at this site exhibit reverse magnetization and are magnetically indistinguishable from other basalt flows found on both sides of the fault along the entire length of Black Ridge. Paleomagnetic vector analysis of basalts on the hanging wall and footwall documents 25 degrees of backtilting toward the fault around a northeasterly trending axis, and little or no tilting of the footwall basalt (appendix E). The axis of rotation in the hanging wall approximately parallels the strike of the fault. Visual examination and dip measurements of the basalts on the hanging wall showed a pronounced tilt toward the fault in a relatively narrow zone–a few hundred meters wide–adjacent to the fault. Basalts west of the zone of back-tilting dip as much as 7 degrees toward the fault, but those dips closely mimic the slope of the alluvial-fan surfaces at the base of the Pine Valley Mountains on which the flows were extruded.

During our field reconnaissance, we recognized a zone of relatively small-displacement synthetic and antithetic faults in the basalts and alluvial-fan units on the hanging wall of the Hurricane fault both at, and extending north from, Anderson Junction. Since the predominant sense of movement across the faults is down-to-the-east, they form the west side of a graben along the Hurricane fault, which is herein named the Ash Creek graben (figure 5). Hurlow and Biek (2003) mapped these faults in more detail in the Pintura 7.5′ quadrangle, which includes the South Black Ridge basalt locality. The graben defines a zone of extensional stress along the axis of an asymmetric anticline created by reverse-drag folding in the Hurricane fault hanging wall. Dip measurements in the basalt confirm the presence of the anticline, the axis of which defines the western limit of pronounced back-tilting of the hanging wall toward the Hurricane fault.

We sampled the uppermost basalt cooling unit on the hanging wall of the fault at the base of the Black Ridge (Hurricane Cliffs) directly below the basalt outcrops on the footwall (ACG, figure 12). The basalt yielded an $^{40}Ar/^{39}Ar$ whole-rock age of 0.81 ± 0.1 Ma.

The highest basalt elevation west of the zone of back-tilting at South Black Ridge is approximately 1217 m. The highest elevation on top of the correlative basalt on the fault footwall is approximately 1585 m. Therefore, for the vertical slip-rate calculation at this site, we chose to use the difference in elevation between the highest basalt outcrop west of the zone of near-fault deformation on the hanging wall and the highest outcrop on the footwall as our value for net slip; that elevation difference is 368 m.

The vertical slip rate at South Black Ridge for the past 810,000 years after converting net vertical displacement to millimeters is:

368,000 mm/810,000 yr = **0.45 mm/yr**

Because this slip rate is at a structural and possibly seismogenic fault boundary (Stewart and Taylor, 1996), its relation to the long-term slip history of the proposed fault segments on either side of the boundary is unknown.

Middle Black Ridge: Anderson and Mehnert (1979) report a slip rate of 1550 feet per million years (0.47 mm/yr) from displaced basalts "*at about latitude 37°20′ N.*" based on the fact that "*A K-Ar age determination on basalt from the upthrown block indicates an age of about 1 m.y.*" (reported as M.G. Best, Brigham Young University, written communication, 1978). Latitude 37°20′ N. is at about the mid-point of Black Ridge on the proposed Ash Creek segment (figure 12). There, a stack of several basalt cooling units occupies a reentrant in the fault footwall high on the cliff face above the town. No corresponding basalt is exposed on the hanging wall at this location, but a similar-appearing basalt outcrop is juxtaposed against the fault on the hanging wall about a kilometer south of Pintura. We originally thought that these two stacks of basalt cooling units, while not in direct physical proximity across the fault, were likely correlative. However, geochemical data (appendix D) showed that this is not the case.

Based on Anderson and Mehnert's (1979) reported location and the 1550 feet (472 m) of vertical separation between the two outcrops, we conclude that these are the basalts they used for their slip-rate calculation. However, since the footwall and hanging-wall basalts are not correlative, they cannot be used to determine a slip rate for the Hurricane fault. While it is possible that Best did date the basalts above Pintura as reported in Anderson and Mehnert (1979), his only published K-Ar age from Black Ridge (1.0 ± 0.1 Ma; Best and others, 1980) came from near the north end of the ridge and not from the flows above Pintura.

Our geochemical data (appendix D) show that the lower and intermediate flows in the footwall cooling unit sequence in the cliff face above Pintura are correlative with the lower two flows in a group of five cooling units exposed in the incised channel of Leap Creek at the base of the Pine Valley Mountains in the fault hanging wall (figures 5 and 12). The Leap Creek exposure is approximately 2.5 km west of the Pintura outcrops. Paleomagnetic data (appendix E) show that the flows at Leap Creek are outside the zone of back-tilting near the fault. The elevation difference between the flows we sampled for geochemistry on the fault footwall and the correlative flows at Leap Creek is approximately 300 m. We consider this to be a minimum displacement because the flows at Leap Creek originally ponded at the base of the Pine Valley Mountains until they overtopped whatever barrier was confining them next to the mountain. They then flowed downhill to the east and are now buried by younger alluvial deposits near the fault. The absence of geochemically correlative outcrops close to the fault makes it impossible to evaluate the effects of near-fault deformation and therefore we were unable to determine net vertical displacement at this location.

North Black Ridge: Basalt flows are present on both sides of the Hurricane fault at the north end of Black Ridge near I-15 Exit 36 (figure 12). This location is at about the midpoint of the proposed Ash Creek fault segment. Geochemical data (appendix D) show that the basalt flows here are correlative across the fault. We sampled the basalts on both the footwall and the hanging wall (table 2) and obtained $^{40}Ar/^{39}Ar$ age estimates of 0.84 ± 0.03 Ma and 0.88 ± 0.05 Ma, respectively. The two-sigma uncertainties reported for these ages overlap, and the NMGRL indicated that the two ages are analytically indistinguishable (Lisa Peters, NMGRL, written communication, 1998).

The flows exhibit reverse magnetization (appendix E) and are magnetically indistinguishable from other basalt flows found along Black Ridge. The orientation of magnetic vectors in the footwall and hanging-wall basalts document 10 degrees of backtilting toward the fault in the hanging wall around a northeasterly trending axis. There is little or no indication of tilting of the basalt in the footwall. Visual examination of the basalt in the hanging wall showed that the zone of near-fault deformation is relatively narrow (a few hundred meters). Within a short distance west of I-15, the dip of the basalt toward the fault is generally less than 3 degrees and is attributed to the slope of the ground surface over which the basalt flowed.

The basalt west of I-15 is displaced by a number of small synthetic and antithetic faults (Grant, 1995; this study). Total displacement across these faults ranges from a few meters to possibly as much as 10 m. However, the faults generally form opposite pairs that create small grabens; therefore, we consider the net vertical displacement across this zone of secondary faulting minimal and of little effect on our vertical slip-rate calculation.

The zone of near-fault deformation associated with the Hurricane fault at North Black Ridge is relatively narrow - a few hundred meters at most. Therefore, on the hanging wall, we chose a basalt location at an elevation of 1475 m which, based on paleomagnetic analysis, visual observation, and dip measurements is clearly west of the zone of near-fault deformation. We then projected the basalt from that point at a 3 degree dip for approximately 200 m to the estimated location of the Hurricane fault, which at this location is buried by young landslide deposits. The resulting elevation of the basalt in the hanging wall at the Hurricane fault is 1465 m. Using that elevation and an elevation of 1951 m on top of the basalt in the footwall results in a net vertical displacement across the fault of 486 m.

The vertical slip rate at North Black Ridge for the past 860,000 years after converting net vertical displacement to millimeters is:

$$486{,}000 \text{ mm}/860{,}000 \text{ yr} = \mathbf{0.57\ mm/yr}$$

Section 19 Site: Based on his mapping of basalt outcrops in the hanging wall of the Hurricane fault at the south end of the North Hills (SE¼NW¼ sections 19, T. 37 S., R. 11 W.; figures 1 and 12), and also of several small basalt remnants in the fault footwall to the east, Averitt (1962, 1967) concluded that basalt lava poured down a steep valley in the Hurricane Cliffs from a source on top of the cliffs to the base of the cliffs. Threet (1963) considered the basalts in the footwall and hanging wall correlative and concluded that they present negative evidence for major displacement on the Hurricane fault since the time the basalt was extruded.

Based on their mapping in the North Hills and a re-examination of Averitt's (1967) mapping in the nearby Hurricane Cliffs, Anderson and Mehnert (1979) concluded that Averitt's basalt remnants are in fact basalt-bearing colluvium and alluvium, and therefore should not be used to infer that the basalt poured down the Hurricane Cliffs to the present cliff base. Anderson and Mehnert (1979) believe that the basalt in section 19 was displaced by the Hurricane fault a minimum of 1300 feet (400 m) down-to-the-west to its present elevation of 6200 feet (1895 m). Anderson and Mehnert (1979) did not explicitly state the elevation of in-place basalt in the fault footwall used for their slip-rate calculation, but adding their net-displacement value to the elevation of the basalt outcrop in the hanging wall (1300 ft + 6200 ft) equals 7500 feet (2295 m). Based on our field reconnaissance, we believe that the lowest elevation of unequivocally in-place basalt in the fault footwall is presently 2440 m (8000 ft).

Anderson and Mehnert (1979) obtained K-Ar ages of 1.06 ± 0.28 Ma and 1.09 ± 0.34 Ma (table 2) for the basalt in the fault footwall and hanging wall, respectively. Using their age estimates and net vertical-displacement value, we calculated a vertical slip rate for the past 1.08 million years (1.06 Ma + 1.09 Ma/2) of 0.37 mm/yr. Using our preferred elevation of in-place basalt in the fault footwall results in a net-vertical-displacement value of 549 m (1800 ft) and a vertical slip rate for the Hurricane fault over the past 1.08 million years of 0.51 mm/yr.

The Section 19 basalts are the only likely correlative basalt flow displaced across the proposed Cedar City section of the Hurricane fault. Based on our field reconnaissance, we agree with Anderson and Mehnert's (1979) interpretation that the Section 19 basalts originated from a cinder cone on top of the Hurricane Cliffs and cascaded part way down the cliff face before being displaced by subsequent faulting. However, how far down the cliff the basalt traveled prior to faulting remains unresolved. Following an examination of the basalt boulder and cobble deposits below an elevation of 2440 m that Averitt (1962) mapped as in-place basalt and Anderson and Mehnert (1979) believe are colluvial and alluvial deposits, we are uncertain what they represent. Some likely are colluvial, but in at least one instance, although of limited extent and highly weathered, the basalt debris has the appearance of a lag deposit remaining following the erosion of a thin basalt flow. The blocks are angular and many appear to be in an upright and orderly position as if separated by joints. The resulting uncertainty regarding the location of the basalt on the cliff face prior to faulting prevented us from making an accurate determination of net vertical displacement. Therefore, we chose not to do additional work (geochemical and geomagnetic sampling) at the Section 19 site. Given the available evidence, we believe a "best estimate" for a long-term vertical slip rate at the Section 19 locality is **0.37 - 0.51 mm/yr**.

Cedar Canyon: Twelve kilometers east of Cedar City in the footwall of the Hurricane fault, erosion on Coal Creek has left a basalt remnant isolated high on a cliff above the stream on the north side of Cedar Canyon (SE¼SW¼ section 25,T. 36 S., R. 10 W; figure 12). Coal Creek is graded to Cedar Valley and crosses the Hurricane fault at the mouth of Cedar Canyon. We believe that the rate of downcutting on Coal Creek is related to the rate of displacement on the Hurricane fault, which changes the stream's base level following each surface-faulting earthquake. Hamblin and others (1981) made a study of late Cenozoic basalts displaced by recurrent movement on fault systems in the western Colorado Plateau. They found that the rate of downcutting of displaced basalts upstream from the faults is largely a function of the rate (amount) of uplift, and that streams readjust to equilibrium conditions following a surface-faulting event almost instantaneously in a geologic time frame. Therefore, we believe the rate of stream downcutting on Coal Creek provides a proxy vertical slip rate for the Hurricane fault at Cedar City. However, because Cedar Valley is a closed basin, this slip rate is likely a minimum value due to the simultaneous filling of the valley with sediment as erosion proceeds and the stream re-establishes equilibrium. Accumulation of sediment in the valley between surface-faulting earthquakes tends to raise the stream's base level, thus slowing the rate of channel downcutting from the maximum it would achieve if sediment were being transported away by a through-going drainage system. A remaining unknown is the effect of climate on channel downcutting rates since the basalt flow displaced Coal Creek. Hamblin and others (1981) noted that the effects of Quaternary climatic change are superimposed on the tectonic perturbations along active faults, and that climate change serves to vary the rate of channel downcutting. We believe that climate change has served both to accelerate and retard downcutting on Coal Creek at different times in the past, and that over time, those changes generally tend to cancel each other out.

Previous workers have typically placed the northern terminus of the Hurricane fault at Cedar City (Huntington and Goldthwait,1904, 1905; Gardner, 1941, 1952; Averitt,1964; Hamblin, 1965b; Anderson and Mehnert, 1979; Anderson and Christenson, 1989, Hecker, 1993). North of Cedar City the fault is thought to transition into the Cedar City-Parowan monocline, a large, active fold that defines the western edge of the Markagunt Plateau for an additional 30 km to the north. Near Parowan, the monocline transitions into the Paragonah fault (Anderson and Christenson, 1989; Hecker, 1993). However, based on detailed geologic mapping and new geophysical information, Maldonado and others (1997) show the Hurricane fault making a sharp left bend at Cedar City toward Cedar Valley where it connects in the subsurface with other faults that continue to the north. A regional gravity survey of the northern Hurricane fault and Iron Springs mining district (Cook and Hardman, 1967) shows large negative gravity anomalies west of the fault in Cedar Valley, implying that down-to-the-west displacement across the Hurricane fault has formed deep, alluvium-filled basins over its hanging wall. We interpret these basins as evidence for large, perhaps maximum, displacement across the Hurricane fault. Such large displacement seems incompatible with the termination of the Hurricane fault at Cedar City, since faults seldom end abruptly where their displacement is large. Whatever the situation regarding the termination or northward extension of the Hurricane fault, displacement at the mouth of Cedar Canyon is significant, probably several hundred meters or more. Such large displacement is indicative of either a high vertical slip rate, or faulting over a long period of time. Little is known about how or where the Hurricane fault initiated or how it has grown and propagated, but if it began in the north and propagated to the south, displacement would likely be greatest in the north where it has been active the longest.

We sampled the basalt in Cedar Canyon for both geochemistry and $^{40}Ar/^{39}Ar$ age analysis. Because the basalt remnant is 12 km east of the Hurricane fault and well outside the influence of near-fault deformation in the fault footwall, back-tilting is not an issue. The basalt flow (possibly two stacked flows) occupies a narrow paleovalley in Cretaceous sedimentary bedrock and rests directly on paleochannel deposits of ancestral Coal Creek. Diverted from its course by the basalt, Coal Creek eroded the Cretaceous sandstone adjacent to the basalt, and now occupies a new channel 335 m below its former channel. Geochemical data show that the basalt remnant is unrelated to any of the other basalt flows we have analyzed along the Hurricane fault (appendix D). We obtained an $^{40}Ar/^{39}Ar$ age of 0.63 ± 0.10 Ma on a sample collected just above the flow contact with the underlying paleochannel deposits (table 2).

After converting net vertical displacement to millimeters, the rate of downcutting by Coal Creek provides an approximate late Quaternary vertical slip rate for the Hurricane fault of:

335,000 mm/630,000 yr = **0.53 mm/yr**

Although likely a minimum value, this slip rate is generally comparable with the other late Quaternary vertical slip rates obtained from displaced basalts north of the proposed seismogenic boundary between the Anderson Junction and Ash Creek segments at South Black Ridge.

Discussion

The slip rates obtained from displaced basalt flows in Utah represent the best constrained long-term, vertical-slip-rate data presently available for the Hurricane fault. We calculated slip rates only where basalt flows could be shown to correlate across the fault, and we attempted to account for near-fault deformation when determining net-vertical-displacement values. Nevertheless, our reported vertical slip rates still have uncertainties associated with them. The nature and possible magnitude of those uncertainties are discussed below.

Open versus closed slip rates: Vertical slip rates on dip-slip faults developed through paleoseismic studies are of two types: "closed" and "open." Closed slip rates are calculated over a closed seismic cycle–a period of time bounded by surface-faulting earthquakes and for which the net vertical displacement that occurred during that time period can be accurately determined . Closed slip rates represent the rate of vertical displacement on a fault for a specific time interval, typically a few hundred to several thousands of years. Where we can determine multiple closed slip rates, they can be used to show changes in the rate of slip over time, or can be averaged to provide a composite long-term slip rate. Closed slip rates are preferred for evaluating the slip history of a fault; however, due to limitations related to depth of trenching and Quaternary dating techniques, we rarely can obtain closed slip rates that extend beyond the Holocene.

Open slip rates may span one to many seismic cycles and are not constrained by the ages of the first earthquake or the most recent earthquake of the sequence. The long-term vertical slip rates developed in this study from basalt flows displaced across the Hurricane fault are open slip rates. The age of the basalts and the size of their displacements are known, but the time interval between extrusion of the basalt flows and the first surface-faulting earthquake to displace them is unknown as is the elapsed time since the most recent surface-faulting earthquake. Therefore, our slip rates determined from displaced basalts are minimum values, because the time period over which the displacements occurred is less than the age of the basalts by some unknown amount; in other words, we are dividing the net vertical displacement recorded by the basalt flows by too much time, which results in a vertical slip rate that is correspondingly too small.

The time interval between the first and last surface-faulting earthquakes (closed seismic cycle) that displaced the basalt flows cannot be quantified, so uncertainty exists regarding the magnitude of the difference between our open slip rates and the true slip rates, which are higher by an unknown amount. However, considering the long time intervals over which the slip rates are measured (hundreds of thousands to more than a million years), the uncertainties associated with the basalt ages, and the recurrence intervals typically associated with normal faults in the Basin and Range Province (several thousand to several tens of thousands years; also see Surface-Faulting Recurrence discussion below), we believe that the problem of open seismic cycles is small by comparison with the total time period of interest. Therefore, with the possible exception of the young flows at Pah Tempe Hot Springs, we believe uncertainty in our long-term slip rates due to the discrepancy between the age of the basalt and the actual period of time over which the net vertical displacement occurred (less than the age of the basalt) is less than 0.01 mm/yr. Because of the relatively young age of the basalt at Pah Tempe Hot Springs, we have assigned an uncertainty of ±0.01 mm/yr to the vertical slip rate determined at that location.

Net-vertical-displacement measurements: Uncertainties associated with our net-vertical-displacement measurements include (1) measuring net-vertical displacement using 1:24,000-scale topographic maps, (2) determining "equivalent" points on displaced basalt flows between which to make vertical displacement measurements, and (3) evaluating and removing the effects of near-fault deformation.

Where available, we used new 1:24,000-scale UGS geologic mapping on U.S. Geological Survey (USGS) 1:24,000-scale topographic base maps to determine the net vertical displacement between correlative basalt flows on either side of the Hurricane fault. Where new mapping wasn't available, we used 1:24,000-scale topographic maps to make our measurements. Making net-vertical-displacement measurements required identifying correlative points on either side of the fault and then interpolating between contour lines to determine their difference in elevation. The contour intervals of the maps ranged between 20 and 80 feet (~6-25 m). We believe that all of our measurements were made with a minimum accuracy of one-half contour interval and therefore, the associated uncertainties are approximately 3 to 12 m, depending on the contour interval of the applicable map. Because interpolation errors can be either positive or negative, they tend to cancel each other and we believe the interpolation process did not introduce significant uncertainty in our net-vertical-displacement measurements. However, because we can only reliably determine elevations from topographic maps to the nearest one-half contour interval, we consider our net-vertical-slip values to have an accuracy of one contour interval (one-half interval each on the up- and downthrown sides of the fault). Varying the net-vertical-displacement measurements by the equivalent of one contour interval showed that our slip-rate values only changed by ±0.02 mm/yr or less.

Establishing equivalent points on displaced basalt flows from which to make net-vertical-displacement measurements across the Hurricane fault was difficult. The "flows" displaced by the fault and correlated on the basis of their geochemistry most likely represent multiple, geochemically similar cooling units erupted from the same magma source over a geologically short time period. Therefore, our geochemical correlations likely do not represent the correlation of individual cooling units. However, we believe that the close vertical proximity and thin (usually a few meters) nature of the cooling units on either side of the fault introduces no more than ±10 m of error in our net-vertical-displacement measurements in the worst case, and less than that at most of our long-term vertical slip-rate sites. The resulting uncertainty amounts to less than ±0.01 mm/yr. A potentially larger error is related to accuracy of locating equivalent points on topographic maps where terrain is steep. In areas where the contours are close together (Grass Valley, South Black Ridge, and Cedar Canyon), a small horizontal error in locating a point can result in a large vertical error. We estimate such errors could be as large as one contour interval, and may affect our vertical-slip-rate calculations by as much as 0.02 mm/yr.

Characterizing near-fault deformation affecting the hanging-wall basalts at Pah Tempe Hot Springs, South Black Ridge, and Cedar Canyon was relatively straightforward. We believe that uncertainties associated with those determinations had little or no effect on the vertical slip rates calculated for those sites. At Grass Valley, correlative basalts close to the fault in the hanging wall are buried by younger alluvial and colluvial deposits. At North Black Ridge, the Hurricane fault is buried by young landslide and talus deposits. The assumptions we made regarding the location of the fault at North Black Ridge and the amount of net vertical displacement across the fault at Grass Valley add uncertainty to our slip-rate values. We believe the assumptions at both sites were reasonable and conservative (see discussions above), but admit that they cannot be rigorously quantified. We estimate that the level of uncertainty at both sites does not exceed ±0.05 mm/yr, and probably does not exceed ±0.01 mm/yr at the other three sites.

A special case exists at Cedar Canyon, where the rate of stream incision on Coal Creek provides a proxy slip rate for the Hurricane fault. We believe that this proxy rate is a minimum value, because as Coal Creek responds to changes in its base level produced by surface faulting and begins to erode headward, it also deposits sediment in Cedar Valley, which is a closed basin. As Cedar Valley fills, it raises the stream's base level and correspondingly slows the rate of stream incision. The approximate vertical slip rate obtained from Cedar Canyon represents a balance between changes in stream base level resulting from surface faulting on the Hurricane fault and the subsequent filling of Cedar Valley. The rate of valley filling is unknown, but is thought to be small. We have assigned an uncertainty value of ±0.01 mm/yr to our Cedar Canyon slip rate to account for uncertainty associated with the equilibrium achieved between increased incision due to surface faulting and slower downcutting produced by valley filling. We believe, as do Hamblin and others (1981), that climate change produces variations in the rate of stream downcutting through time. We believe that those changes have served to both increase and decrease the rate of stream incision during different time periods and therefore tend to cancel each other out.

Basalt age two-sigma uncertainty limits: Table 2 presents the basalt ages used in this study and their associated two-sigma uncertainty limits. Uncertainty for the $^{40}Ar/^{39}Ar$ ages ranges from ±0.03 to ±0.1 million years. Uncertainty assigned to the older K-Ar ages ranges from ±0.28 to ±0.34 million years. We used the reported (preferred) ages of the basalts for our vertical-slip-rate calculations, and consequently report our slip rates as a single value rather than as a range of values. Incorporating the two-sigma uncertainty limits shows that slip rates calculated using $^{40}Ar/^{39}Ar$ ages can vary between ±0.01 and ±0.03 mm/yr depending on the magnitude of the reported uncertainty and the age of the basalt. The range can be as much as ±0.20 mm/yr at the Section 19 site because the two-sigma uncertainty limits for the K-Ar ages there are correspondingly greater.

Assigning composite uncertainty limits: Assigning composite uncertainty limits to complex, non-linear natural geologic processes and relations cannot be accomplished in a rigorously quantitative manner. The discussion presented above of the uncertainties associated with the long-term slip rates we obtained from displaced basalt flows along the Hurricane fault shows that, with the exception of the two-sigma uncertainty limits assigned to the basalt radiometric ages, quantification of uncertainty is made on a "best estimate" basis. Table 3 summarizes our evaluation of the uncertainties associated with each of our long-term slip-rate sites and presents our "best estimate" of the uncertainty limits that should be assigned to each slip-rate value.

Surface-Faulting Recurrence

The long-term, vertical slip rates reported in this study (table 4) are based on correlated and dated basalt flows, from which we have removed, to the extent possible, the effects of near-fault deformation to ensure that the vertical slip rates reflect true net vertical displacement across the fault over the time periods represented by the basalt flows. The locations of correlative flows along the Hurricane fault are entirely a matter of chance. As a result, we obtained two long-term slip rates from the proposed Anderson Junction segment (Grass Valley and Pah Tempe Hot Springs), one at the proposed boundary between the Anderson Junction and Ash Creek segments (South Black Ridge), one from the Ash Creek segment (North Black Ridge), and a proxy slip rate from Cedar Canyon for the proposed Cedar City segment. Additionally, we discovered that the basalt outcrops near the midpoint of Black Ridge likely used by Anderson and Mehnert (1979) to estimate slip across the Hurricane fault are not correlative. We also examined the only basalt flow displaced across the proposed Cedar City segment (Section 19 site), but could not determine the net vertical displacement there with sufficient accuracy to improve on Anderson and Mehnert's (1979) estimated slip rate at that location. Similarly, we could not adequately constrain the net vertical displacement across the fault on the Ivans Knoll flow between Ivans Knoll and Mollies Nipple, so we could not make a slip-rate estimate at that location.

The slip rates at Grass Valley and at both the south and north ends of Black Ridge characterize activity on the Hurricane fault since the early Quaternary (table 4). The displaced basalt at Pah Tempe Hot Springs is younger (353 kyr) and the slip rate there reflects fault activity in middle to late Quaternary time. The basalt remnant in Cedar Canyon is intermediate in age (0.63 Ma) and gives a proxy slip rate at the north end of the fault for the middle to late Quaternary, although the time frame is nearly twice that at Pah Tempe Hot Springs. Our vertical-slip-rate data remain sparse for a fault as long and complex as the Hurricane; however, we now have at least one long-term slip rate for all three proposed fault segments in Utah. Those rates cover a wide range of time intervals, and provide insight into the slip history of the Utah part of the Hurricane fault over the past approximately one million years.

Anderson and Mehnert (1979) contrasted the evidence for recent surface faulting (scarps formed on geologically young deposits) between the Hurricane and Wasatch faults, and concluded that little evidence exists for latest Pleistocene-Holocene surface faulting along the Utah part of the Hurricane fault. Anderson and Christenson (1989) made a similar comparison, and while they did not preclude the possibility of young surface faulting, they concluded that it has probably been longer than 10,000 years since the last surface-faulting earthquake on the Utah part of the fault. The field reconnaissance conducted for this study resulted in the discovery of several previously unknown fault scarps formed on alluvial and colluvial deposits, but even with the addition of those scarps, the evidence for repeated, large surface-faulting earthquakes on the Hurricane fault in the recent geologic past remains meager. Only one of the newly discovered scarps likely dates from the Holocene.

The general lack of evidence for geologically young surface faulting along the Ash Creek and Anderson Junction segments is puzzling, since we can document at least one Holocene surface-faulting earthquake on each segment. Possible reasons for the lack of young scarps include (1) characteristic earthquakes in the M 6.6-6.9 range, which produce comparatively small surface displacements, (2) evidence for lower slip rates (<0.2 mm/yr) in more recent geologic time (see Shurtz Creek discussion above), which results in longer

Table 3. Best-estimate uncertainty limits associated with long-term vertical slip rates developed from displaced basalt flows along the Hurricane fault in Utah.

Long-Term Slip-Rate Sites	Slip-Rate (mm/yr)	Estimated Uncertainty (mm/yr)			Cumulative Uncertainty
		Open vs. Actual Slip Rate	Net Displacement	Two-Sigma Uncertainty	
Grass Valley	0.44	<0.01	±0.07	±0.02	±0.09
Pah Tempe	0.21	+0.01[1]	—	±0.03	±0.04
S. Black Ridge	0.45	<0.01	±0.03	±0.01	±0.04
Section 19	0.37 - 0.51	<0.01	±0.05	±0.14 - ±2.0	±0.19 - ±0.25
Cedar Canyon	0.53	<0.01	±0.03	±0.01	±0.04

[1]Because of the comparatively young age of the Pah Tempe Hot Springs basalt, we assigned an uncertainty of ±0.01 mm/yr to the vertical slip rate at that location.

Table 4. Vertical slip rates derived from displaced basalt flows along the Utah portion of the Hurricane fault.

Location	Slip Rate mm/yr	Basalt Age Ma	Segment	Comments
Grass Valley	0.44	1.0	AJ	Based on Hayden (2004) $^{40}Ar/^{39}Ar$ ages
Pah Tempe	0.21	0.353	AJ	—
S. Black Ridge	0.45	0.81	AJ/AC	At proposed segment boundary
N. Black Ridge	0.57	0.86	AC	—
Section 19	0.37 - 0.51	1.08	CC	From Anderson and Mehnert (1979)
Cedar Canyon	0.53	0.63	CC	Surrogate rate - stream downcutting

recurrence intervals between surface-faulting earthquakes and provides more time for scarp erosion and burial, (3) the presence in many areas along the fault of easily eroded bedrock units (Anderson and Christenson, 1989), which permits rapid burial of scarps at the base of the Hurricane Cliffs, and (4) faulting confined to bedrock or at the bedrock contact with unconsolidated deposits where scarps are difficult to detect or are rapidly buried, rather than in the unconsolidated basin-fill deposits at the cliff base.

Comparison of long-term, vertical slip-rate data developed from displaced basalt flows during this study with vertical-slip-rate data available for displaced late Pleistocene and Holocene alluvial and colluvial deposits along the fault in Utah and northern Arizona (Stenner and others, 1999) shows that the long-term slip rates are higher than those for the shorter time intervals (0.21- 0.57 mm/yr versus < 0.1 - 0.4 mm/yr). The difference is even more pronounced if the vertical slip rate from Pah Tempe Hot Springs (0.21 mm/yr) is not included with the vertical slip rates derived from the older basalt flows (0.44-0.57 mm/yr). Cosmogenic isotope ages and soil-profile data indicate that the displaced alluvial surface at Shurtz Creek on the proposed Cedar City segment is between 30,000 and 100,000 years old. Net vertical displacement across the scarp is a minimum of 12 m, resulting in a late Quaternary slip rate of 0.12-0.40 mm/yr, with a preferred vertical slip rate of 0.18 mm/yr. Stenner and others (1999) profiled several scarps formed on unconsolidated deposits along the southern part of the proposed Anderson Junction segment in Arizona, and documented slip rates ranging from >0.1 to 0.3 mm/yr. Their estimated ages for the displaced surfaces range from 8,000-15,000 to 70,000-125,000 years, respectively, demonstrating that the rate of slip has also decreased significantly along the Arizona part of the Anderson Junction segment.

Information on displacements produced by surface-faulting earthquakes on the Hurricane fault is limited. Stenner and others (1999) trenched a small scarp formed on a young (estimated 8-15 ka) alluvial terrace at Cottonwood Canyon (figure 5) on the southern Anderson Junction segment about 10 km south of the Utah-Arizona border. Additionally, Stenner and others (2003) excavated a trench across a single fault scarp formed on an alluvial fan at Rock Canyon, approximately 4 km south of Cottonwood Canyon. The Cottonwood Canyon trench exposed evidence for a single surface-faulting earthquake that produced 0.6 m of net vertical displacement in the terrace deposits. Stenner and others (1999) consider the displacement at Cottonwood Canyon atypical of the long-term faulting record at that site and believe it likely represents a smaller than normal earthquake. However, the trench at Rock Canyon revealed evidence for three surface-faulting earthquakes of variable displacement based on stratigraphic separation, shear fabric, fault drag, fissuring, and minor graben formation. Stenner and others (2003) assigned 0.3-0.4 m of net vertical displacement to the most recent earthquake and were unsure how the remaining displacement (2.6-3.7 m) should be partitioned between the two older earthquakes. Stenner and others (2003) concluded that the variable displacements at Rock Canyon may indicate that (1) the size of earthquakes on the Anderson Junction section vary significantly, (2) rupture overlap from adjacent segments has occurred in the past, or (3) the rate of vertical slip on the Hurricane fault has been decreasing in more recent geologic time. To the north at Coyote Gulch on the Ash Creek segment, a Holocene alluvial fan is displaced about 3 m across what appears to be a single-event fault scarp. A scarp profile there indicates that the net vertical displacement across the scarp is 2.5 m (appendix B).

We can calculate preliminary recurrence intervals for the Hurricane fault at each of our long-term, vertical-slip-rate locations by dividing the vertical slip rate into a per-event estimated average net vertical displacement (table 5). For example, dividing the 0.57 mm/yr slip rate at North Black Ridge into an estimated per-event net vertical displacement of 2500 mm, similar to that seen at Coyote Gulch, results in a 4400 year recurrence interval for surface-faulting earthquakes at that location. Obviously, the value selected for per-event net vertical displacement is critical in a calculation of this kind. If we assume an average displacement of 1.5 m, the recurrence interval at North Black Ridge is reduced to 2600 years, because the smaller average displacement requires more earthquakes over the same time period to achieve an equivalent amount of long-term displacement The estimated long-term recurrence intervals for the proposed segments of the Hurricane fault in Utah shown in table 5 are approximately one-half to two-thirds of the Holocene recurrence intervals determined for the active central segments of the Wasatch fault, all of which have experienced at least one Holocene surface-faulting earthquake (Swan and others, 1980; Schwartz and Coppersmith,1984; Jackson, 1991; Lund and others, 1991; Personius, 1991; Machette and others,1992; Black and others, 1996; Lund and Black, 1998; Lund, 2005). However, as discussed above, evidence from Shurtz Creek, Pah Tempe Hot Springs, and Cottonwood Canyon indicates that slip on the Hurricane fault has slowed considerably in the late Quaternary. Considering the 0.21 mm/yr slip rate obtained from the displaced basalt at Pah Tempe Hot Springs, slowing likely began more than 350,000 years ago. Using the estimated 2.5 m displacement from Coyote Gulch and the 0.12-0.40 mm/yr vertical slip rates from the displaced Shurtz Creek pediment gives recurrence for surface faulting of 6300 to 20,800 years, considerably longer than the long-term average recurrence shown in table 5.

Table 6 presents estimated recurrence intervals for average displacements of 2.5, 1.5, and 0.6 m at Shurtz Creek and Cottonwood Canyon for the late Quaternary. These estimates, while based on limited data, demonstrate that large, surface-faulting earthquakes on the Hurricane fault in Utah are less frequent now than in the geologic past. However, while a less active Hurricane fault is good news for southwestern Utah from a seismic-hazard standpoint, it is important to note that both the Ash Creek and Anderson Junction segments show evidence of Holocene surface faulting, and must be considered active and capable of generating future large-magnitude earthquakes. Similarly, although it lacks evidence of young scarps, the proposed Cedar City segment has a comparatively high long-term vertical slip rate, and also must be considered potentially active.

Segmentation

Because of its 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 argue for a fault segment boundary at the south end of Black Ridge (figure 1) where the Hurricane fault makes a pronounced bend after intersecting a Sevier-age fold and thrust belt. They named the fault segment north of the proposed boundary the Ash Creek segment, and believe it may be up to 24 km long based on map-view geometry and major changes in fault strike. They named the segment south of the boundary the Anderson Junction segment, which they estimated could be as long as 45 km.

The single-event fault scarp formed on a young alluvial fan at Coyote Gulch, and the absence of young faulting north of that point is evidence for a possible second seismogenic

Table 5. *Estimated recurrence intervals for the Hurricane fault at long-term vertical slip-rate locations.*

Location	**Slip Rate mm/yr**	**Recurrence (years)[1]** d^2 = 2.5 m	d^2 = 1.5 m	d^2 = 0.6 m	**Segment**	**Comments**
Grass Valley	0.44	5700	3400	1400	AJ	Near Cottonwood Canyon
Pah Tempe	0.21	11,900	7100	2900	AJ	—
S. Black Ridge	0.45	5600	3300	1300	AJ/AC	Segment boundary
N. Black Ridge	0.57	4400	2600	1100	AC	—
Section 19	0.37-0.51	6800-4900	4100-2900	1600-1200	CC	Near Shurtz Creek
Cedar Canyon	0.53	4700	2800	1000	CC	Surrogate site, off fault

[1]Recurrence intervals rounded to nearest 100 years
[2]Estimated average net-vertical displacement

Table 6. Estimated recurrence intervals for the Hurricane fault at late Quaternary vertical slip-rate locations in Utah.

Location	Slip Rate mm/yr	Recurrence (years)[1]			Segment	Comments
		d[2] = 2.5 m	d[2] = 1.5 m	d[2] = 0.6 m		
Shurtz Creek	0.12-0.18[3]-0.40	6300-13,900-20,800	3800-8300-12,500	1500-3300-5000	CC	30-100 kyr surface
Cottonwood Canyon	0.1-0.3	9200-27,500	5000-15,000	2000-6000	AJ	70-125 kyr surface

[1]Recurrence intervals rounded to nearest 100 years
[2]Estimated average displacement
[3]Preferred vertical slip-rate value

boundary north of Coyote Gulch, most likely at the bend in the Hurricane fault at Murie Creek. We named the proposed new segment north of that bend the Cedar City segment (see above).

During several of the 11 historical surface-faulting earthquakes in the Basin and Range Province, surface faulting ruptured through or occurred on both sides of pronounced geometric and structural discontinuities along the fault (dePolo and others, 1991). Evidence from those earthquakes shows that not all geometric or structural aberrations along a fault are seismogenic boundaries, and of those that are, some leak displacement across them. Multiple lines of supporting evidence are preferred when defining seismogenic segment boundaries, but the only conclusive evidence for a seismogenic segment is a difference in the timing of surface faulting on either side of a suspected boundary. Unfortunately, there are few sites suitable for the detailed trenching studies required to evaluate the timing of paleoearthquakes on the Hurricane fault in Utah, and no such detailed studies have been conducted.

Lacking the necessary trench sites, other means must be found to evaluate whether or not geometric and structural features along the fault in Utah are seismogenic barriers. Although of limited extent, the new long-term, vertical-slip-rate data developed by this study provide a means of comparing long-term slip histories at different points along the fault. A significant difference in vertical slip rate on either side of prominent geometric or structural features would be strong evidence for a seismogenic boundary, especially if supported by additional corroborative data.

The long-term, vertical-slip information developed in this study is dispersed across all three proposed seismogenic segments on the Utah part of the Hurricane fault (table 4, figure 1). For this comparison, we use only slip-rate data applicable to the period from the early Quaternary to the present. This avoids potential complications associated with slowing of the Hurricane fault in more recent geologic time (see above). The slip rate on the Anderson Junction segment is 0.44 mm/yr since the early Quaternary (past 1 myr). Slip on the Ash Creek segment to the north is 0.57 mm/yr at North Black Ridge, indicating a net increase in the long-term, vertical slip rate of 0.13 mm/yr between the two segments.

Continuing north, the slip rate at the Section 19 site on the proposed Cedar City segment, calculated from information provided in Anderson and Mehnert (1979), is 0.37-0.51 mm/yr. However, the uncertainty associated with the slip rate at Section 19 precludes drawing firm conclusions regarding slip distribution on the northern part of the Hurricane fault. Slip at the far north end of the fault is estimated from the stream incision rate of Coal Creek, which crosses the Hurricane fault, of 0.53 mm/yr. We believe that the 0.53 mm/yr rate, although an approximate value, represents a valid lower bound for long-term, vertical slip at the north end of the Hurricane fault.

Based on the general increase in slip rate from south to north along the Hurricane fault in Utah, and the fact that the increase appears to occur across the proposed Anderson Junction/Ash Creek segment boundary, we believe that our new long-term, vertical-slip-rate data are consistent with the presence of a seismogenic fault boundary at South Black Ridge. Information on the timing of the most recent surface faulting at Cottonwood Canyon (Stenner and others, 1999) and Coyote Gulch provides additional evidence that the Anderson Junction and Ash Creek sections of the fault are independent seismogenic segments. The most recent event on the southern Anderson Junction segment occurred in middle to early Holocene time. Conversely, radiometric dates on detrital charcoal and soil development information indicate that the most recent surface-faulting earthquake at Coyote Gulch on the proposed Ash Creek segment occurred in the late Holocene. Because the timing of the most recent surface faulting at Cottonwood Canyon and Coyote Gulch are different, the two sites are likely on different seismogenic segments.

The difference in timing of surface faulting at the Coyote Gulch and Middleton sites is evidence for a possible third, previously unrecognized, seismogenic segment at the north end of the Hurricane fault. We have named this proposed new segment the Cedar City segment (see above). The long-term, vertical-slip-rate data for the proposed Cedar City segment do not show the same marked change across the proposed Ash Creek/Cedar City boundary as is observed in the slip-rate data for the Anderson Junction and Ash Creek segments to the south. Therefore, these new data do not provide strong independent evidence for two seismogenic segments, but vertical slip-rate data reported for other segmented Basin and Range normal faults show that segment boundaries are not always accompanied by large changes in slip (Machette and others, 1992). Therefore, the slip-rate data available for the Cedar City segment, while equivocal, still permit a segment boundary.

Paleoearthquake Magnitude Estimates

Wells and Coppersmith (1994) provide empirical relations among earthquake magnitude, rupture length, and surface displacement that can be used to estimate the moment magnitude (**M**) of paleoearthquakes. Seismic moment (M_o) provides a physically based connection between earthquake size and fault rupture parameters. $M_o = \mu$ ö A, where μ is the shear modulus (typically $3x10^{11}$ dyne/cm^2 for crustal faults; Hanks and Kanamori, 1979), ö is average displacement across the fault surface, and A is the area of the fault surface that ruptured. M_o is related to earthquake magnitude by the formula $\mathbf{M} = 2/3 * \log M_o - 10.7$ (Hanks and Kanamori, 1979). M_o provides a direct measure of the energy radiated by an earthquake, and therefore **M** provides a more reliable measure of the energy released during an earthquake than do magnitude estimates based on seismograph response (Hanks and Kanamori, 1979).

Regressions of surface rupture length (SRL) and M and of displacement (MD [maximum] and AD [average]) and M take the forms $\mathbf{M} = a + b * \log$ (SRL) and $\mathbf{M} = a + b * \log$ (MD or AD), respectively, where a and b are coefficients derived for various fault slip types (strike slip, reverse, normal, and all) from a worldwide database of 244 earthquakes having well-constrained source parameters (Wells and Coppersmith, 1994). At the 95% confidence level the relations between the various fault types are not statistically different, and therefore Wells and Coppersmith (1994) recommend that the coefficients for all slip types be used for most paleomagnitude estimates; we follow that recommendation in this study.

Table 7 shows paleomagnitude estimates for the Cedar City, Ash Creek, and Anderson Junction segments based on the surface rupture lengths of the segments reported in the *Quaternary Fault and Fold Database and Map of Utah* (Black and others, 2003). Because the northern termination of the Cedar City segment remains uncertain, table 7 includes a second paleomagnitude estimate for the Cedar City segment based on a postulated maximum surface rupture length of 20 km.

Information on displacement produced by individual paleoearthquakes on the Hurricane fault in Utah is limited. Based on trenching, Stenner and others (1999) determined that the most recent surface-faulting earthquake at Cottonwood Canyon on the Anderson Junction segment about 6 km south of the Utah-Arizona border produced 60 cm of net slip. Stenner and others (2003) found evidence for variable slip from the last three surface-faulting earthquakes in a trench at Rock Canyon, also on the Anderson Junction segment in Arizona. See Stenner and others (1999, 2003) for a discussion of paleomagnitude estimates for the Anderson Junction segment based on their trenching results.

Due to the limited number of scarps formed on unconsolidated deposits, land owner restrictions, and geologic complications at the few existing scarp locations (see above), trenching was not possible on the Ash Creek or Cedar City segments of the Hurricane fault. A scarp profile at Coyote Gulch near the north end of the Ash Creek segment yielded the only likely single-event vertical-net-slip measurement available for the Utah part of the Hurricane fault. Because displacement generally tends to decrease toward the ends of segments (Crone and others, 1985; Nelson and Personius, 1993), it is possible that the 2.5 m of vertical net slip measured at Coyote Gulch could represent more than one surface-faulting earthquake; however, the young age of the displaced alluvial-fan deposits (see above) argues for a single surface-faulting earthquake. It is unknown if the 2.5 m represents a maximum, average, or intermediate value of displacement for the Ash Creek segment. Table 8 shows paleomagnitude estimates for the Ash Creek segment based on a regression of displacement and **M** (Wells and Coppersmith, 1994) assuming alternatively that the 2.5 m represents the average and maximum displacement for the segment. No information is currently available regarding displacements produced by individual paleoearthquakes on the Cedar City segment.

A comparison of paleomagnitude estimates in tables 7 and 8 shows that magnitudes based on a regression of displacement and **M** are consistently larger than estimates based on a regression of surface rupture length and **M**. Hemphill-Haley and Weldon (1999) state that rupture length is not a reliable parameter for estimating prehistoric earthquake magnitudes because (1) rupture length estimates are based upon identification of often subtle, fragile geomorphic features which are easily eroded or buried, especially along long-recurrence faults, (2) recent earthquakes have demonstrated that surface ruptures can integrate faults that were previously not known to be related, (3) difficulties are often associated with assessing single-event rupture segments on even the most active, mature faults with relatively short recurrence, and (4) segmentation schemes generally are not

Table 7. *Paleomagnitude estimates for the Cedar City, Ash Creek, and Anderson Junction segments based on a regression of surface rupture length and moment magnitude.*

Segment	SRL[1] (km)	log SRL	a^2	b^2	$\mathbf{M}^3$
Cedar City A	13	1.11	5.08	1.16	6.4
Cedar City B	20	1.30	ditto	do.	6.6
Ash Creek	32	1.51	ditto	do.	6.8
Anderson Junction	42	1.62	ditto	do.	7.0

[1]Surface rupture lengths are straight-line distances from Black and others (2003) with the exception of Cedar City B, which is an estimated maximum possible length

[2]Coefficients for all slip types (Wells and Coppersmith, 1994 [table 2A])

[3]$\mathbf{M} = a + b * \log$ (SRL)

Table 8. Paleomagnitude estimates for the Ash Creek segment based on a regression of displacement (average and maximum) and moment magnitude.

Relative Displacement	Displacement (D) (m)	log D	a^1	b^1	$\mathbf{M}^2$
Average (AD)	2.5	0.398	6.93	0.82	7.3
Maximum (MD)	2.5	0.398	6.69	0.74	7.0

[1]Coefficients for all slip types (Wells and Coppersmith, 1994 [table 2B])
[2]$\mathbf{M} = a + b * \log(AD)$ or $\mathbf{M} = a + b * \log(MD)$

quantifiable in the sense that one can assign an uncertainty to the choice of a segment boundary. Hemphill-Haley and Weldon (1999) present a statistical method for estimating paleomagnitude based on combining multiple net displacement measurements along a preserved fraction of a rupture to reduce the uncertainty in the magnitude estimate. We are unable to employ their methodology because we are limited to a single displacement measurement (a minimum of three to five measurements are recommended), but due to the uncertainties imposed on paleomagnitude estimates based on surface rupture length (see above), we prefer the paleomagnitude estimates for the Ash Creek segment based on displacement shown in table 8 rather than those based on surface rupture length shown in table 7. However, we are aware that a single displacement measurement limits the paleomagnitude estimate for the most recent event on the Ash Creek segment to a first order approximation.

SUMMARY

This study of the Hurricane fault provides new information critical to earthquake-hazard assessment in southwestern Utah. In summary, our study results show the following:

1. Long-term, vertical slip rates on the Hurricane fault in Utah range from 0.44 to 0.57 mm/yr and generally increase from south to north, indicating that for the past approximately one million years, the north end of the Hurricane fault has been the most active part of the fault in Utah.

2. Although long-term, vertical-slip-rate data are sparse, increases in slip rate appear to be incremental across a previously suspected fault segment boundary at Anderson Junction, lending support to the presence of a seismogenic boundary at South Black Ridge between the proposed Anderson Junction and Ash Creek segments. These data also permit, but do not necessarily support, a second seismogenic boundary farther north at the bend in the fault at Murie Creek.

3. Vertical slip rates determined from displaced late Pleistocene and Holocene alluvial and colluvial deposits along the fault are lower (<0.01 - 0.35 mm/yr) than the long-term rates and show that slip on the Hurricane fault has slowed (generated fewer surface-faulting earthquakes) in more recent geologic time. This decrease in activity helps explain the sparse distribution of young fault scarps on unconsolidated deposits at the base of the high, steep Hurricane Cliffs in Utah. This slowing may have begun more than 350,000 years ago as evidenced by the 0.21 mm/yr slip rate determined from the displaced basalt flow at Pah Tempe Hot Springs.

4. The most recent surface faulting on the Anderson Junction segment occurred 5000-10,000 years ago. The most recent surface faulting on the Ash Creek segment occurred in the late Holocene sometime after about 1260 cal yr B.P. The most recent surface faulting on the proposed Cedar City segment occurred prior to 1530 cal yr B.P. How much prior is unknown, but the absence of young scarps on the Cedar City segment argues for a considerable period of time since the most recent surface faulting.

5. The timing of the most recent surface faulting on the Ash Creek and northern Anderson Junction segments is different, demonstrating that the two adjacent proposed segments are in fact independently seismogenic. Because the most recent surface faulting on both segments occurred in the Holocene, both segments must be considered active and capable of generating additional large earthquakes in the future.

6. The presence of a faulted late Holocene alluvial-fan deposit at Coyote Gulch on the Ash Creek segment near Murie Creek, and the absence of evidence for young faulting along the fault north of that point, argues for a possible third fault segment in Utah with the seismogenic segment boundary likely at the bend in the Hurricane fault near Murie Creek. We have named this proposed new northern segment the Cedar City segment.

7. The decrease in slip rate from middle to late Quaternary time along the Hurricane fault translates into longer average recurrence intervals between surface-faulting earthquakes. The average recurrence interval for surface faulting on the Hurricane fault's Utah segments is presently measured in several thousand to possibly more than ten thousand years.

8. Based on 2.5 m of likely single-event displacement at Coyote Gulch, the most recent surface faulting on the Ash Creek segment had an estimated moment magnitude of **M** 6.8-7.3.

9. Based on an estimated segment length of 20 km, the Cedar City segment is thought capable of producing **M** 6.6 events.

CONCLUSIONS

The Hurricane fault in Utah likely consists of three seismogenic segments. Two of the segments, Ash Creek and Anderson Junction (Stewart and Taylor, 1996), share a boundary at a large bend in the fault at South Black Ridge near Toquerville (figure 1) and both segments have generated surface-faulting earthquakes in the Holocene. Because of their Holocene activity, both segments are considered active and capable of producing future damaging earthquakes. The proposed Cedar City segment at the north end of the fault shows no evidence of geologically recent faulting. However, long-term, vertical slip-rate data for the Cedar City segment are comparable to the long-term vertical slip rates determined for the Ash Creek and Anderson Junction segments, indicating that the Cedar City segment has also been active in the late Quaternary. Shorter term vertical slip rates show that slip has slowed in recent geologic time on the Ash Creek and Anderson Junction segments, even though both segments have experienced Holocene surface faulting. Because its long-term, vertical slip rate is comparable with the segments to the south, the Cedar City segment should also be considered active and capable of generating future surface-faulting earthquakes.

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APPENDIX A

HURRICANE FAULT RECONNAISSANCE OBSERVATIONS

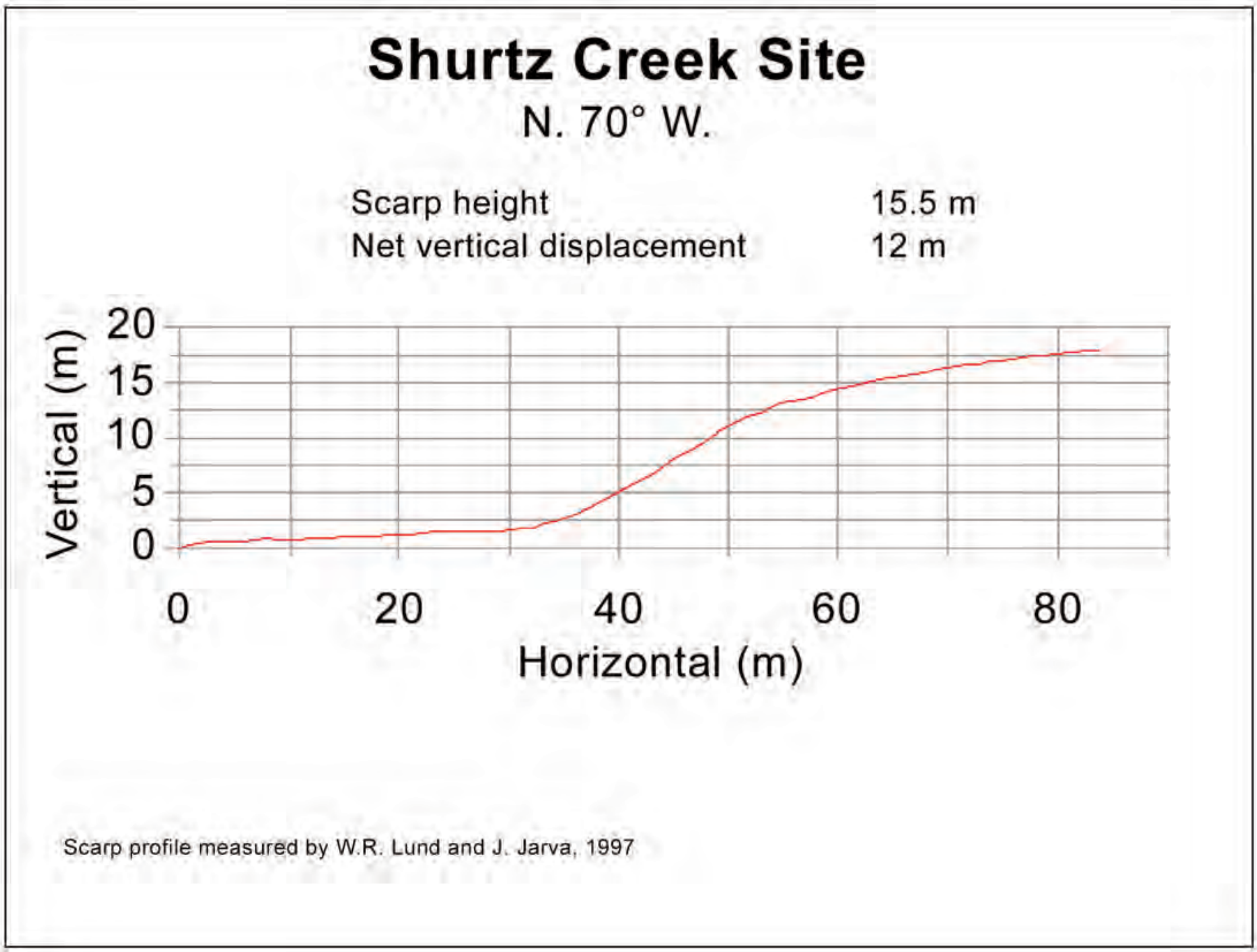
Field Number	Fault Section	7.5′ Quadrangle	Location Township, Range, Section	Feature Type	Remarks
FS1-1	1	The Divide	43S,13W,SW¼34	Fault scarp	~3 meters high, bedrock cored, slope angle ~22°
FS1-2	1	" "	43S,13W,NE¼34	" "	~6 meters high, bedrock cored; young stream terrace deposits in incised drainage cross the fault and are not displaced
FS1-3	1	" "	43S,13W,SW¼26	Stream channel	Large stream channel, fault not exposed, young stream terrace deposits cross the fault and are not displaced
FS2-1	2	" "	43S,13W,SW¼23	Rock fall?	Fault zone obscured, possibly by ancient rock-fall deposits derived from the Hurricane Cliffs
FS2-2	2	" "	43S,13W,NE¼10	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,NW¼3	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,NW¼22	Gravel pit	Gravel pit near base of Hurricane Cliffs - no fault exposure
FS2-5	2	Hurricane	42S,13W,NE¼15	Canyon mouth	Alluvial fan at canyon mouth heavily modified by human activity, no sign of scarps; smaller alluvial fans in the area do not appear displaced
FS3-1	3	"	42S,13W,SE¼10	Fault exposure	Fault exposure in bedrock, fault dips steeply to the west, 86° rake to the north (right lateral)
FS3-2	3	"	42S,13W,SE¼10	Lot excavation	Rough graded lot for home construction just west of Hurricane fault, final grading may expose fault
FS3-3	3	"	42S,13W,NW¼10	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,NW¼10	Fault exposure	Bedrock and older colluvium in fault contact; large cut that requires extensive cleaning to determine geologic relations
FS3-5	3	"	42S,13W,NE¼24	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,SE¼13	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,SE¼23	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,NE¼24	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 these scarps in places (see Stewart and Taylor, 1996)
FS4-4	4	"	40S,13W,NE¼23	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,SE¼14	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

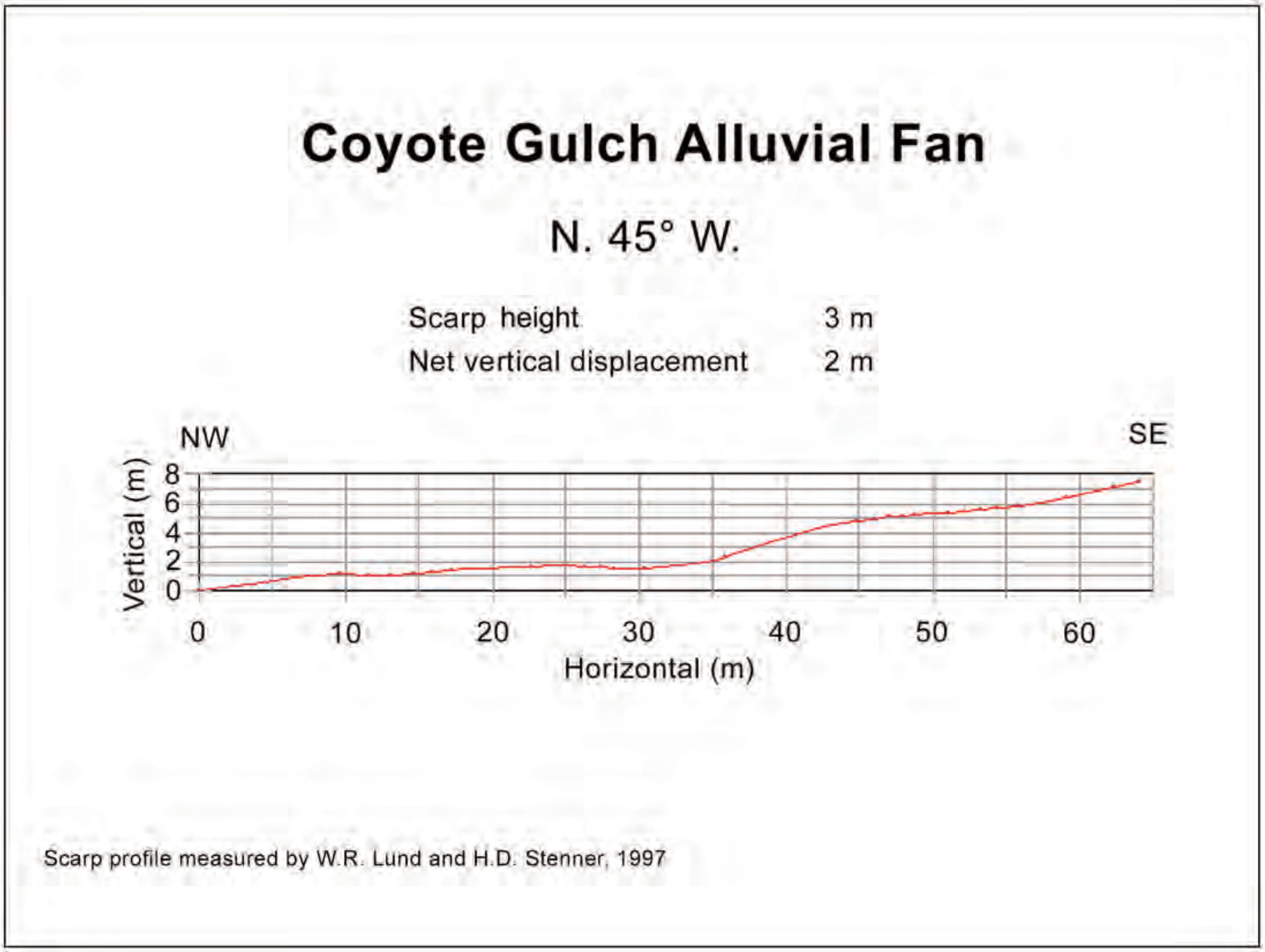
Field Number	Fault Section	7.5′ Quadrangle	Location Township, Range, Section	Feature Type	Remarks
FS4-6	4	Pintura	40S,13W,SE¼14	Fault exposure	Hurricane fault, buff Paleozoic rock in fault contact with red Mesozoic rock; FS4-5 basalt is a few meters to the west and is not faulted, Ash Creek has incised in to the basalt flow more than 50 meters
FS4-7	4	"	40S,13W,SW¼1	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,W½1	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,NE¼1	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,SE¼36	Anomalous draw	Linear, NW-trending drainage near alluvial-fan apex, no fault exposure but rock in cliff face exhibits weathered fault slick surfaces
FS4-11	4	"	39S,12W,NW¼31	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,SE¼18	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,SW¼8	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, NW¼8	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 knickpoints at the fault
FS4-15	4	" "	39S,12W,SW¼5	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,SE¼32	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,NE¼16	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,NE¼16	Fault scarp?	At least two, possibly three ages of alluvial fans developed at base of Hurricane Cliffs; older, higher fan appears truncated and displaced; slope inflections on intermediate and younger fans may be scarps
FS5-3	5	Kanarraville	38S,12W,NW¼10	Fault exposure	Road to water tank crosses Hurricane fault, fault plane exposed in footwall, dips steeply to the northwest
FS5-4	5	"	38S,12W,SE¼3	Fault scarp	Short, likely bedrock-cored fault scarp, ~20 meters high, 30° + slope
FS5-5	5	"	37S,12W,SE¼26	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

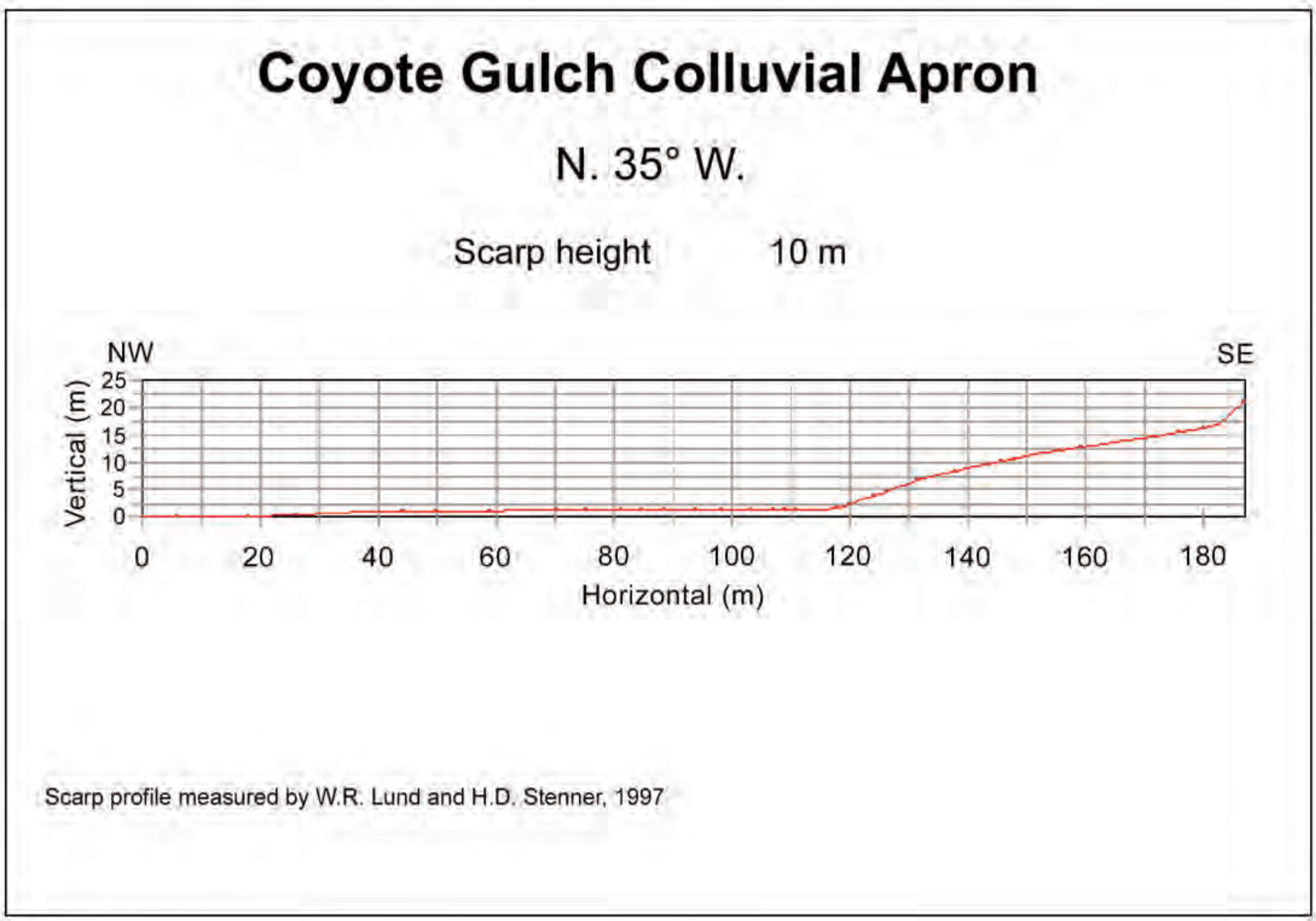
Field Number	Fault Section	7.5′ Quadrangle	Location Township, Range, Section	Feature Type	Remarks
FS5-6	5	“	37S,12W,SW¼24	Fault scarp	Possible single-event scarp, ~3 meters high formed on young (Holocene - latest Pleistocene) alluvial fan at the mouth of a small drainage - Murie Creek site (Coyote Draw)
FS5-7	5	“	37S,12W,SW¼24	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 earth quakes - Murie Creek site
FS6-1	6	Cedar Mountain	37S,11W,SW¼17	Fault scarps	Alluvial-fan surface is displaced across three parallel fault scarps, scarps range from ~3-7 meters high and are ~50 meters long, fan surface is inactive - Bauer site
FS6-2	6	“ ”	37S,11W,NE¼17	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,NE¼17	Fault scarp?	Possible small scarp displaces alluvial-fan deposits at the mouth of a small drainage, area has been chained and is highly disturbed
FS6-4	6	“ ”	37S,R11W,SE¼8	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,SW¼9	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,NW¼9	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,NW¼9	Alluvial terraces	Strong terrace along both sides of lower Shurtz Creek upstream from Hurricane fault - possibly tectonically related
FS6-8	6	“ ”	37S,11W,SE¼4	Alluvial terraces	Drainage incised into pediment on Hurricane fault foot wall 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,NE¼4	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, 2,3,&4	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
FS6-12	6	Cedar City	36S,11W, 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,SE¼14	Stream morphology	Squaw Creek flows westward until issuing from the Hurri cane 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

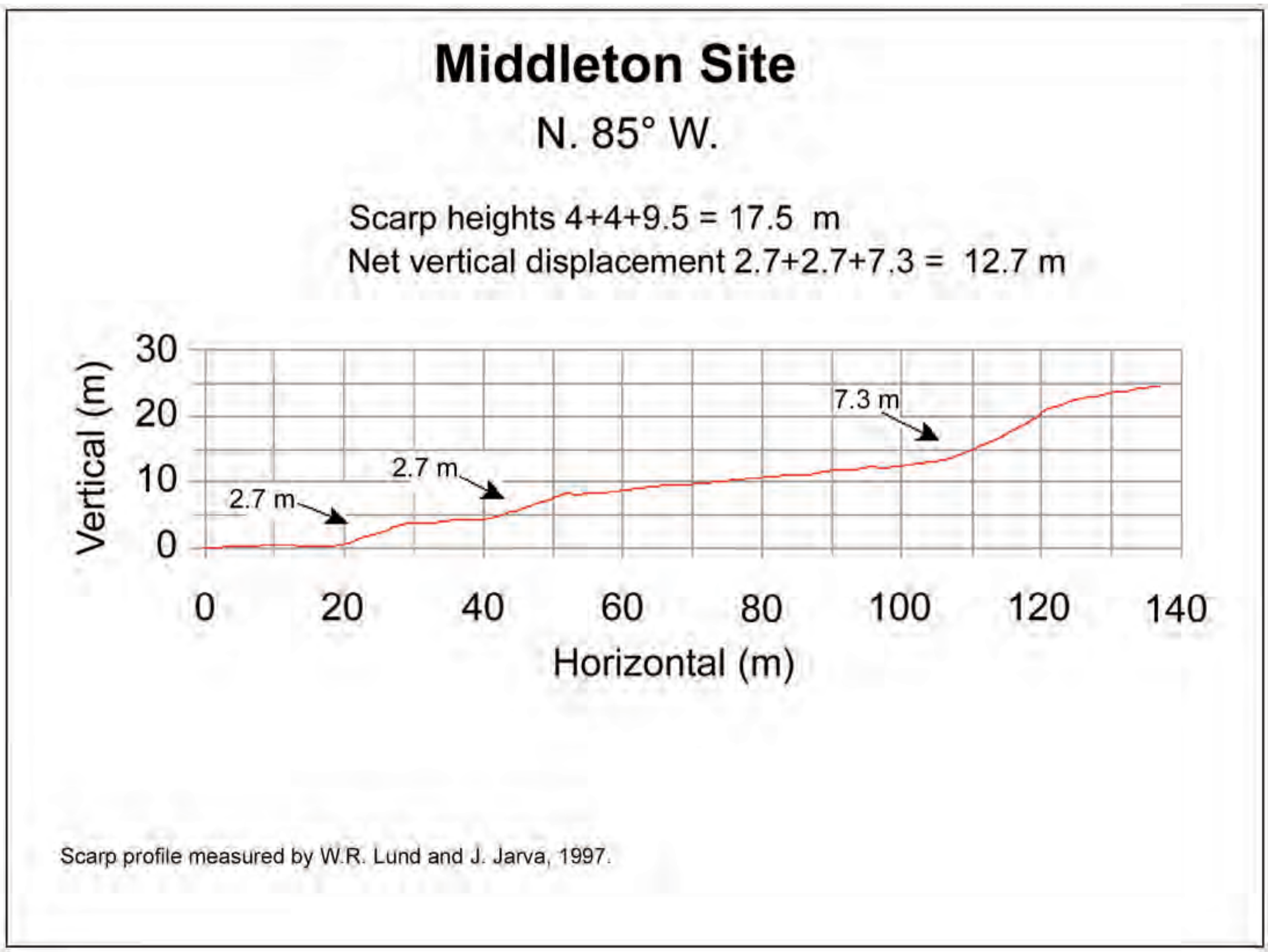
APPENDIX B

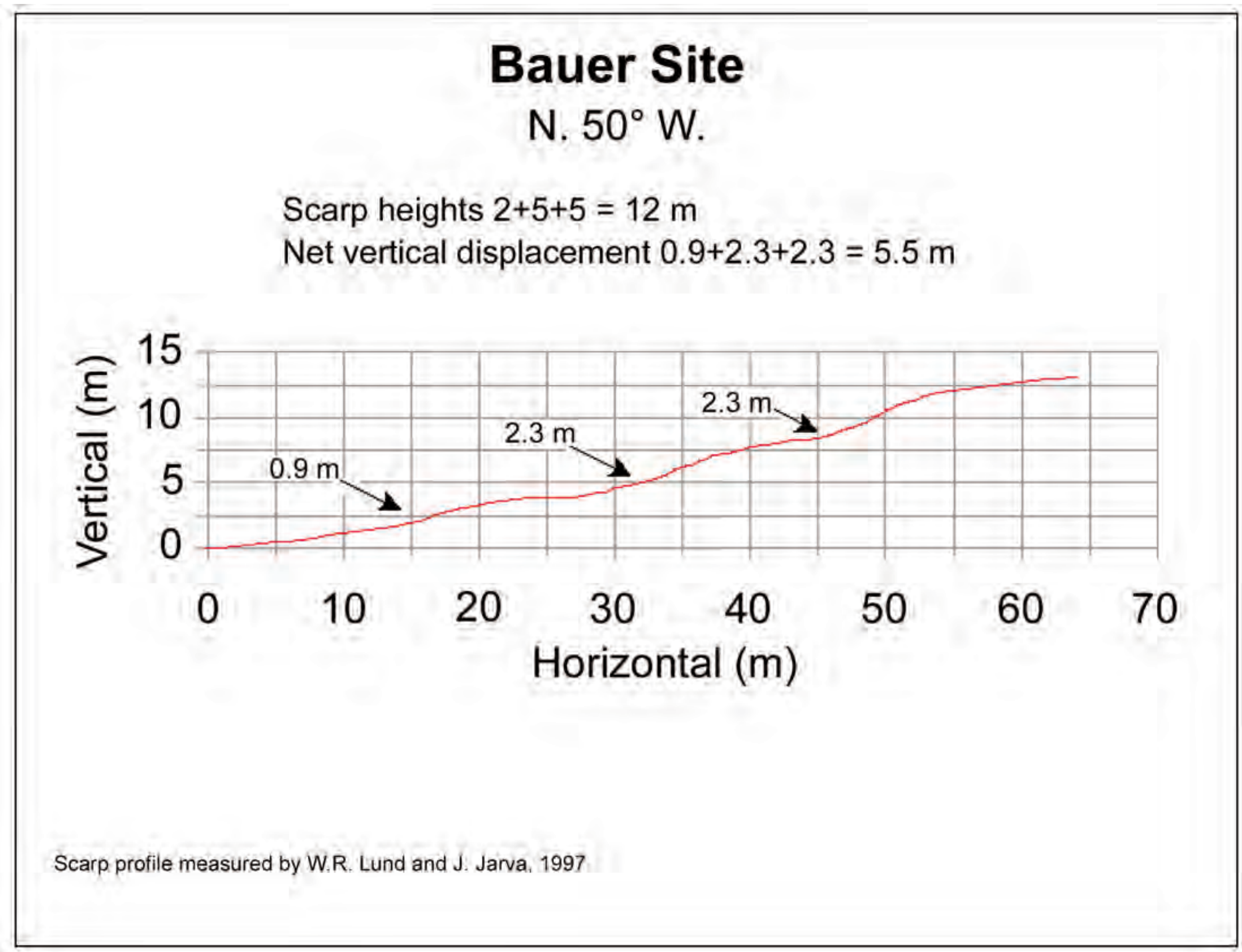
SCARP PROFILES

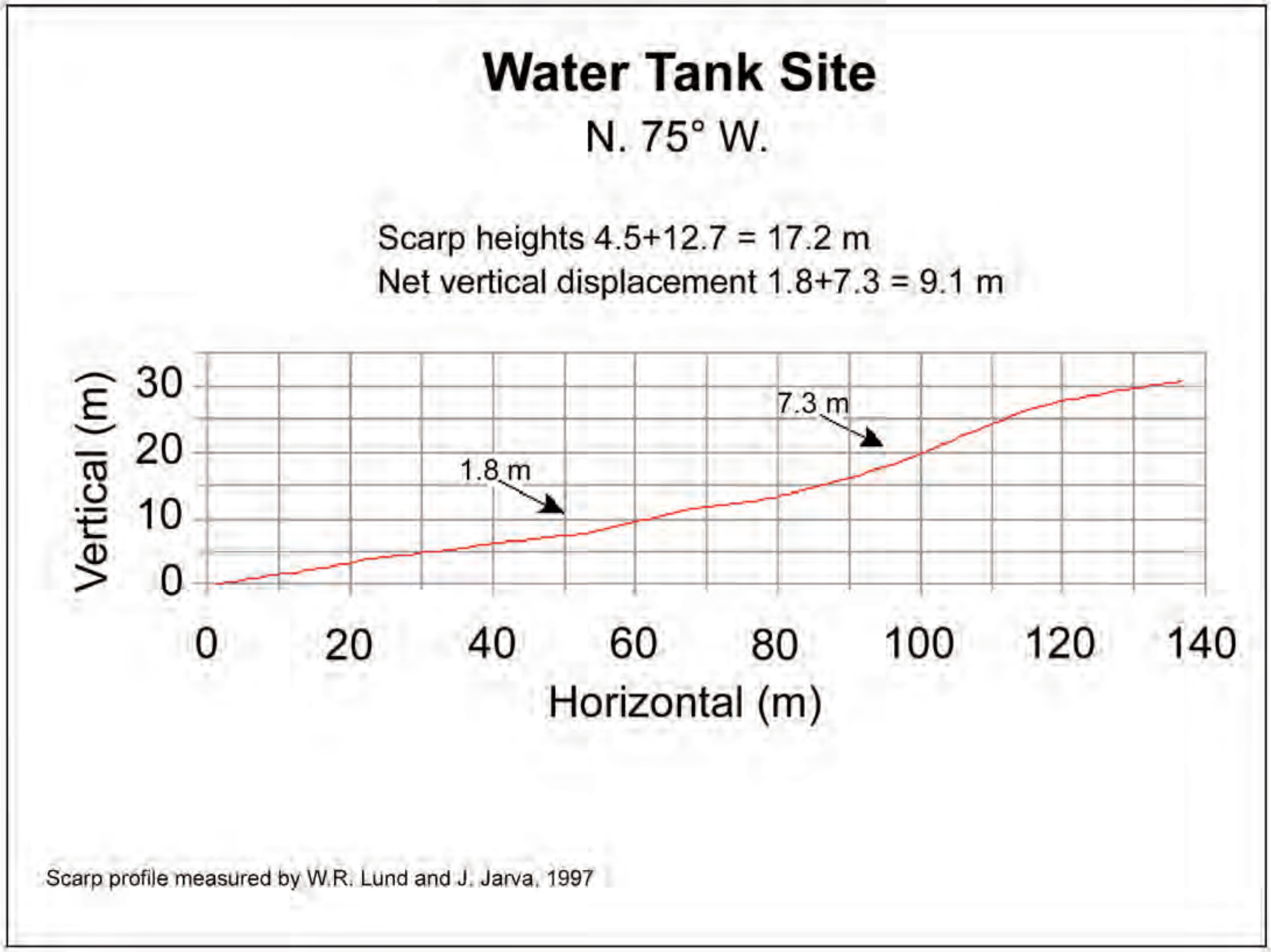



Coyote Gulch Alluvial Fan
N. 45° W.
Scarp height 3 m
Net vertical displacement 2 m
NW
SE
Vertical (m)
8
6
4
2
0
0
10
20
30
40
50
60
Horizontal (m)
Scarp profile measured by W.R. Lund and H.D. Stenner, 1997


Coyote Gulch Colluvial Apron
N. 35° W.
Scarp height 10 m
NW
SE
Vertical (m)
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
Horizontal (m)
Scarp profile measured by W.R. Lund and H.D. Stenner, 1997


Middleton Site
N. 85° W.
Scarp heights 4+4+9.5 = 17.5 m
Net vertical displacement 2.7+2.7+7.3 = 12.7 m
Vertical (m)
30
20
10
0
2.7 m
2.7 m
7.3 m
0
20
40
60
80
100
120
140
Horizontal (m)
Scarp profile measured by W.R. Lund and J. Jarva, 1997.


Bauer Site
N. 50° W.
Scarp heights 2+5+5 = 12 m
Net vertical displacement 0.9+2.3+2.3 = 5.5 m
0.9 m
2.3 m
2.3 m
Vertical (m)
0
5
10
15
0
10
20
30
40
50
60
70
Horizontal (m)
Scarp profile measured by W.R. Lund and J. Jarva, 1997


Water Tank Site
N. 75° W.
Scarp heights 4.5+12.7 = 17.2 m
Net vertical displacement 1.8+7.3 = 9.1 m
Vertical (m)
30
20
10
0
7.3 m
1.8 m
0
20
40
60
80
100
120
140
Horizontal (m)
Scarp profile measured by W.R. Lund and J. Jarva, 1997

APPENDIX C

SOIL DATA

Shurtz Creek Soil Morphology Data — **Soils described by Utah State University**

Horizon	Depth (cm)	Boundary (lower)	Munsell Color dry	Munsell Color 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.

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

Shurtz Creek Site - Soil Laboratory Results				Analyses performed by Utah State University		
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	No data	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

Coyote Gulch Soil Morphology Data — **Soils described by the Utah Geological Survey**

Horizon	Depth (cm)	Boundary (lower)	Munsell Color moist	Munsell Color dry	Texture	Structure	Consistence dry	Consistence moist	Consistence wet	HCl Reaction	Roots	>2 mm % volume	Other
Colluvium - Base Hurricane Cliffs													
A1	0-5	c,w	5YR3/2	5YR 4/1	sil	sg vf gr	lo	vfr	s	eo	3f	10*	-
A2	5-17	g,w	5YR 3/2	7.5YR 4/2	sil	sg vf	so	vfr	s	eo	3f	10	-
Bt	17-27	g,s	5YR 3/3	5YR 4/3	sicl	1 f sbk	so	vfr	s	es	2f	20	pf
2Btk	27-56	g,w	5YR 3/3	5YR 5/3	sicl	1 m sbk	sh	vfr	ss	ev	1f	50	d
2Bk	56-85	-	5YR 3/4	5YR 4/2	sil	2 m sbk	sh	fr	ss	ev	1f	50	d, 2n coat
Clasts are predominately resistant limestone from the Permian Kaibab Formation													
Alluvial Fan - Single event scarp													
A	0-7	c,s	5YR 4/4	5YR4/3	sicl	m	sh	fr	s	eo	3f	10	-
Bw1	7-17	g,w	2.5YR 3/4	2.5YR 4/4	sicl	m	sh	fr	s	eo	3f	10	-
Bw2	17-44	g,w	2.5YR 4/4	2.5YR 4/6	sicl	2 m sbk	sh	fr	s	eo	2f	25	-
Bk	44-80	-	2.5YR 3/4	2.5 YR5/4	sicl	2 m sbk	sh	fr	s	es	1f	25	d, 1n coat
Parent material for this soil is alluvium derived from the lower red member of the Moenkopi Formation, therefore the alluvium contains considerable primary clay.													

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; vf = very fine; f = fine; m = medium; sg = single grain; c = coarse; gr = granular; sbk = subangular blocky. **Consistence:** lo = loose; so = weakly coherent; sh = slightly hard; vfr = very friable; fr = friable; ss = slightly sticky; s = sticky. **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.

Middleton, Bauer, and Coyote Gulch Site Soil-Profile and Laboratory Results

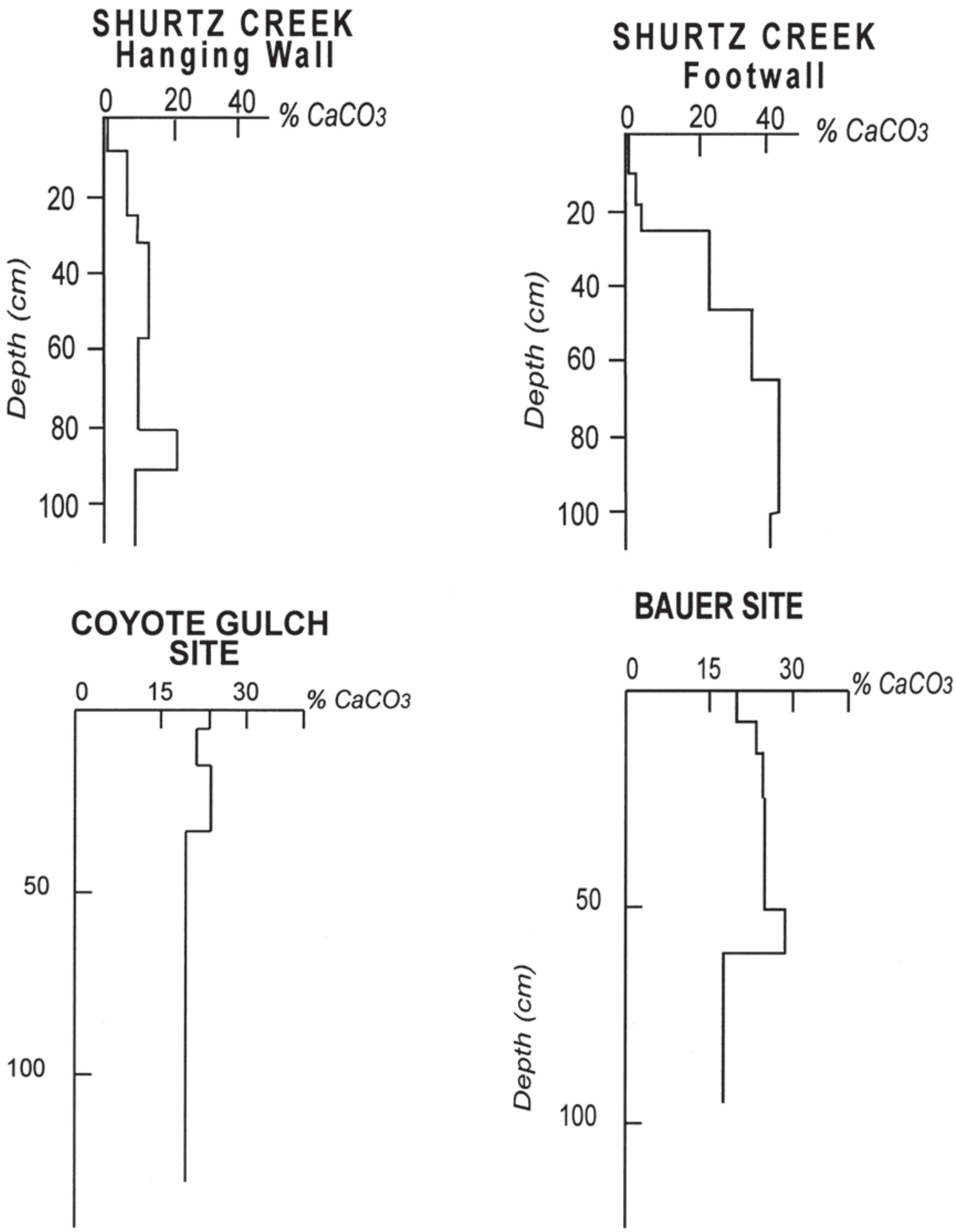
**Soils described by the Utah Geological Survey;
Soil Analyses performed by Utah State University**

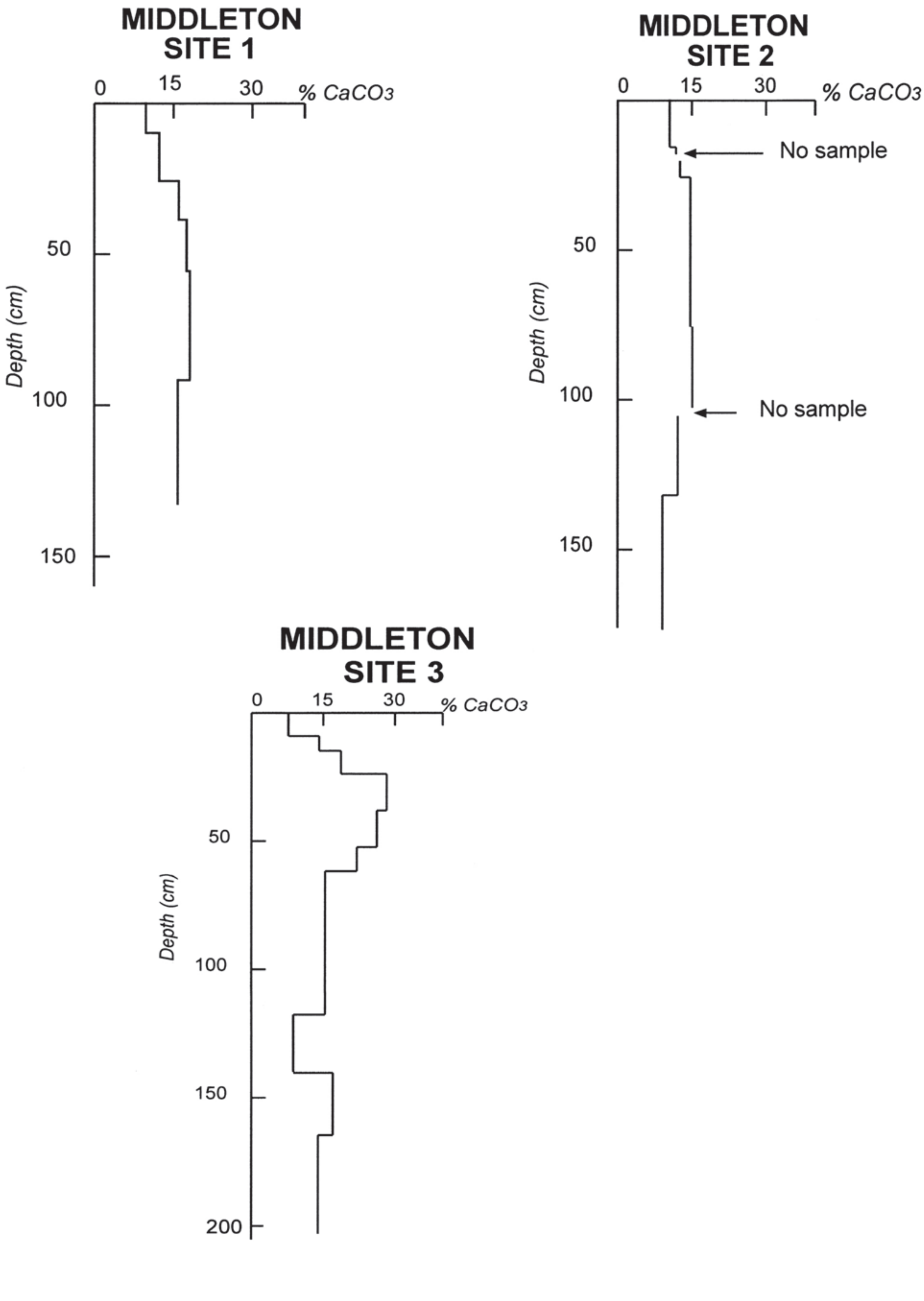
Depth cm	Soil Horizon	Color moist-dry	Sand %	Silt %	Clay %	USDA Texture	Wet Consist.	Plasticity	Structure/ Grade	Clay Films	$CaCO_3$ %	Carbonate Morp.	Lower Boundary	Remarks
Middleton Site: Soil Profile MS-1														
0-12	A1	5YR3/2-5YR4/3	52	18	30	sicl	ss-s	ps	abk/1		10.1		c	
12-25	A2	5YR3/2-5YR4/3	50	19	31	sicl	ss-s	ps-p	abk/1		12.4		a	
25-38	Bw	2.5YR4-2.5YR4/44	51	14	35	sicl	ss-s	p	abk/2	vf/f/po	15.7		g	
38-56	Bk1	5YR3/3-5YR5/4	52	14	34	sicl	ss	ps	abk/2	vf/f/po	17.8	I-II	g	
56-92	Bk2	5YR3/3-5YR6/4	56	13	31	sicl	ss	ps	abk/2		18.3	II	a	
92-132	2Bk	5YR3/3-5YR5/4	75	13	12	sil	ss	ps	m		15.2	I+		Bouldery debris-flow deposit
Middleton Site: Soil Profile MS-2														
0-9	A	5YR3/3-7.5YR4/4	51	13	36	sicl	ss	ps	abk1		11.1		a	Numerous fine roots - forest duff
9-17.5	Bw	5YR4/4-2.5YR4/4	55	11	34	sicl	ss	ps	abk1		12.3		a	
17.5-20.5	Ab	7.5YR3/2-5YR4/1	54			est. sicl	ss	po	abk1				a	Paleosol
20.5-26.5	Bwb	2.5YR3/3-2.5YR4/4	51	10	37	SC	ss	ps	sg		13.2		a	
26.5-76	2Bkb	2.5YR4/4-5YR5/4	55	10	39	SC	ss	p	abk2		16.1	I	c	Bouldery debris-flow deposit
76-103	3Bk2b	5YR4/4-5YR5/4	55	10	35	SC-sicl	ss	p	abk2		16.9		c	Sandy fluvial deposit
103-107	Burn Horizon	5YR2.5/1											a	
107-131	4Bk3b	2.5YR4/6-2.5YR5/6	55	14	31	sicl	ss	ps	abk2		13.4	I	c	Bouldery debris-flow deposit
131-177	Cox	2.5YR4/8-2.5YR5/8	65	5	30	sicl	ss	ps	sg		9.7			Debris flow deposit with sandy matrix
Middleton Site: Soil Profile MS-3														
0-15	Cox	2.5YR3/4-2.5YR4/4	61	8	30	sicl	ss	ps	m		11.5		a	Slope wash deposit

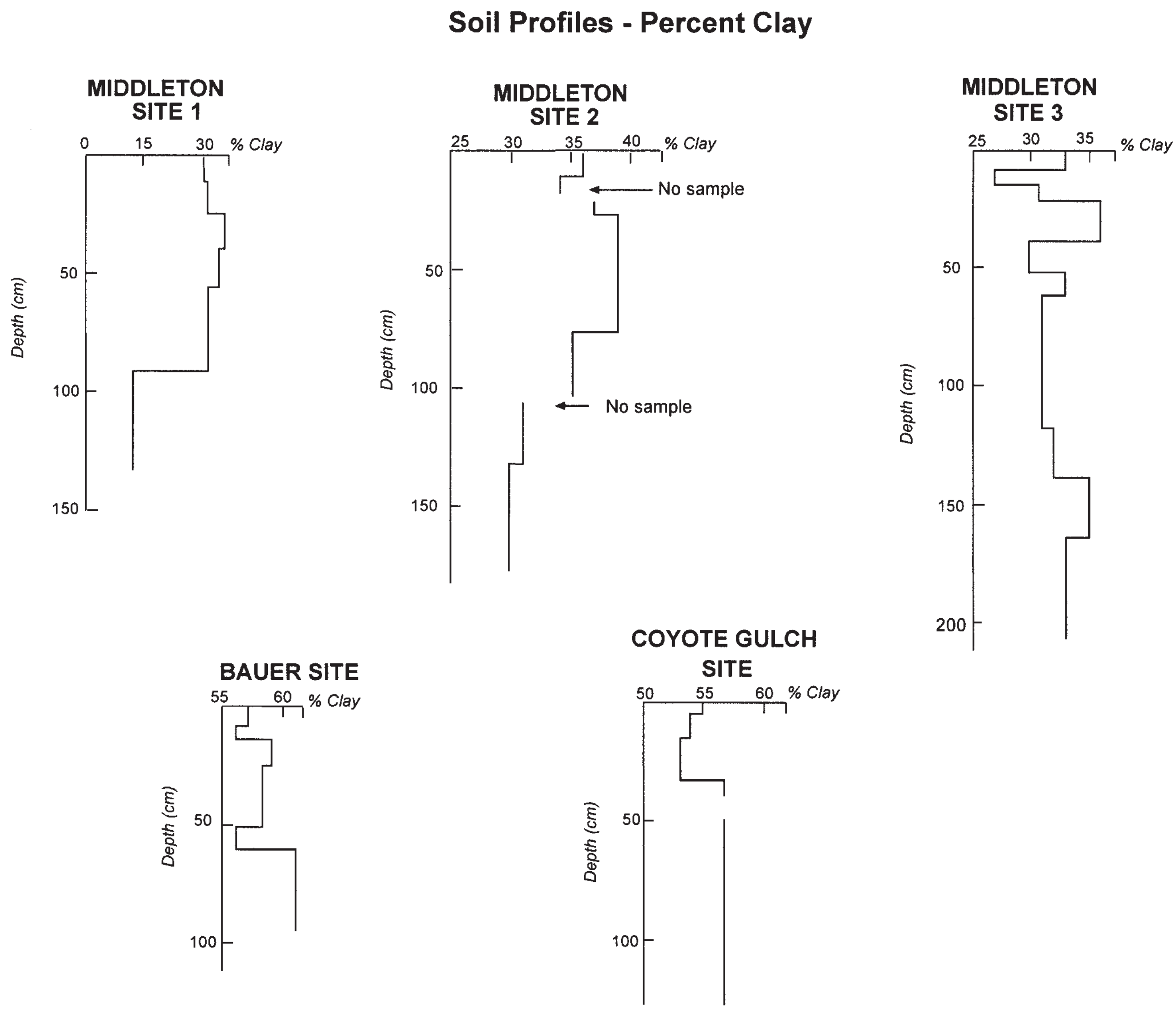
15-23	Ab1	5YR3/1-5YR4/1	51	18	31	sicl	ss	ps	m		19.6		c	Buried A horizon
23-38	Btkb1	7.5YR4/4-7.5YR6/2	45	19	36	sc-cl	ss	ps	m		28.7	I	g	
38-52	Bkb1	2.5YR-4/4-2.5TR5/4	57	13	30	sicl	s	p	m		26.8	I	c	
52-62	2Bk2b1	2.5YR4/4-2.5YR5/4	55	12	33	sicl	ss	ps	m		22.3	I	c	Debris-flow/flod deposit
62-117	3Bk3b1	2.5YR4/4-2.5YR5/4	57	13	30	sicl	ss	ps	m		15.8	I	a	Coarse, stratified fluvial deposit
117-139	4Ab2	5YR3/3-5YR5/3	56	13	31	sicl	ss	ps	m		9		a	Paleosol on a debris-flow deposit
139-164	4Btkb2	2.5YR4/6-2.5YR4/4	53	12	35	sicl	ss	ps	m		17.5	I	c	Coarse debris-flow deposit
164-207	5Bkb2	2.5YR4/4-2.5YR5/4	51	16	33	sicl	ss	ps	m		14.3	I-		
Bauer Site: Soil Profile BS-1														
0-7	A1	5YR3/4-5YR4/4	6	37	57	cl	s	p	g		19.7		c	Numerous fine roots - forest duff
7-13	A2	5YR3/3-5YR4/6	6	37	56	cl	s	p	abk/1		23.4	I	c	
13-24	Bwk	5YR4/4-5YR5/4	5	36	59	cl	s	p	abk/2	vf/f/po	25.1	I	c	
24-50	Bk1	5YR4/4-5YR5/4	7	35	58	cl	s	p	abk/3	1/f/po	25.6	I	g	
50-60	Bk2	5YR4/4-5YR5/4	7	37	56	cl-sicl	s	p	abk/2		28.6	I	g	
60-94	2Bk3	5YR4/4-5YR5/4	4	35	61	cl	s	p	m		17	I-		Coarse debris-flow deposit
Coyote Gulch Site: Soil Profile CG-1														
0-5	AB	2.5YR3/6-2.5YR4/4	7	38	55	cl-sicl	s	p	g		23.5		g	Weakly developed A horizon
5-15	Bw	2.5YR3/4-2.5YR4/4	8	39	54	cl	s	p	g		21.3		g	Root zone
15-33	Bk1	2.5YR3/4-2.5YR5/4	5	42	53	sicl	s	p	g		25.2	I	g	Weak HCl reaction, mostly gypsum
33-128	Bk2	2.5YR3/4-2.5YR5/4	7	36	57	cl	s	p	g		19.9	I		Weak HCl reaction, mostly gypsum

USDA Texture: sil = silt loam; sicl = silty clay loam; cl = clay loam. **Wet Consistence**: s = sticky; ss = slightly sticky. **Plasticity**: ps = slightly plastic; p = plastic. **Structure/Grade**: ma = massive; f = fine; m = medium; c = coarse; gr = granular; sbk = subangular blocky; 1 = weak; 2 = moderate; s = strong. **Clay films**: po = clay films lining pores, vf = very fine pore, f = fine pore. Boundary: a = abrupt; c = clear; g = gradual. **Carbonate morphology**: I = stage I; I- = stage I minus; I+ = stage I plus; II = stage II (Machette, 1985a).

Soil Profiles - Percent CaCO3




MIDDLETON SITE 1
0
15
30
% CaCO3
Depth (cm)
50
100
150
MIDDLETON SITE 2
0
15
30
% CaCO3
No sample
No sample
Depth (cm)
50
100
150
MIDDLETON SITE 3
0
15
30
% CaCO3
Depth (cm)
50
100
150
200


Soil Profiles - Percent Clay
MIDDLETON SITE 1
0
15
30
% Clay
50
100
150
Depth (cm)
MIDDLETON SITE 2
25
30
35
40
% Clay
No sample
50
100
150
No sample
Depth (cm)
MIDDLETON SITE 3
25
30
35
% Clay
50
100
150
200
Depth (cm)
BAUER SITE
55
60
% Clay
50
100
Depth (cm)
COYOTE GULCH SITE
50
55
60
% Clay
50
100
Depth (cm)

Appendix D

GEOCHEMISTRY AND PETROLOGY

by

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Citations in the appendix text are listed in the REFERENCES section of the main report.

GEOCHEMISTRY AND PETROLOGY

by
Stanley Hatfield

INTRODUCTION

I collected basalt samples along the Ash Creek and Anderson Junction segments of the Hurricane fault (figure 12 main text) at various locations on both the hanging wall and footwall of the fault. The Washington State University GeoAnalytical Laboratory analyzed 59 samples for major, minor and trace elements using x-ray fluorescence (tables 1 and 2). Peter Hooper of Washington State University has shown conclusively (Hooper, 2000) that individual basalt flows can be correlated over long distances using certain geochemical parameters. Hooper has worked extensively on the Columbia River basalts where individual basalt flows are traceable for long distances in outcrop. He sampled numerous locations along individual flows and analyzed to determine if certain geochemical characteristics were identifiable along the entire length of the flow. He analyzed for 27 different elements for each sample; however, only a few minor and trace elements were found to be relatively consistent throughout the entire length of a flow. These included P_2O_5, TiO_2, Cr, Zr, Sr and Ba. By constructing a series of variation diagrams using these elements, numerous basalt flows are identifiable as distinctive individuals when comparing samples from several locations. The level of confidence is extremely high when making such correlations since the geochemical signature is unique for each flow within a very small range. In some instances, two or three successive flows might show the exact same geochemical pattern, which is interpreted to indicate that the flows collectively came from the same magma source over a relatively short period of time.

We applied this same logic to the Quaternary basalt flows that crop out along the Hurricane fault in Utah (figure 12 main text). Basalt flows provide the only viable marker units to correlate across the fault zone; previous work in the area has examined only major element chemistry along with visible phenocryst mineralogy. Both major element chemistry and phenocryst mineralogy often vary significantly within an individual flow and therefore are unreliable parameters for correlation purposes. I did a detailed petrologic examination of the basalts in this study as a possible correlation aid, but the main focus of our work was using minor and trace elements to correlate flows in a manner similar to that done on the Columbia River basalts.

ASH CREEK SEGMENT

I analyzed 37 samples (table 1) from both the footwall and hanging wall along the Ash Creek segment from the north end of the Black Ridge to Ash Creek gorge just north of the town of Toquerville, Utah. The resulting geochemical plots (figure 1) show that most of the basalt flows along the Ash Creek segment fall into one of three distinctive geochemical groups (Groups A, B, and C).

Four trace element plots (P_2O_5 vs. TiO_2, Cr vs. P_2O_5, Sr vs. Zr, and TiO_2 vs. Ba) proved the most effective in discriminating the Columbia River basalt flows (Hooper, 2000). These particular plots have no known geologic or geochemical significance except that they permit individual basalt flows to be distinguished from one another. Each of the three correlative groups identified along the Ash Creek segment contain several members such that three or four basalt cooling units probably comprise each group. The cooling units most likely represent multiple eruptions from the same magma source over a short period of time. Although this doesn't necessarily indicate correlation of individual flows, the close vertical proximity and thin (usually a few meters) nature of the cooling units permits the correlation of marker units across the Hurricane fault. Also, because the three geochemical groups along the Ash Creek segment each contain several cooling units, I was able to establish three locations along the fault where correlative flows are present in both the hanging wall and the footwall. The three locations, along with radiometric dating of the basalt flows, provide the control necessary for vertical-slip-rate determinations along the fault. This, of course, is assuming that the three locations represent lava flows displaced by movement on the fault rather than flows that cascaded across the fault. The samples in each group are listed in table 3 and indicate correlative units at the southern, central, and northern portions of the Ash Creek segment. It should be noted that the correlations indicated in table 3 are considered quite reliable since at least three of the four geochemical plots were conclusive for every sample listed and in many cases all four plots showed agreement. Samples with uncertain or non-correlative plots are listed in table 3 with question marks and the word NO, respectively. Finally, the three correlative groups are easily distinguished when viewed on the four geochemical plots for the Ash Creek segment (figure 1).

Three samples collected along the Ash Creek segment do not fit into the three groups discussed above. The samples are MH, from the crest of Black Ridge on the footwall of the Hurricane fault; MP35, collected from the fault hanging wall near milepost 35 along Interstate 15; and CCB, collected east of Cedar City, Utah in Cedar Canyon (now considered on the Cedar City segment).

Samples MH and MP35 are both from eruptive centers (as evidenced by cinder cones) and they are in the footwall and hanging wall, respectively, of the Hurricane fault. It was our hope that they would correlate with some of the flows along the Ash Creek segment, thus providing important information regarding whether some flows cascaded across the Hurricane fault at the time of their extrusion, or if they were in place and displaced by the fault. However, MH and MP35 do not correlate to any of the flows in the three groups identified along the Ash Creek segment, nor do the two samples correlate with each other. I am puzzled by why no correlative flows were found for MH or MP35, since they represent the only two eruptive centers identified along this segment of the Hurricane fault. CCB does not correlate with any of the basalts sampled, but it does provide a clue to the movement history of the Hurricane fault near Cedar City. The location of CCB, in a canyon on the footwall of the Hurricane fault, can be used to estimate the rate of downcutting of Coal Creek in Cedar Canyon. The rate of downcutting can then be used to calculate an approximate vertical slip rate at the north end of the Hurricane fault.

ANDERSON JUNCTION SEGMENT

There are several areas along the Anderson Junction segment where basalt flows crop out on adjacent sides of the Hurricane fault, and initially I thought that many of these flows were likely correlative. I collected 12 hanging-wall and 11 footwall samples along the Anderson Junction segment from just south of Hurricane, Utah southward to Grass Valley near the Arizona-Utah border. The Washington State University GeoAnalytical Laboratory analyzed selected samples (table 2) and I plotted key minor and trace elements (figure 2).

As observed along the Ash Creek segment, the basalt flows along the Anderson Junction segment could be divided into three groups based on geochemical data. However, the Anderson Junction segment groups are geochemically distinct from the Ash Creek segment groups, and there is no apparent genetic relation between the basalt flows along the two segments. Basalt along the two segments may overlap in time, but they do not represent the same flows or eruptive centers. As on the Anderson Junction segment, only samples with three out of four geochemical plots agreeing were considered correlative. Despite the close proximity of basalt flows on either side of the fault along the Anderson Junction segment, only the flows at the Grass Valley North # 2 site (figure 12 main text) are geochemically correlative across the fault. These flows were re-sampled and analyzed a second time to eliminate the possibility of sample error, and the second set of results were identical to the first. Thus the flows at Grass Valley North # 2 provide the only control point along the Anderson Junction segment were basalt flows on either side of the fault are geochemically correlative. Therefore, despite the geochemical discrimination of three distinct groups of basalt flows along the fault, I only identified a single site where the basalts on either side of the Hurricane fault are geochemically correlative. However, note that I did not sample the displaced basalt flow at Pah Tempe hot springs since Biek (2003) had already done so and showed that flow to be correlative across the fault.

PETROLOGY

I thin-sectioned all of the basalt samples and examined them initially without regard to the geochemical data. Such characteristics as major phenocryst composition, mineral percentages, textures, and any other discernible features were noted for each sample. No patterns were found which would allow the correlation of individual flows using petrologic data. In fact, many of the flows were highly variable in appearance exhibiting a wide range of mineral percentages, textures, and other characteristics such as oxidation of iron in the groundmass. Therefore, I concluded that petrology alone offered no aid in the correlation of basalt flows in the study area.

I re-examined the petrologic data after the geochemical correlations were established in the hope that perhaps more subtle petrologic characteristics might become apparent after the basalt flows had been grouped and correlated with a high degree of confidence. In some instances the correlative flows did look somewhat similar in thin section, but I could identify no single qualitative or quantitative feature which would allow correlation of the flows using only petrology. After careful examination, I concluded that the petrologic characteristics of the basalt flows are so variable that they offer no aid or improvement to the correlation relations established with geochemical data.

SUMMARY

I correlated basalt flows along and across the Ash Creek and Anderson Junction segments of the Hurricane fault using minor and trace element geochemistry. I plotted P_2O_5, TiO_2, Cr, Zr, Sr, and Ba on a series of variation diagrams (figures 1 and 2) to discriminate individual basalt flows, or groups of cooling units from one another. The methodology I applied is the same technique used successfully to correlate individual basalt flows over long distances on the Columbia River Plateau in the northwestern United States (Hooper, 2000).

Using plots of P_2O_5 vs. TiO_2, Cr vs. P_2O_5, Sr vs. Zr, and TiO_2 vs. Ba, I identified three correlative groups of flows along the Ash Creek segment. The three groups all had representative flows on either side of the fault, thus allowing for definitive marker units to be established for purposes of calculating vertical slip rates along the fault. However, two samples (MH and MP35) from the two eruptive centers identified along the segment did not correlate with any of the three groups identified along the Ash Creek segment or with each other. The relation of the samples and the eruptive centers they represent to the basalt flows and the movement history of the Hurricane fault remains unknown. I also identified three geochemical groups of flows along the Anderson Junction segment (figure 2), but only one of the groups is correlative across the fault.

I studied the petrologic characteristics of the basalt flows to determine if they could further aid the correlations established by the geochemical data. The petrology of the basalt flows, either alone or in conjunction with the geochemistry, offered no help in identification of individual flow units.

BASALT GEOCHEMISTRY AND PETROLOGY SAMPLE LOCATIONS

(see figure 12 in text)

Hurricane Fault - Ash Creek Segment

Pace Knoll

PK-1 Northeast side of Pace Knoll on top.

PK-2 South side of Pace Knoll on top.

North Black Ridge

BR-1 North end of Black Ridge near the Zion National Park boundary, also 40Ar/39Ar radiometric dating site.

BR-2 West edge of Black Ridge on top. Just above Dead Mans Hollow.

BR-3 West edge of Black Ridge just south of I-15 exit 36.

BR-4 Approximately 35 m southwest and below BR-3. Appears to be the next major cooling unit below BR-3.

BR-4 A second sample of cooling unit BR-4.

BR-5 Sample of third cooling unit directly beneath samples BR-4 and BR-4A.

BR-6 Possible fourth cooling unit directly below BR-5; difficult to determine if it is a separate unit.

Leap Creek

LC-1 Lowermost cooling unit exposed at this locality approximately 275 m upstream from where the gas line crosses Leap Creek.

LC-2 Downstream about 180 m from LC-1. Massive cooling unit at creek level; appears to be the cooling unit above LC-1.

LC-3 Third cooling unit up from the base of this sequence, directly above LC-2.

LC-4 Fourth cooling unit from the bottom; sample was taken from the north side of Leap Creek.

LC-5 Fifth cooling unit, on the north side of Leap Creek where a gas line crosses the creek.

Pintura Graben

PG-1 Massive cooling unit on the west side of the graben just west of Pintura (west of I-15)

PG-2 Approximately 1 km north of PGW-1, perhaps along the same graben; sample appears very similar to PGW-1.

PG-3 West central graben area.

PG-4 Near graben center between samples PG-2 and PG-3.

PG-5 Northeast graben area.

PG-6 Northwest graben area.

Pintura Graben West

PGW-1 Lower cooling unit on the west side of the graben just south of Pintura.

PGW-2 Upper cooling unit on the west side of the graben just south of Pintura.

Pintura Graben East

PGE-1 Lower cooling unit on the east side of the graben just south of Pintura.

PGE-2 Upper cooling unit on the east side of the graben just south of Pintura.

Ash Creek

ACI: Sample from the upper cooling unit just east of I-15 at exit 36, also 40Ar/39Ar radiometric dating site.

ACG Uppermost cooling unit west side of hanging-wall flows at south end of Black Ridge, also $^{40}Ar/^{39}Ar$ radiometric dat ing site.

ACS-1 Lower cooling unit along Ash Creek north of Toquerville, near farthest downstream paleomagnetic samples.

ACS-2 Second cooling unit, directly above ACS-1; sample is approximately 35 m upstream from ACS-1 sample site.

ACS-3 Approximately 85 m upstream along the streambed on the east side of Ash Creek; still cooling unit 2?

ACS-4 Approximately 55 m upstream, appears to be the next cooling unit up in the sequence.

South Black Ridge

BRN-1 Uppermost cooling unit at the Radio Towers at the south end of Black Ridge.

BRN-2 Second cooling unit down at paleomagnetic drilling location.

BRN-3 Third cooling unit just below BRN-2.

BRN-4 Fourth cooling unit moving down and toward the southwest near the nose of the basalt trough.

BRN-5 Fifth cooling unit down at BRN-2 paleomagnetic drilling site.

BRN-6 Sixth cooling unit down? Vesicle patterns above and below BRN-5 stop; vesicles become vertical and stretched and massive cooling unit 6 (?) begins.

Black Ridge Above Pintura

PR-1 Lower cooling unit along the top of Black Ridge above the town of Pintura.

PR-2 Upper cooling unit along the top of Black Ridge above the town of Pintura.

PR-3 Apparently same lower flow approximately 480 m south of PR-1.

PR-4 Upper cooling unit directly above PR-3.

Eruptive Centers

MH Basalt sample collected from cinder cone on fault footwall on top of Black Ridge near Pintura, also $^{40}Ar/^{39}Ar$ radio metric dating site.

MP35 Basalt sample collected from cinder cone on the fault hanging-wall west of I-15 near mile post 35.

Hurricane Fault - Anderson Junction Segment

Grass Valley South

GVS -1 Sample from southeastern top of large flow just west of the main north-south road.

GVS-2 Sample from the south end of this same flow on top. Appears to be the flow on top of GVS-1 flow, but it may be a horst block which repeats GVS-1?

GVS-2a Same flow as GVS-2 approximately 25 m east of GVS-2.

GVS-3 North edge of the GVS lava flow in the prominent drainage, along the east side of the drainage.

GVS-4 Radial dike on the north side of the GVS cinder cone. Sample east side of the dike just above the draw on the north side of the cone.

Grass Valley North

GVN-1 North of Sky Ranch on the west side of the ridge which is immediately east of the water tank. Sampled the promi nent ledge near the ridge crest.

GVN-2 Sampled three outcrops of basalt along the west side of the ridge top, approximately 90 m north of the Sky Ranch water tank, also $^{40}Ar/^{39}Ar$ radiometric dating site.

GVN-3 Sample from the west side of the flow at the corral.

GVN-4 Farther south from GVN-3 near the small shack at the southwestern edge of the GVN flow? All of the outcrop at this location is along the west side of the flow, perhaps along a fault scarp?

Mollies Nipple

MN Sampled the flow near the top of Mollies Nipple on the east side.

The Divide

TD-1 Sampled the dike at "The Divide." Sample taken on the west side of the dike approximately 100 m from the road.

TD-2 Sampled the flow which caps the ridge just west/northwest of the dike. Sampled the south side of the ridge.

TD-3 Sampled the flow which caps the ridge approximately ? km northwest of the dike.

TD-4 Basalt flow just west of where the main north-south road crosses Gould Wash the first time when traveling north. This flow is probably from the cone complex to the east, which flows down Gould Wash.

TD-5 Basalt flow where the road crosses Gould Wash (second time). Again, appears to be related to the Gould Wash flows, perhaps the same flow as TD-4.

The Brothers

TBN Basalt flow which caps the northernmost "Brothers" or remnant flows.

TBM Basalt flow which caps the middle of the "Brothers" or remnant flows.

TBS Basalt flow which caps the southern "Brothers" or remnant flows.

WF Basalt flow located directly south of TBS 1; another remnant flow.

TW Basalt flow south of WF 1; southernmost remnant flow sampled in our project.

PT Basalt flow sampled along the road leading into the Pah Tempe Hot Springs. Sample approximately 80 m east of the main north-south road in Hurricane.

Table 1. *Ash Creek segment basalt geochemistry results (weight percent).*

Sample	J code	K code	L code	SiO_2	Al_2O_3	TiO_2	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
PR-1	1	0	0	50.55	16.56	1.865	8.78	0.154	8.54	7.78	1.4	3.82	0.546	142	223	22	185	506	12	665	244	30	21.3	18	42	75	3	24	54	1
PR-2	1	0	0	49.38	16.12	1.794	8.87	0.152	10.22	7.81	1.35	3.76	0.551	141	218	21	152	503	12	681	238	29	19	17	43	73	4	22	67	2
PR-3	1	0	0	50.4	16.73	1.861	8.86	0.153	8.22	7.93	1.43	3.89	0.543	141	225	26	176	481	14	677	247	28	20.2	20	46	77	4	39	82	3
PR-4	1	0	0	50.66	16.83	1.878	8.97	0.153	7.98	7.73	1.42	3.82	0.55	141	223	20	170	425	15	648	251	30	21.5	17	44	79	1	30	68	1
BR-1	1	0	0	52.92	16.66	1.627	8.28	0.146	8.3	6.4	1.5	3.72	0.447	95	182	27	170	603	21	548	224	31	21.6	20	35	82	6	31	75	3
BR-3	1	0	0	52.63	17.24	1.677	8.33	0.15	7.95	6.47	1.53	3.56	0.467	97	175	27	174	709	18	511	228	33	22	18	27	81	6	32	75	4
BR-4	1	0	0	52.88	16.7	1.61	8.27	0.146	8.34	6.47	1.49	3.68	0.43	97	177	27	173	629	22	551	222	33	20.7	20	35	75	8	27	69	4
BR-4A	1	0	0	53.16	16.77	1.612	7.78	0.146	8.29	6.5	1.52	3.78	0.445	93	174	26	176	602	21	544	221	30	20.2	19	32	77	5	31	69	3
BR-5	1	0	0	53	16.88	1.629	8.12	0.145	8.36	6.15	1.54	3.72	0.464	88	168	21	176	628	21	573	230	31	21.3	16	37	82	6	30	74	4
BRN-1	1	0	0	50	15.67	1.895	11.31	0.19	9.99	6.39	0.77	3.44	0.348	55	166	36	252	337	8	372	184	35	11	18	75	98	3	26	46	0
BRN-2	1	0	0	50.08	16.87	1.528	10.28	0.17	10.24	6.82	0.65	3.09	0.288	70	167	38	205	332	8	406	152	29	9.7	18	69	81	0	2	31	0
BRN-3	1	0	0	49.92	16.87	1.54	10.19	0.172	10.03	7.02	0.65	3.33	0.285	75	179	34	211	280	10	392	148	29	8.4	21	65	83	2	11	46	3
BRN-4	1	0	0	50.91	16.83	1.505	9.28	0.16	10.47	6.34	0.87	3.31	0.323	57	164	25	188	503	12	476	168	28	11.2	17	42	84	7	37	56	1
BRN-5	1	0	0	51.57	16.74	1.513	9.24	0.162	9.6	6.41	0.95	3.49	0.329	58	161	23	199	430	15	472	170	30	10.5	16	45	81	6	12	50	3
BRN-6	1	0	0	50.98	16.82	1.776	8.45	0.149	8.13	7.93	1.37	3.88	0.517	144	225	20	167	418	12	657	228	28	20.4	20	46	78	3	29	59	3
ACI	1	0	0	53.05	16.59	1.589	7.98	0.145	8.25	6.76	1.51	3.68	0.438	107	184	26	162	601	24	542	222	29	19.6	18	40	80	2	34	76	2
ACS-1	1	0	0	51.71	16.85	1.604	9.23	0.171	9.53	6.11	0.95	3.5	0.339	58	159	34	207	496	14	454	176	31	11.2	20	44	86	8	23	50	0
ACS-2	1	0	0	51.27	16.58	1.63	9.59	0.176	9.98	6.09	0.93	3.42	0.337	54	160	25	206	423	14	442	174	30	11.3	19	46	86	1	17	44	4
ACS-3	1	0	0	50.84	16.72	1.516	9.75	0.162	9.96	6.41	0.88	3.45	0.307	56	165	31	190	376	14	463	165	28	10.8	19	51	87	2	17	50	1
ACS-4	1	0	0	50.87	16.43	1.616	9.52	0.168	10.07	6.57	0.91	3.51	0.332	56	159	24	201	363	15	462	170	30	11.3	20	45	81	5	17	32	2
PK-1	1	0	0	52.51	17.13	1.601	7.82	0.145	8.92	6.51	1.27	3.65	0.456	98	177	27	171	826	14	594	223	31	20.2	19	38	82	5	37	60	4
PK-2	1	0	0	53.19	16.54	1.579	8.07	0.145	8.17	6.65	1.52	3.68	0.453	105	181	26	164	613	23	548	223	28	19.6	19	41	80	6	9	81	5
PG-1	1	0	0	53.34	16.67	1.593	8.17	0.139	8.12	6.11	1.54	3.84	0.474	96	174	27	172	749	20	581	230	34	19	19	28	75	5	35	76	4
PG-2	1	0	0	52.27	17.04	1.55	9.4	0.156	8.79	5.61	1.17	3.55	0.457	52	149	34	189	700	16	552	209	31	12.9	17	32	84	7	24	62	4
LC-1	1	0	0	51.23	16.39	1.758	9.04	0.148	8.32	7.15	1.43	4.03	0.51	133	220	26	166	519	16	642	225	28	19.7	12	49	78	4	25	73	3
LC-2	1	0	0	51.05	16.83	1.786	9.09	0.151	8.08	6.97	1.42	4.1	0.514	130	211	24	165	503	16	653	233	28	21.4	16	47	76	2	31	68	3
LC-3	1	0	0	52.57	16.56	1.568	8.58	0.145	8.14	6.56	1.54	3.88	0.464	97	172	20	150	639	22	577	226	30	17.4	19	35	78	5	25	74	3
LC-4	1	0	0	51.27	16.34	1.557	9.06	0.152	8.32	7.66	1.4	3.71	0.531	135	220	22	163	575	18	563	211	28	21.2	17	45	81	3	28	74	4
LC-5	1	0	0	52.55	16.58	1.45	9.01	0.152	8.63	6.27	1.21	3.74	0.406	59	148	27	181	564	19	555	200	30	12.2	21	40	79	7	40	65	2
PGE-1	1	0	0	49.49	16.99	1.485	10.29	0.174	10.33	6.89	0.63	3.43	0.276	74	170	34	206	355	8	411	144	28	8.4	21	55	79	3	11	40	2
PGE-2	1	0	0	49.63	17.08	1.495	10.24	0.171	9.98	7.08	0.63	3.41	0.278	75	164	24	195	288	9	400	147	28	9	16	68	81	1	17	48	1
PGW-1	1	0	0	49.66	16.86	1.567	10.55	0.173	9.91	7.03	0.64	3.32	0.296	70	175	31	200	282	8	388	154	31	9.8	17	54	86	4	11	38	2
PGW-2	1	0	0	49.71	17.01	1.522	10.43	0.173	10.06	7.24	0.48	3.06	0.297	73	172	28	203	305	5	396	149	29	9.9	19	18	78	0	12	42	0
MH	1	0	0	50.09	16.52	1.983	9.22	0.157	8.27	7.5	1.52	4.12	0.62	123	180	26	171	553	13	786	261	29	25.4	18	43	81	8	44	75	2
ACG	1	0	0	50.13	16.83	1.529	10.15	0.176	9.97	6.92	0.66	3.29	0.344	72	177	29	188	317	10	396	151	29	9.1	18	60	83	6	31	39	1
MP35	1	0	0	52.85	15.9	1.374	8.98	0.15	7.96	7.39	1.14	3.43	0.495	162	221	22	159	1013	22	779	197	28	17.9	19	51	87	12	46	100	3
CCB*	1	0	0	47.53	13.3	1.907	10.25	0.18	11.19	10.77	1.24	2.92	0.7	189	544	33	253	861	15	792	198	25	52.4	22	69	89	4	46	108	6

*Sample CCB is now considered to be on the newly designated (this report) Cedar City segment of the Hurricane fault.

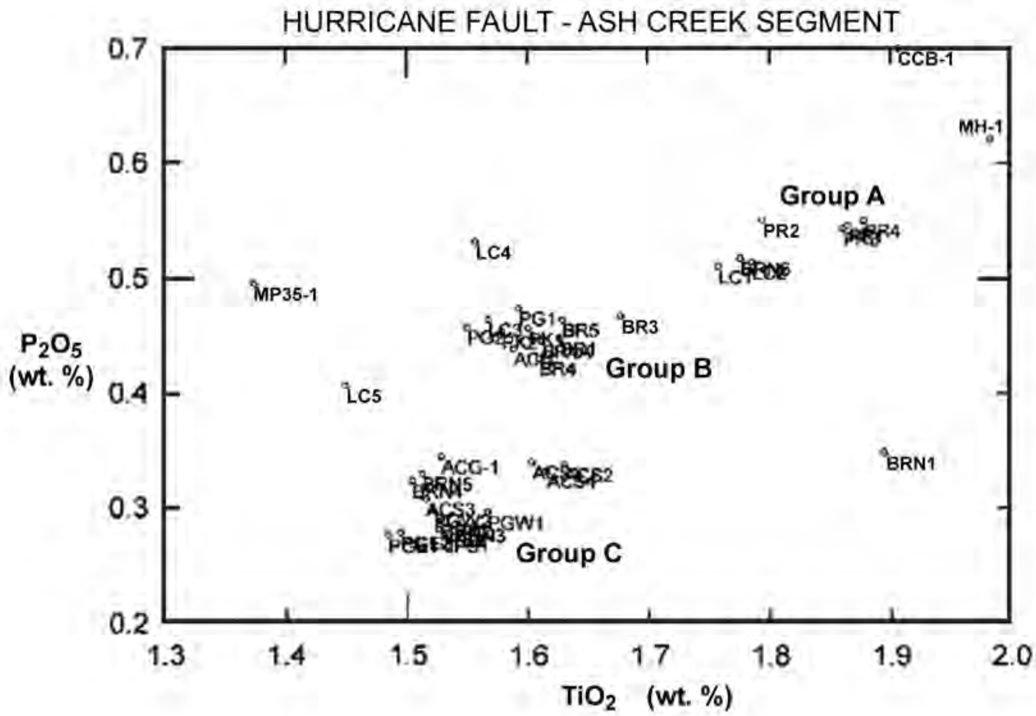
Table 2. *Anderson Junction segment basalt geochemistry results (weight percent).*

Sample	J code	K code	L code	SiO_2	Al_2O_3	TiO_2	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
TBS	1	0	0	41.54	12.2	1.896	11.06	0.206	14.13	13.97	0.74	3.13	1.12	259	565	27	293	2168	9	1253	237	26	88.7	18	67	93	9	98	160	21
TW	1	0	0	42.74	12.7	1.897	10.95	0.202	12.87	13.11	1.04	3.36	1.12	246	523	22	255	2038	12	1204	241	27	87.4	19	66	96	11	105	168	19
GVS-1	1	0	0	48.44	16.24	1.761	9.49	0.162	9.98	8.31	1.22	3.81	0.583	132	260	32	186	546	13	689	234	28	25.6	17	48	72	5	20	80	4
GVS-2	1	0	0	48.69	16.27	1.764	9.28	0.163	9.63	8.49	1.24	3.89	0.587	129	254	35	186	499	12	694	235	29	25.7	17	46	73	1	30	66	5
GVS-2A	1	0	0	48.85	16.34	1.753	9.39	0.163	9	8.71	1.23	3.97	0.574	133	263	30	194	501	14	681	233	28	24.4	19	48	71	3	25	67	7
GVS-3	1	0	0	48.91	16.43	1.767	9.34	0.16	9.76	8.04	1.32	3.68	0.587	128	230	25	162	511	12	738	242	28	26.4	16	48	69	2	21	76	2
GVS-4	1	0	0	48.18	16.24	1.807	9	0.161	10.55	7.98	1.36	4.03	0.68	120	213	17	176	489	12	725	249	29	26.8	16	52	66	4	27	59	2
GVN-1	1	0	0	48.84	16.31	1.793	9.26	0.165	9.52	8.35	1.29	3.88	0.594	131	248	24	183	676	12	719	239	29	25.6	17	51	69	5	18	62	6
GVN-2	1	0	0	42.79	12.75	1.871	10.93	0.202	13.05	12.96	1.03	3.3	1.12	242	522	24	269	2317	13	1224	240	28	86.5	17	68	91	9	83	176	19
GVN-3	1	0	0	48.43	16.3	1.779	9.43	0.165	10.22	8.51	1.11	3.47	0.573	130	252	27	193	686	8	725	236	28	25.9	18	49	72	2	28	71	3
GVN-4	1	0	0	48.74	16.26	1.739	9.38	0.16	9.59	8.52	1.26	3.79	0.572	135	257	25	196	531	10	691	224	29	25.8	16	53	70	4	34	53	4
TBS	1	0	0	41.75	12.19	1.904	11.21	0.207	13.47	14.13	0.66	3.35	1.13	264	569	29	291	2232	8	1297	238	27	89.2	14	77	93	12	116	176	18
WF	1	0	0	42.45	12.45	1.92	10.96	0.206	12.68	13.9	1.02	3.28	1.13	256	549	26	263	2002	14	1204	242	28	90.9	17	77	93	9	106	170	17
TBM	1	0	0	44.12	13.21	1.86	10.57	0.199	12.06	12.72	0.83	3.32	1.11	242	489	28	256	2021	17	1192	247	28	83.5	19	65	96	8	109	170	20
TBN	1	0	0	41.97	12.22	1.895	11.09	0.208	13.24	14.02	0.92	3.32	1.12	257	571	23	274	2216	6	1264	239	26	89.1	16	65	95	10	98	174	17
MN	1	0	0	50.72	16.69	1.431	9.46	0.162	10.02	6.73	0.92	3.48	0.38	59	174	30	198	748	10	627	178	28	13.2	16	49	79	6	29	49	0
PT	1	0	0	49.94	16.16	1.53	9.49	0.133	10.79	7.62	0.88	3.12	0.337	151	283	23	178	545	10	550	135	23	15.9	19	52	84	2	32	36	3
TD-1	1	0	0	44.62	11.38	2.625	11.98	0.195	11	13.34	1.24	2.81	0.8	333	468	26	250	688	16	822	242	28	63.3	17	71	107	2	43	89	6
TD-2	1	0	0	50.57	15.14	1.697	9.86	0.164	10.11	7.5	0.98	3.46	0.512	99	232	28	200	681	13	654	157	25	32.6	16	56	97	4	58	82	5
TD-3	1	0	0	49.73	14.27	1.686	10.71	0.167	9.95	8.9	0.85	3.28	0.455	175	359	23	181	560	9	591	147	23	29.8	18	59	101	5	30	73	3
TD-4	1	0	0	44.12	11.16	2.608	12.31	0.197	10.83	13.59	1.36	3.03	0.79	344	470	28	258	654	18	786	238	28	64.3	19	75	108	0	52	90	7
TD-5	1	0	0	43.6	11.24	2.626	12.55	0.199	12.18	13.06	1.34	2.37	0.83	322	439	27	251	999	16	826	243	29	64.2	18	67	107	4	57	103	7

Table 3. *Ash Creek segment correlations*

Sample	TiO_2 vs. P_2O_5	Cr vs. P_2O_5	Sr vs. Zr	TiO_2 vs. Ba
PR-1	A	A	A	A
PR-2	A	A	A	A
PR-3	A	A	A	A
PR-4	A	A	A	A
BRN-6	A	A	A	A
LC-1	A	A	A	A
LC-2	A	A	A	A
BR-1	B	B	B	B
BR-3	B	B	B	B
BR-4	B	B	B	B
BR-4A	B	B	B	B
BR-5	B	B	B	B
ACI	B	B	B	B
PK-1	B	B	B	B
PK-2	B	B	B	B
PG-1	B	B	B	B
PG-2	B	NO	B	B
LC-3	B	B	B	B
LC-4	B?	A?	B	B?
LC-5	NO	NO	B	B?
BRN-1	NO	C	NO	NO
BRN-2	C	C	C	C
BRN-3	C	C	C	C
BRN-4	C	C	C	C
BRN-5	C	C	C	C
ACS-1	C	C	C	C
ACS-2	C	C	C	C
ACS-3	C	C	C	C
ACS-4	C	C	C	C
PGE-1	C	C	C	C
PGE-2	C	C	C	C
PGW-1	C	C	C	C
PGW-2	C	C	C	C
ACG	C	C	C	C
MH	NO	NO	NO	NO
MP35	NO	A	NO	NO
CCB	NO	NO	NO	NO

A "NO" indicates no correlation with the three groups "A", "B", or "C".
Also, MH, MP-35, and CCB do not correlate with one another as well.



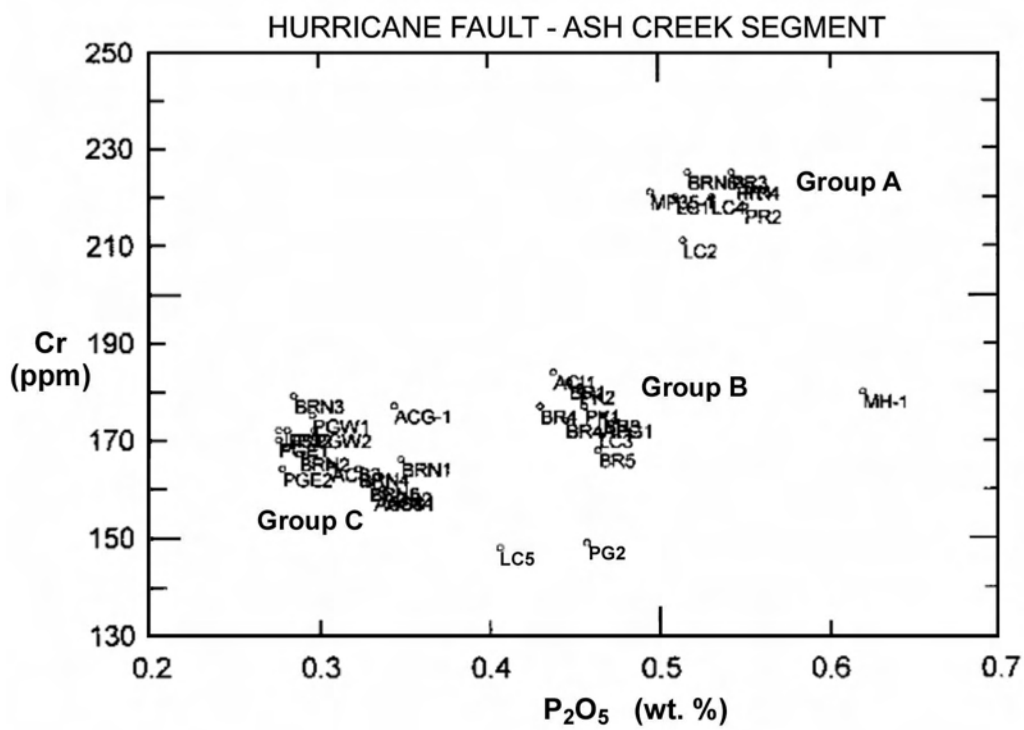
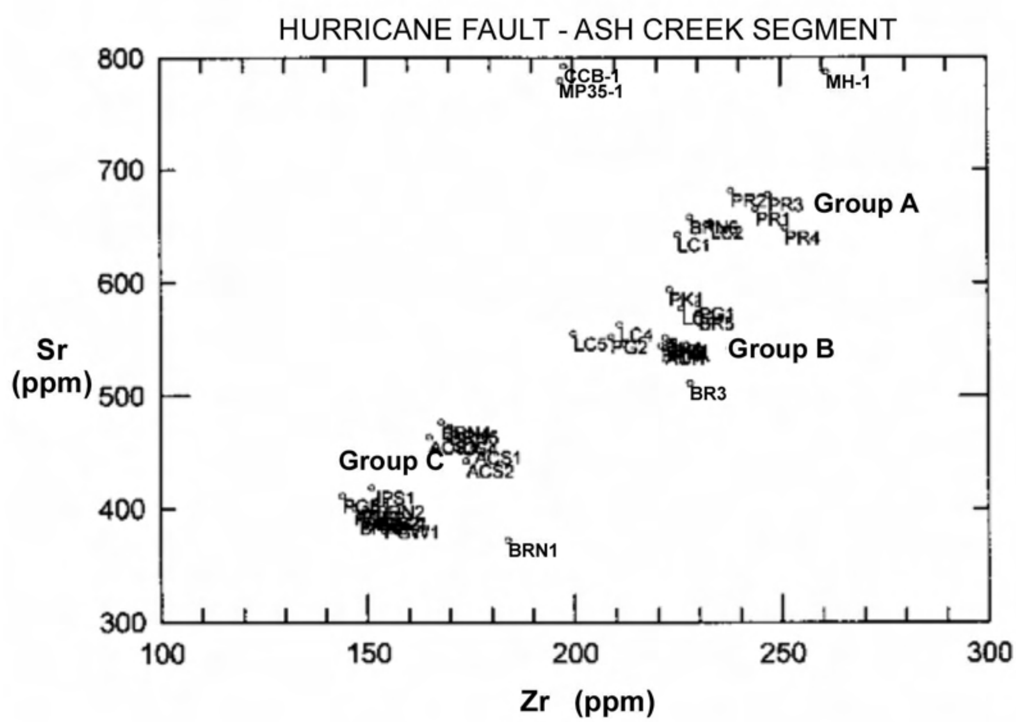
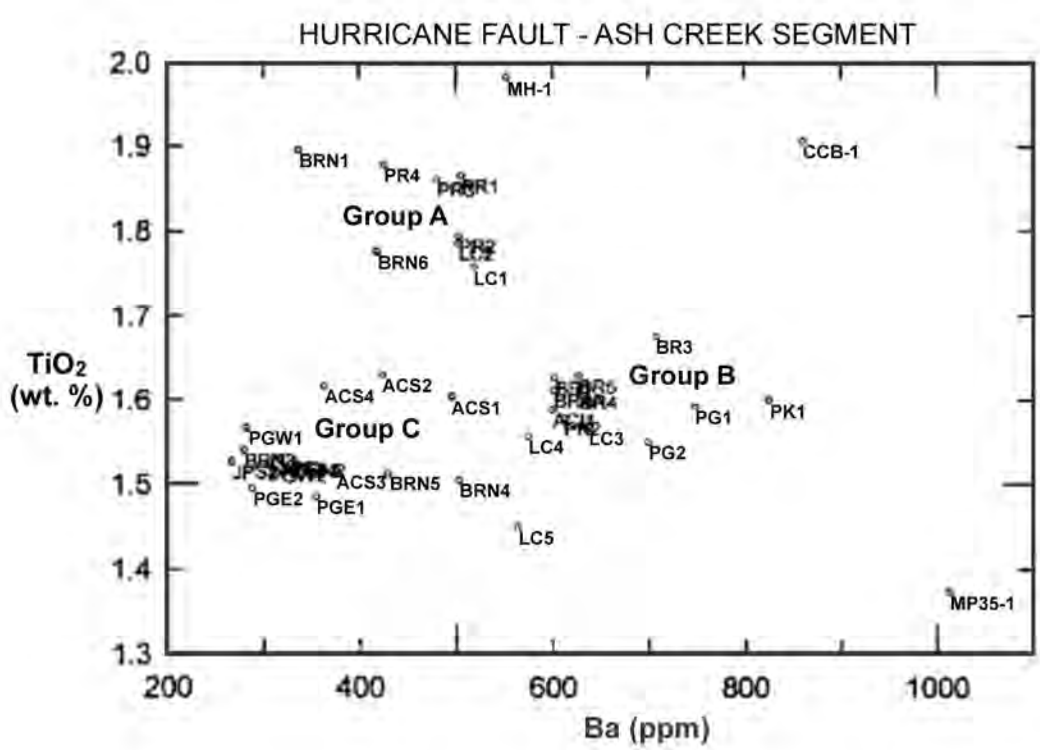
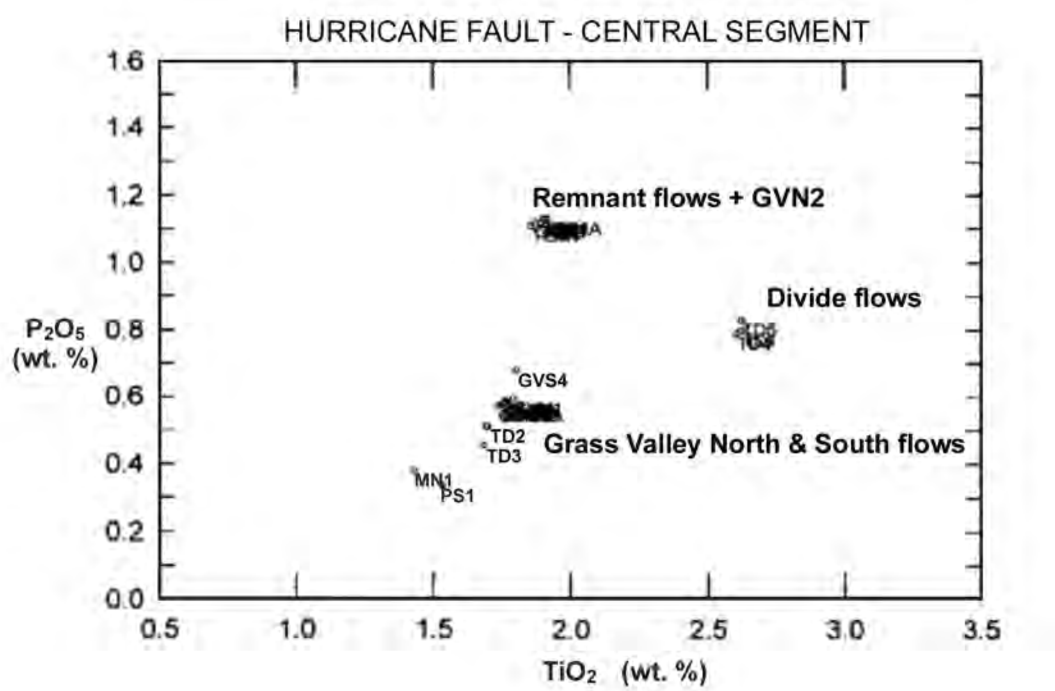


Figure 1 . *Ash Creek segment variation diagrams (see Basalt Geochemistry and Petrology Sample Locations section for sample identification). Groups A. B, and C represent distinctive geochemical clustering of trace elements that permit basalt units to be correlated across the Hurricane fault.*

Figure 1. *(continued)*







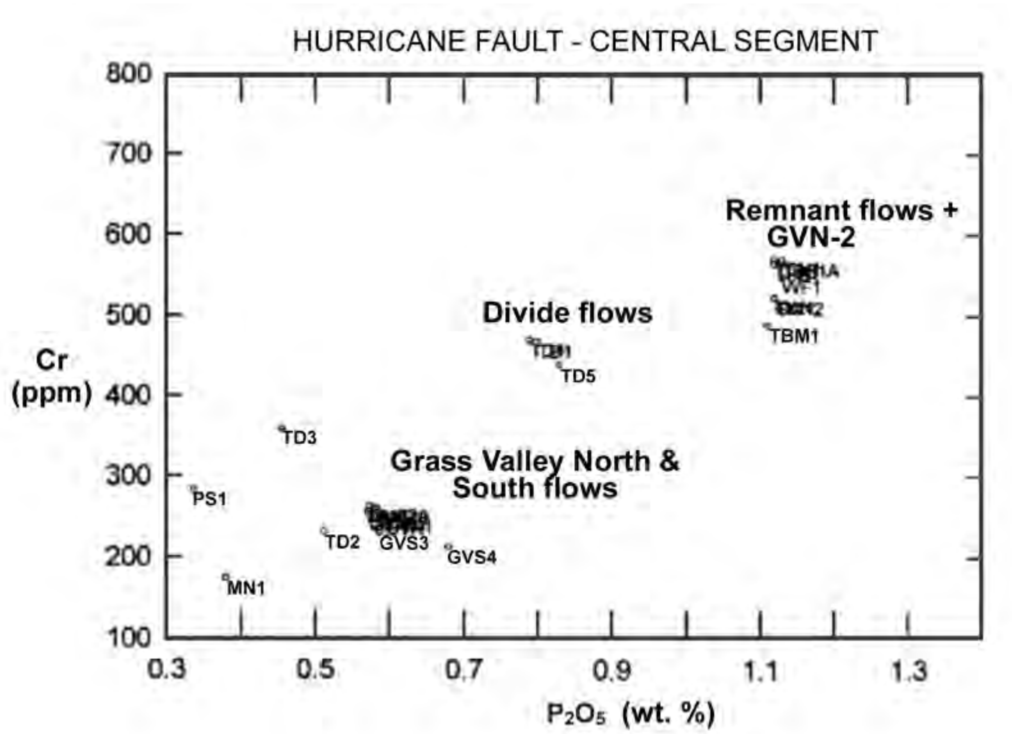
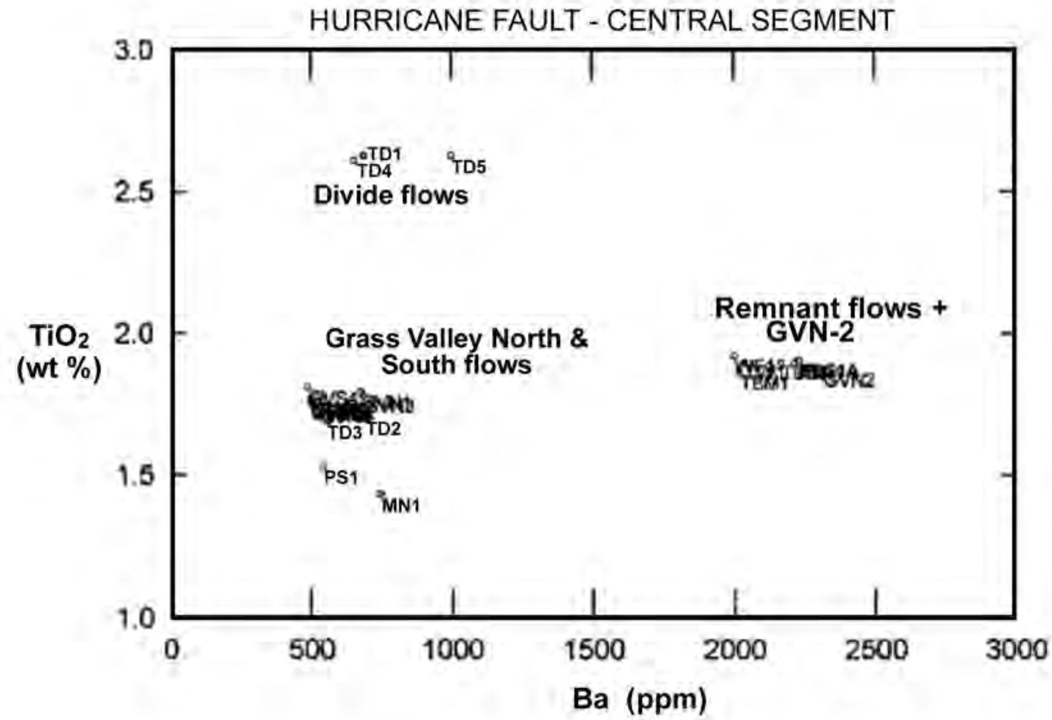
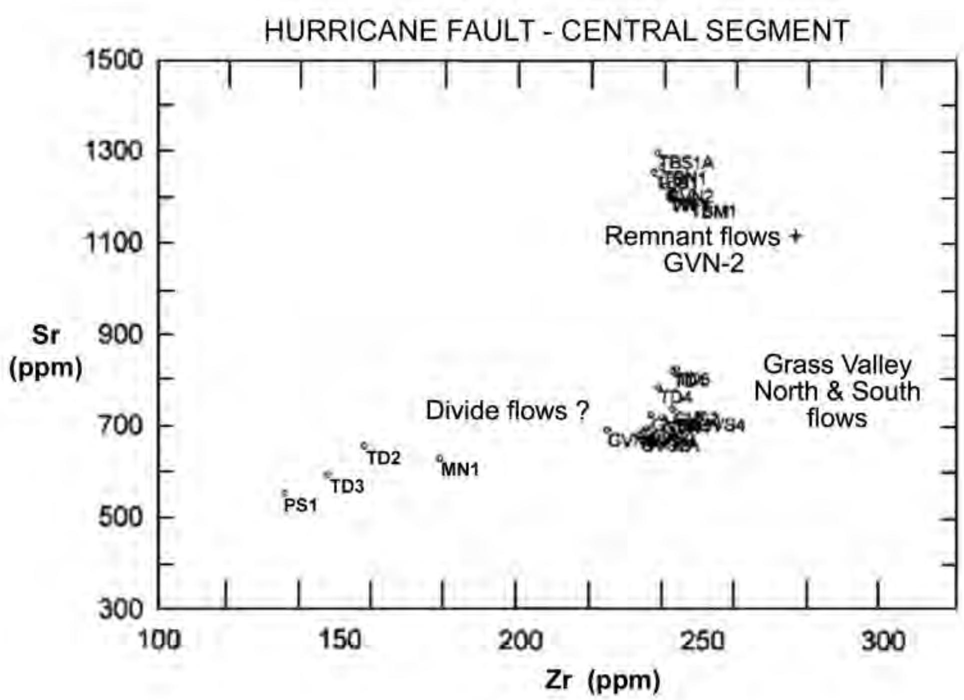


Figure 2. *Anderson Junction segment variation diagrams (see Basalt Geochemistry and Petrology Sample Locations section for sample identification). The three sample clusters show that the basalts on the Anderson Junction segment are geochemically distinctive and permit the basalt units to be correlated across the Hurricane fault.*

***Figure 2.** (continued)*





APPENDIX E

PALEOMAGNETISM OF BASALTS CUT BY THE HURRICANE FAULT

by

Michael Hozik
The Richard Stockton College of New Jersey

Citations in the appendix text are listed in the REFERENCES section of the main report.

PALEOMAGNETISM OF BASALTS CUT BY THE HURRICANE FAULT

by
Michael J. Hozik

INTRODUCTION

The Hurricane fault extends more than 200 km from the vicinity of Cedar City, Utah, to south of the Grand Canyon in Arizona. The fault, which strikes generally to the north and dips to the west, is a normal fault with the down-dropped side to the west (figure 1). The intent of this study was to use the orientation of paleomagnetic vectors preserved in correlative lava flows that had been displaced by the fault to document the amount and nature of the rotation of the various fault blocks.

I selected three areas along the fault in Utah for study based on the presence of lava flows thought to correlate across the fault. The southernmost study area included lava flows on the fault hanging wall in Grass Valley, separated into Grass Valley North (GVN) and Grass Valley South (GVS), and lava flows on the footwall at Mollies Nipple (MN), The Brothers (separated into The Brothers North [TBN], The Brothers Middle [TBM], and The Brothers South [TBS]), White Face (WF), and The Wart

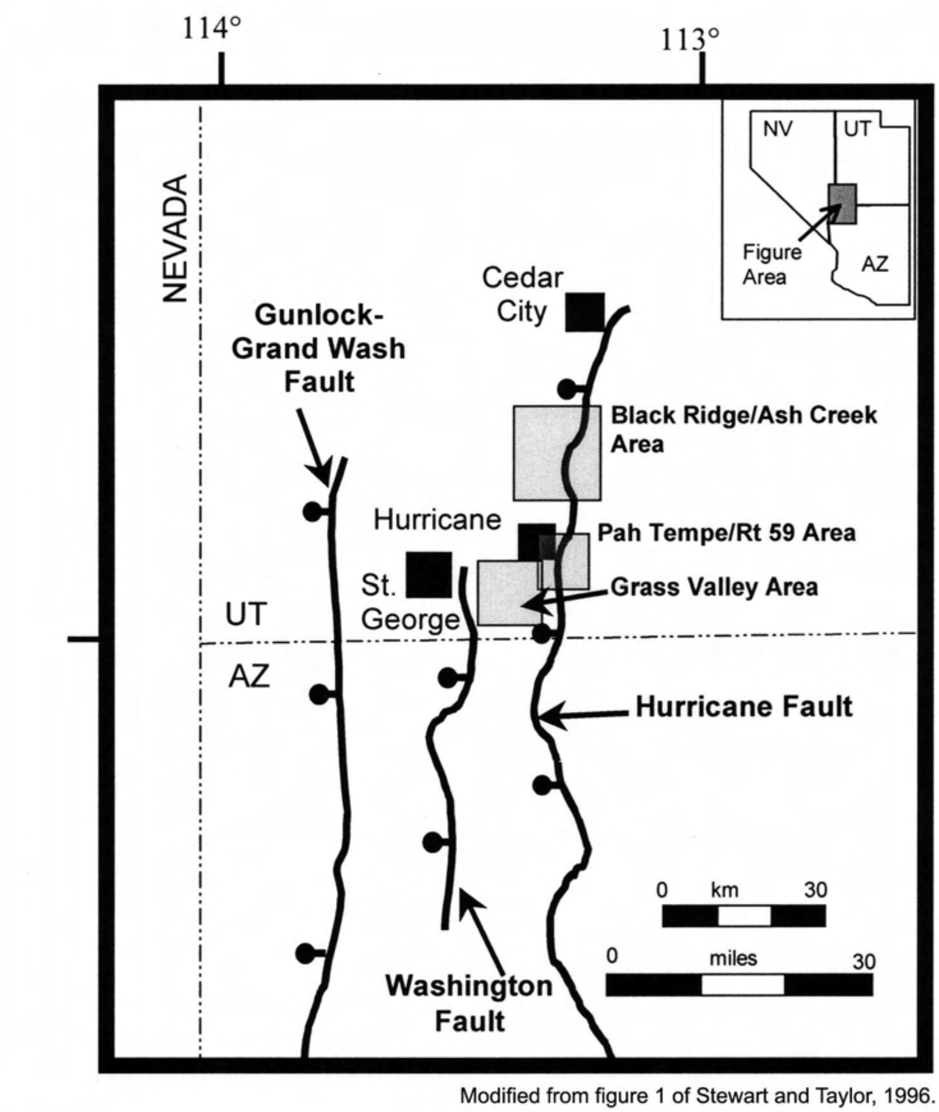


Figure 1. *Index map showing the Hurricane fault, related faults, and the study areas in gray. Towns are shown as black squares for reference.*

(TW). The central study area included lava flows on the hanging wall at Pah Tempe Hot Springs (PT), and on the footwall along Route 59 (RT59). The northern study area included flows on the hanging wall at three localities along Ash Creek: Ash Creek South (ACS), Ash Creek North (ACN), and Ash Creek Interstate (ACI); in the area designated Pintura Graben (PG); along Leap Creek (LC); and an area to the west designated PGW. Localities on the footwall included flows on the southern end of Black Ridge above the town of Toquerville (BRN, BRM, BRS]), and at the northern portion of Black Ridge (BR). Figure 2 (also figure 12 in the main text) shows the site locations.

PROCEDURE

At each locality, I collected at least six samples spaced more than one meter apart from each flow cooling unit. Individual cooling units consist of basaltic layers separated by vesicular rubble zones, thought to mark the tops of flows. I drilled all samples with a portable diamond drill that yielded cores 2.54 cm in diameter and 10 to 20 cm long, and I oriented each core with both a magnetic compass and a sun compass, marking each core with orientation information prior to extraction. After cutting the cores into 2.54 cm lengths for measurement of the remnant magnetism, the individual specimens were labeled A, B, C, etc. with A being the specimen at the bottom of the core.

One specimen from each core was subjected to alternating field demagnetization in a series of steps, and magnetic remanence was measured after each demagnetization step. Measurements were made prior to any demagnetization (NRM), and after demagnetization to 2.5, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, and 90 mT.

I plotted the demagnetization results on Vector Endpoint Diagrams (Zijderfeld, 1967). Study of those diagrams yielded the appropriate demagnetization level for each core. I defined the appropriate level as the minimum level at which the direction of

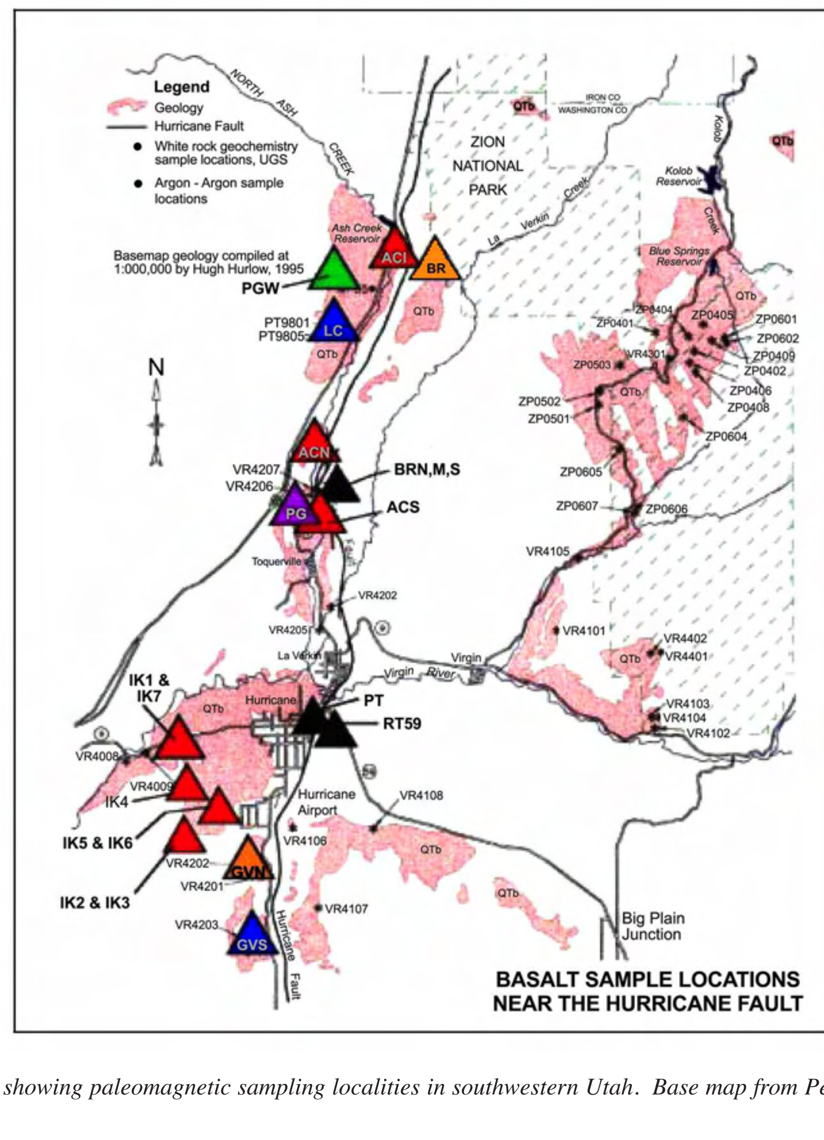


Figure 2. *Sample map showing paleomagnetic sampling localities in southwestern Utah. Base map from Pearthree and others (1998).*

magnetization ceased to change. At higher demagnetization levels, the direction remained constant, but the intensity decreased toward zero. Samples not exhibiting a demagnetization pattern that decreased toward zero were rejected.

I averaged the magnetic declination and inclination from samples that were not rejected using standard paleomagnetic statistical techniques (Fisher, 1953) to determine an average orientation for the site, and an estimate of the error (95% confidence limits). Geochemical data from Stewart and others (1997), Hatfield (2000, personal communication; this report), and Biek (2003) established correlations of flows from the hanging wall and footwall.

RESULTS

Table 1 summarizes the study results. For each locality, the table shows the site designation; the trend and plunge of the mean magnetic vector for the site; the cone of confidence that, at the 95% confidence level, contains the true mean orientation; the radiometric age of the flow based on measurements of correlative flows; Hatfield's (appendix D) geochemical correlation; and a comment on the location.

All of the flows sampled in the Black Ridge/Ash Creek area exhibit reversed magnetization, implying that they are older than 780,000 years, consistent with the radiometric dates. Furthermore, all of the samples on the footwall (BRN, BRM, BRS) yield the same magnetic direction, suggesting that all the flows erupted over a very short period of time. On the hanging wall, localities far from the fault such as Pintura Graben West (PGW), Leap Creek (LC), and the east side of Pintura Graben (PG-2 and PG-4), yield directions indistinguishable from those on Black Ridge. Figure 3, a lower hemisphere, equal area plot of the trend and plunge of the magnetic vectors, shows those results. I am unable to explain the anomalous results at LC-2, although it is worth noting that the uncertainty (α_{95}) is larger for that flow than for any other at that site.

Results from the Ash Creek Interstate (ACI) and Ash Creek South (ACS) sites indicate significant back-tilting toward the fault, referred to as "reverse drag" by Hamblin (1965a). The amount of back-tilting is larger near Toquerville (25 degrees around a horizontal axis trending N 22° W between BRN, BRM, BRS, and ACN) than farther north at Ash Creek Interstate (10 degrees around a horizontal axis trending N 20° E between NBR and ACI). The axes around which the rotation occurred approximately parallel the local strike of the fault.

The western side of the Pintura graben suggests block rotation away from the Hurricane fault, presumably controlled by faulting in Pintura graben and on additional faults farther west. Specifically, rotation between BRN, BRM, BRS and PG-5 is about 8 degrees around a horizontal axis trending N 4° E, and between SBRN, SBRM, SBRS and PG-1 is about 17 degrees around a horizontal axis trending N 28° W. Both of these rotations are away from the fault.

Figure 4 is a lower hemisphere, equal area plot of the trend and plunge of the magnetic vectors from lava flows in the southern portion of the study area. All of these lava flows have a normal magnetization. In the case of the flows at PT and RT59, normal magnetization is consistent with their young radiometric age. The flows from Ivans Knoll and probably correlative flows in the northern part of Grass Valley apparently were extruded during the Jaramillo normal event, 0.99-1.07 million years ago based on radiometric dates from Ivans Knoll (Biek, 2003).

Biek (2003) correlated the lava flows on the hanging wall at Pah Tempe Hot Springs and on the footwall on Route 59 across the Hurricane fault. The similarity in the orientations of the paleomagnetic vectors at those two sites suggests less than 10 degrees of fault-block rotation across the fault.

Lava flows at Ivans Knoll and in the northern part of Grass Valley (GVN), both on the hanging wall of the fault, appear to be correlated magnetically. Unfortunately, results from correlative basalts on the footwall at Mollies Nipple, each of the three Brothers, The Wart, and White Face were unusable. None of those sites gave consistent results within the site, which I interpret to be due to remagnetization resulting from lightning strikes.

Lava flows on the hanging wall in the southern part of Grass Valley (GVS) could correlate with the Ivans Knoll flow, or they could represent another group of lavas entirely. The paleomagnetic results are not precise enough to provide a definitive answer.

DISCUSSION

Figure 5 summarizes the orientations of magnetic vectors. The simplest interpretation of these data is that there are three groups of lavas. The oldest set dates from the time of the Jaramillo event (around 0.99-1.07 million years ago) and includes all the sites labeled IK (Ivans Knoll), Grass Valley North (GVN) and perhaps, Grass Valley South (GVS). Hatfield (this report) separates the GVN and GVS flows geochemically (appendix D). Whether or not they are truly separate events is unclear given the current data. Unfortunately, there is nothing to correlate with them from the footwall on this portion of the fault, because lightning has destroyed the magnetism at Mollies Nipple, The Brothers (North, Middle, and South), White Face, and The Wart; consequently, it is impossible to use them to learn anything about the rotation of fault blocks.

The second group of lavas dates from about 860,000 years ago (Lund and others, 2001). This group includes all the lavas immediately adjacent to the fault on Black Ridge, and most of the lavas on the hanging wall in the Pintura area. The paleomagnetic data indicate about 25 degrees of back-tilting near Toquerville (based on the flows at the southern end of Black Ridge and in Ash Creek), a similar amount in the vicinity of Ash Creek North (although the direction is slightly different, but the axis of rotation is nearly parallel to the strike of the fault at both localities), and about 10 degrees of back-tilting near Ash Creek Interstate.

As distance from the fault increases, the rotation between the hanging wall and the footwall appears to decrease. On the eastern margin of the Pintura graben, there seems to be very little rotation. On the western margin of the Pintura graben, the

Table 1. *Paleomagnetic data from the Hurricane fault study.*

Column labels are self-explanatory, except for Chem, which shows Hatfield's correlations based on geochemistry. Ages for BR and ACI are from Stenner and others (1999). Ages for ACS and GVN are from this study. Ages for IK are from Biek (2003). Ages for RT59 and PT are from Sanchez (1995).

Site	Trend	Plunge	α_{95}	Age	Chem	Comments
BR	166.27	-63.61	3.21	880,000 ± 20 ka	B	Footwall North
BRNMS	164.0	-64	4.39		C	Footwall near Toquerville
AC1	153.51	-58.05	8.23	840,000 ± 30 ka	B	Hanging wall
ACN	145.52	-46.0	3.98			Hanging wall
ACS	119.2	-55.4	4.24	810,000 ± 100 ka	C	Hanging wall
LC1	164.9	-65.6	2.53		A	Hanging wall
LC2	149.9	-64.8	7.9		A	Hanging wall
LC3	169.7	-64.5	2.23		B	Hanging wall
LC4	170.4	-65.9	3.86		B	Hanging wall
PGW1	165.5	-60.2	5.91		B	Hanging wall
PG1	191.1	-56	8.24		C	Pintura Graben - west side
PG4	170.5	-64	9.1		C	Pintura Graben - east side
PG5	186.4	-66.2	6.56		C	Pintura Graben - west side
PG6	164.5	-67.9	4.38		C	Pintura Graben - east side
IK1	333.14	44.9	7.46	1,030,000 ± 20 ka 970,000 ± 70 ka		Ivans Knoll flow (HW)
IK2	333.1	38.5	20.97	1,030,000 ± 20 ka 970,000 ± 70 ka		Ivans Knoll flow (HW)
IK3	Inconsistent		—	1,030,000 ± 20 ka 970,000 ± 70 ka		Ivans Knoll flow (HW)
IK4	312.5	39.0	21.78	1,030,000 ± 20 ka 970,000 ± 70 ka		Ivans Knoll flow (HW)
IK5	Inconsistent		—	1,030,000 ± 20 ka 970,000 ± 70 ka		Ivans Knoll flow (HW)
IK6	327.0	43.4	10.3	1,030,000 ± 20 ka 970,000 ± 70 ka		Ivans Knoll flow (HW)
IK7	324.1	52.7	6.02	1,030,000 ± 20 ka 970,000 ± 70 ka		Ivans Knoll flow (HW)
GVS1	314.8	53.4	5.74			Grass Valley South (HW)
GVS2	Lightning Damage		—			Grass Valley South (HW)
GVS3	310.3	45.6	7.31			Grass Valley South (HW)
GVN1	334.3	44.7	32.3			Grass Valley North (HW)
GVN2	330.5	37.2	24.3	1,470,000 ± 430 ka		Grass Valley North (HW)
Pah Temp	343	50	5.88	353,000 ± 45 ka		Hanging wall
RT59	346	59	2.65	353,000 ± 45 ka		Footwall
MN	Lightning Damage		—			Footwall
TBN	Lightning Damage		—			Footwall
TBM	Lightning Damage		—			Footwall
TBS	Lightning Damage		—			Footwall
WF	Lightning Damage		—			Footwall
TW	Lightning Damage		—			Footwall

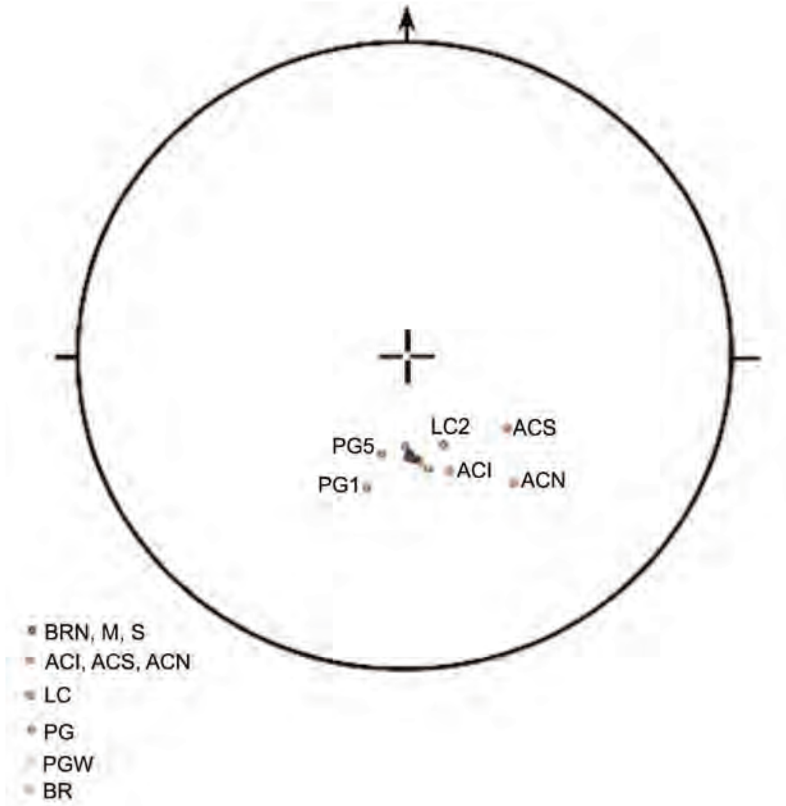


Figure 3. *Magnetic vectors from basalts on Black Ridge and correlative lava flows.*

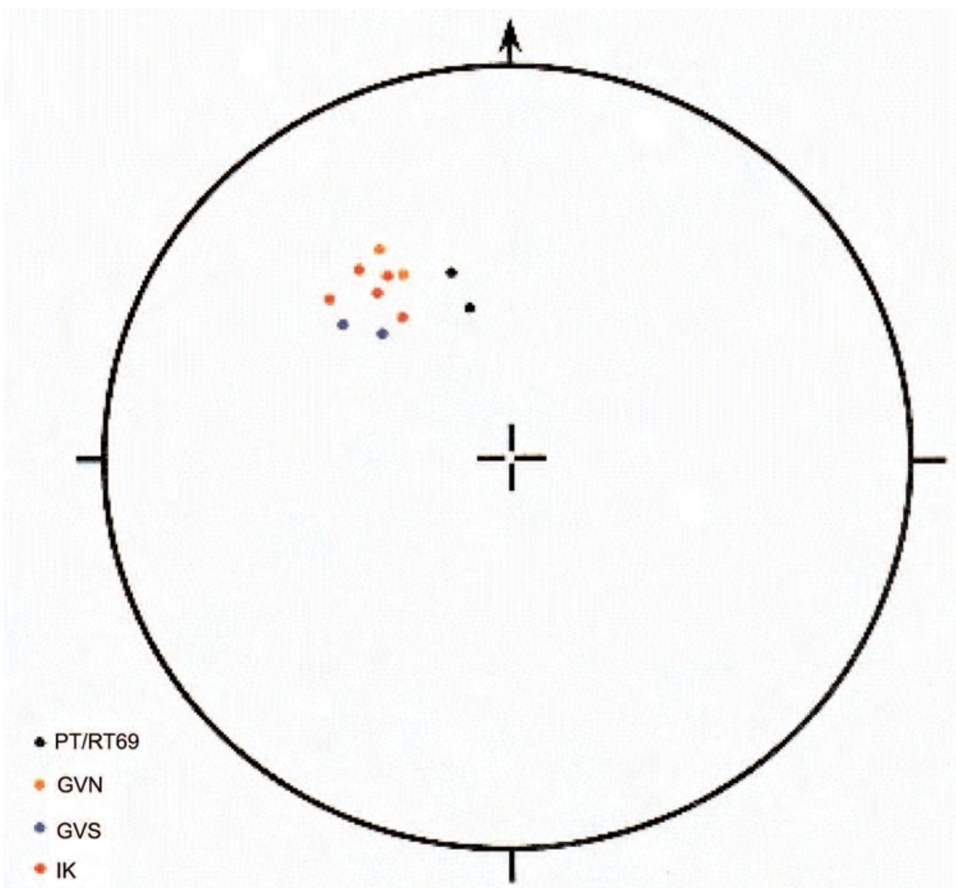


Figure 4. *Magnetic vectors from basalts from Ivans Knoll, Grass Valley, and Pah Tempe/RT59.*

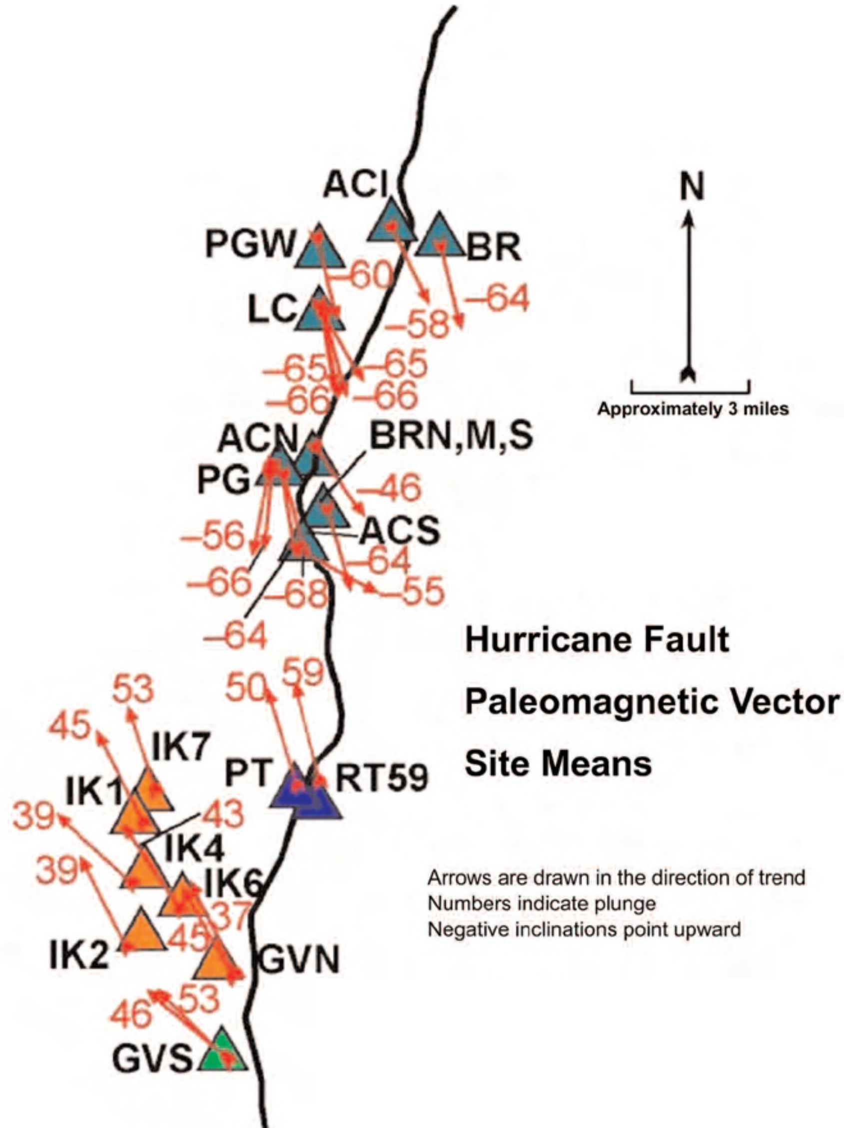


Figure 5. Summary of magnetic vector orientations.

rocks are tilted away from the fault, relative to the rocks on Black Ridge. Finally, at Leap Creek (with the possible exception of the second flow from the bottom) and at our westernmost site, PGW, there appears to be no rotation relative to the basalts on Black Ridge. The simplest interpretation for these data is that there is back-tilting immediately adjacent to the fault, a gradual return to untilted lavas at Pintura graben, with motion on the faults in the graben and to the west tilting the western margin of the graben away from the Hurricane fault. To the west, that rotation is taken out on other antithetic faults, so that at PGW, there is no rotation relative to Black Ridge.

The third group of lavas appears at Pah Tempe and Route 59 (hanging wall and footwall, respectively). There is less than 10 degrees of rotation between these two sites. These lavas are thought to be about 353,000 years old (Sanchez, 1995), and that is consistent with the normal magnetization found in those rocks.

CONCLUSIONS

- The oldest lava flows appear to be those of Ivans Knoll and Grass Valley North. This group may or may not include flows at Grass Valley South, which are geochemically different, although the magnetic data are ambiguous. These flows all carry normal magnetization and were extruded during the Jaramillo normal magnetic event between 0.99 and 1.07 million years ago. These flows are on the hanging wall of the fault, and there is no useable magnetic data from flows on the footwall to permit a calculation of back-tilting.

- All of the lava flows in the Black Ridge/Ash Creek area are reversely magnetized and older than 780,000 years, consistent with radiometric dates which give an age of approximately 860,000 years. The flows are magnetically indistinguishable, but can be subdivided based on geochemistry. They may be treated as a single group for the purposes of analyzing the amount of back-tilting.

- There is approximately 25° of back-tilting between Black Ridge and Ash Creek South and between Black Ridge and Ash Creek North. The amount of back-tilting decreases northward to Ash Creek Interstate where it is about 10 degrees. The axis of rotation tends to parallel the strike of the fault.

- West of Pintura graben it appears that there is no back-tilting toward the Hurricane fault, and that the lavas are essentially lying on the original paleoslope.

- In the vicinity of Pintura graben, the western margin has been tilted away from the Hurricane fault, probably due to movement on multiple synthetic and antithetic faults associated with the formation of small grabens there and to the west.

- The youngest lava flows are those at Pah Tempe and along RT 59. Sanchez (1995) dated them at 353,000 years, and they are normally magnetized. Biek (2003) correlates these two flows. There is less than 10 degrees of rotation across the fault in this area.