12-1994

Structural analysis of the Hurricane fault in the transition zone between the basin and range province and the Colorado Plateau, Washington County, Utah

Meg E. Schramm
University of Nevada, Las Vegas

STRUCTURAL ANALYSIS OF THE HURRICANE FAULT IN THE TRANSITION ZONE BETWEEN THE BASIN AND RANGE PROVINCE AND THE COLORADO PLATEAU, WASHINGTON COUNTY, UTAH

by

Meg E. Schramm

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

Geoscience

Department of Geoscience
University of Nevada, Las Vegas
December 1994

The Thesis of Meg E. Schramm for the degree of Master of Science in Geoscience is approved.

[redacted]

Chairperson, Wanda J. Taylor, Ph.D.

[redacted]

Examining Committee Member, Eugene I. Smith, Ph.D.

[redacted]

Examining Committee Member, David L. Weide, Ph.D.

[redacted]

Examining Committee Member, Michael L. Wells, Ph.D.

[redacted]

Graduate Faculty Representative, Margaret M. Lyneis, Ph.D.

Dean of the Graduate College, Ronald W. Smith, Ph.D.

University of Nevada, Las Vegas
December 1994

ABSTRACT

This study defines fault segments and segment boundaries along the Hurricane fault in southwestern Utah and determines the geometric and kinematic relationship to other regional structures. Fault segment identification is critical for understanding fault processes and seismic risk; segment length is the maximum earthquake rupture length along a fault. Segment boundaries may act as barriers to earthquake propagation.

Normal fault segmentation only recently has received attention and has never been studied along the Hurricane fault. The fault changes strike along its length, and is thus a segmented fault. This study documents one nonconservative segment boundary and two fault segments, the Ash Creek segment and the Anderson Junction segment, based on fault geometry, scarp shape, and shortening structures in the hanging wall and footwall. A rupture along the Ash Creek segment may affect Cedar City, UT, and a rupture along the Anderson Junction segment may affect St. George, UT and a number of smaller nearby towns. Previously undocumented surface offsets were observed along both segments. Evidence that Quaternary slip along the Hurricane fault is predominately normal includes offset of geochemically identical Quaternary (?) basalt, slickenlines, hanging wall dip analysis, and the 89° rake of the 1992 St. George earthquake.

The Hurricane fault and the Gunlock-Grand Wash fault system, which lies 50 km to the west, may be a linked system whereby the two en echelon faults form a displacement transfer zone that generates the relatively wide transition zone between the Basin and Range province and the Colorado Plateau in the region. Data from both faults that support the existence of a transfer zone include symmetric changes in stratigraphic separation, similar timing of fault motion, and balanced regional cross sections.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

ACKNOWLEDGEMENTS

Financial support for this research project was provided by grants from the Geological Society of America, Sigma Xi Grants-in-Aid, the University of Nevada, Las Vegas Graduate Student Association, the Business and Professional Women's Foundation Career Advancement program, the University of Nevada, Las Vegas Geoscience Department Scroungers, and the University of Nevada, Las Vegas-National Science Foundation Women in Science program. I also acknowledge a University of Nevada, Las Vegas Grant and Fellowships Committee Research Grant to Wanda Taylor.

A number of people helped directly to bring this project to fruition and must be thanked individually. Much gratitude is due to my advisor, Wanda Taylor, and to my committee members, Gene Smith, Dave Weide, Michael Wells, and Margaret Lyneis, who reviewed and helped improved the manuscript. Gene Smith provided his invaluable expertise with the basalt analyses. Shirley Morikawa kindly performed the XRF analysis. Insights and encouragement in the field were provided by Lehi Hintze, Gary Christenson, and Phil Pearthree. Susan Nava generously provided unpublished earthquake data. Kelly Rash made thin sections in a pinch. Alex Sanchez and Holly Langrock read a draft of the manuscript which helped to improve content and flow. In addition to supplying field and travel gear, moral support was freely given to me by Peg Rees. Additional moral support, field encouragement and prodding were provided by Jill Schneiderman.

CHAPTER 1

INTRODUCTION

The mechanics of normal faults have been modeled by many, but the processes involved remain unclear and controversial. Several different models have been constructed to explain the processes of intracontinental extension (Bally, 1981; Gibbs, 1983; 1984; Wernicke, 1981; 1985; Lister and others, 1986; Buck, 1988; Buck and others, 1988; Wernicke and Axen, 1988), but they do not provide a single definitive answer. To further the understanding of extensional faulting processes, in particular fault kinematics, fault segmentation, displacement transfer and footwall flexure, this detailed study of the less-extended border region of the Basin and Range was conducted. This less-extended area is the physiographic province boundary region termed the transition zone, which lies between the Basin and Range province to the west and the Colorado Plateau to the east (figure 1). The Basin and Range province exhibits widespread Cenozoic normal faulting whereas the Colorado Plateau, a late Cenozoic epeirogenic uplift of the Cambrian to Mesozoic cratonal section, is only slightly extended (Bjarnason and Pechmann, 1989). The transition zone is a complex structural zone that displays tectonic features common to both provinces. It has experienced less strain than internal parts of the Basin and Range and is an ideal location to study normal faulting because important data may not be obliterated by multiple overprinting faulting events such as in more highly extended regions in the Basin and Range. The transition zone, and the study of the normal faults therein, may provide a near end member model

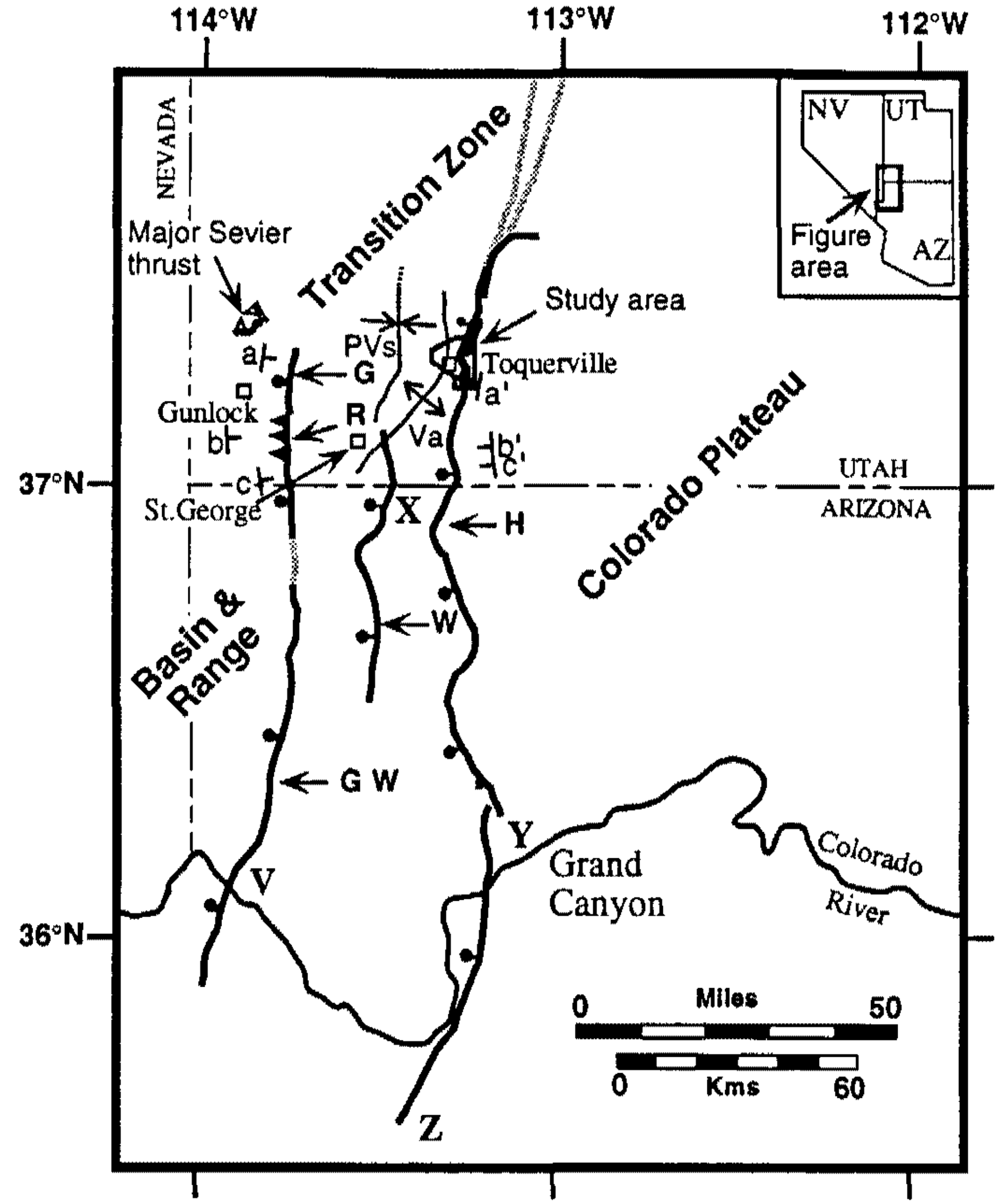


Figure 1: Location map of major faults in southwestern Utah and northwestern Arizona (bar and ball on downthrown side, stippled where the fault is concealed; teeth on upper plate.) G = Gunlock fault; GW = Grand Wash fault; H = Hurricane fault; R = Reef Reservoir fault; W = Washington fault; PVs = Pine Valley syncline; Va = Virgin anticline. Major thrust is the Sevier-age Square Top Mountain thrust. Symbols V, X, Y, and Z are referred to in the text. Area outlined near the town of Toquerville is the study area and is shown in greater detail in figure 3. Cross sections drawn along a-a', b-b', and c-c' are shown in figure 17. Structural data compiled from Hintze (1975) and Reynolds (1988).

on a continuum with the more extremely thinned Basin and Range province at the other end.

A section of the Hurricane fault in southwestern Utah marks the western boundary of the Colorado Plateau, and so, lies within the transition zone (figure 1). The Hurricane fault is a major, active, high-angle west-dipping normal fault. Because the strike of the fault changes along its length, the Hurricane fault is a segmented fault. The purpose of this study is to analyze in detail part of the Hurricane fault to define segment boundaries and determine the geometric and kinematic relationship to other structures in the region. This study focuses on 1) the kinematics of the fault, including total amount of stratigraphic separation, sense of motion, and direction of motion; 2) the amounts of stratigraphic separation observed in the Quaternary and the Holocene units; 3) the structural effects of fault segment boundaries on the hanging wall and footwall blocks; and 4) the potential geologic hazards of the area. On a more regional scale the relationship of the Hurricane fault to other nearby structures, such as regional scale folds and faults, is addressed.

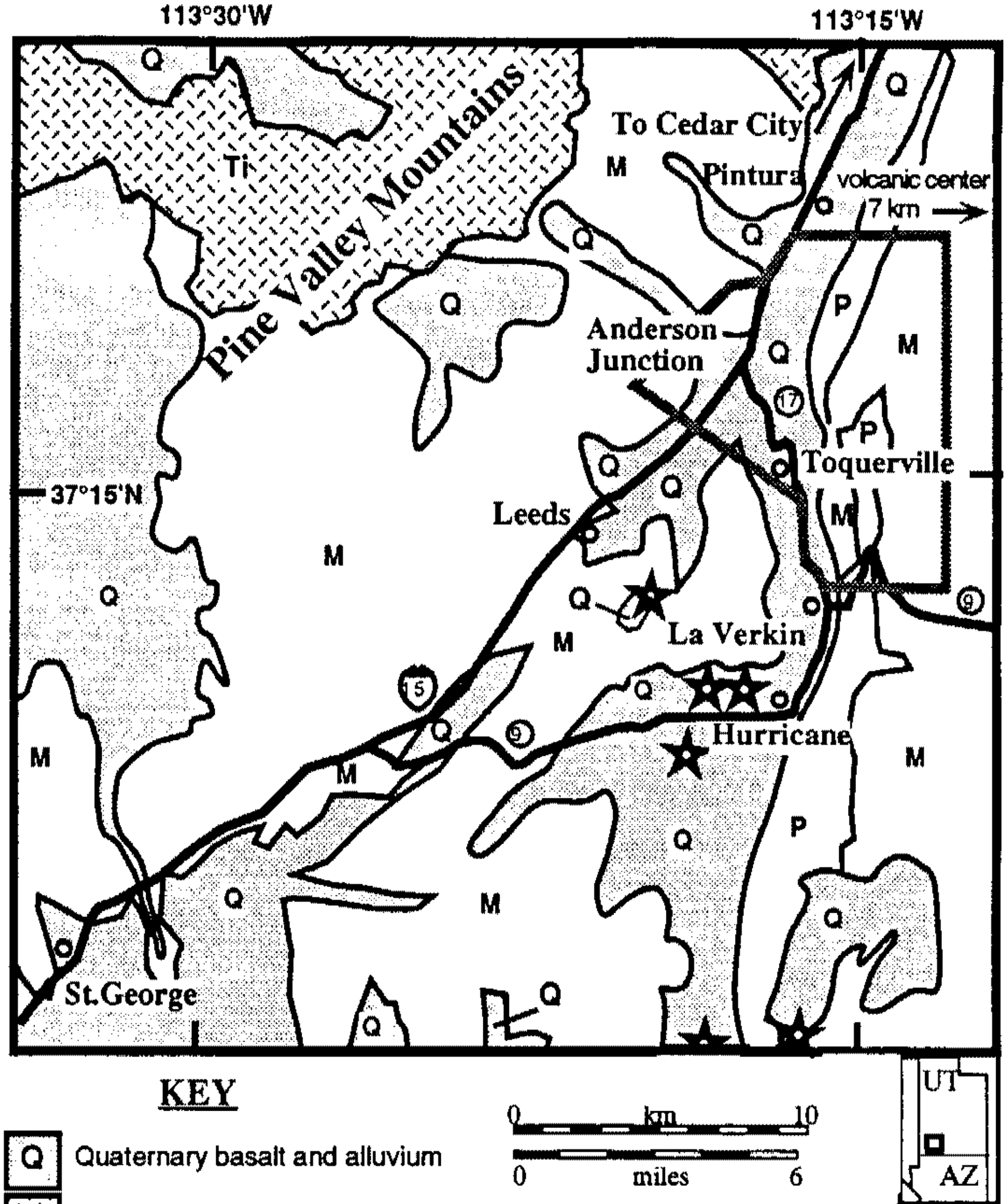
Fault segments were not identified previously along the Hurricane fault in Utah. This study documents a fault segment boundary near a major bend in the Hurricane fault. Along the fault segment to the north of the segment boundary, here termed the Ash Creek segment, motion is purely dip-slip, but along the southern fault segment, here termed the Anderson Junction segment, motion is dominantly normal dip-slip with a slight dextral component. Previous fault segmentation studies concluded that segment boundaries may be the sites of significant strain, may impede rupture propagation, and may greatly influence the locations of earthquakes (e.g., Schwartz and Coppersmith, 1984 ; Bruhn and others, 1987; Bruhn and others, 1990; Susong and others, 1990; DePolo and others, 1991).

Holocene ruptures along much of the Hurricane fault have not been recorded previously. This study, however, documents three locations along the fault where

Holocene alluvium is offset within the study area; the greatest offset measures 6 m. A range of fault slip vectors was determined from the 450 m of stratigraphic separation of Quaternary (?) basalt cropping out in the hanging wall and footwall of the Hurricane fault and analyzed in this study to be geochemically the same. The slip vector data used in conjunction with hanging wall dip analysis, which provides direction of transport information (Scott and others, 1994), indicates a slip direction of approximately N75°W in the study area, which also agrees with regional stress field analyses (Zoback and Zoback, 1980; Arabasz and Julander, 1986).

The Hurricane fault study area is located approximately 30 km northeast of St. George, Utah (figure 2). The 92 km^2 mapped area straddles the Hurricane fault with the relatively flat-lying strata of the Colorado Plateau to the east. To the west are the Pine Valley Mountains, predominantly composed of a large Cenozoic laccolith, and the deep basins and high ranges typical of the Basin and Range province. Two regional scale anticlines, the Pintura fold and the Virgin anticline, crop out within the study area; based on gravity anomaly data (Cook and Hardman, 1967) and a balanced and restored cross section, the anticlines are interpreted to be genetically related, Sevier-age structures. A third large fold, the Toquerville fold, is unrelated to the other two folds but may be a product of footwall flexure (cf., Buck, 1988; Wernicke and Axen, 1988).

Previous studies (e.g., Huntington and Goldthwait, 1904; Dobbin, 1939; Gardner, 1941; Cook, 1957; Averitt, 1962; Hamblin, 1965; 1970; Lovejoy, 1964; Kurie, 1966; Watson, 1968; Anderson and Mehnert, 1979) provided a basis for this study but lacked the more recent insights and hypotheses on normal fault kinematics and fault segmentation theories. Also, the present study employed a larger map scale than was previously utilized which furnished detail for the analysis of structures found in the hanging wall and footwall of the Hurricane fault to formulate more accurate interpretations in light of the new normal faulting theories.



KEY

Figure 2. Location map of the study area (outlined by dark stipple) with highways, towns and generalized geology labeled. The index map (lower right) outlines area of figure 2. Geology modified from Hintze (1963) and Hintze (1980).

Geologic Background

The geologic history of southwestern Utah includes a time when the area was a passive margin, which was followed by a period of regional compression and uplift. Tectonic quiescence followed orogenic activity, and the current tectonic regime is extensional. A more detailed geologic history of the area follows.

Southwestern Utah was the site of a passive margin during the late Paleozoic and into the Mesozoic. Sedimentary rock formations were deposited dominantly in the miogeocline of the passive margin and near the craton margin and record a fluctuating sea level but an overall regressive series for the area. The Paleozoic and Mesozoic units predate all deformation in the region (Armstrong, 1968).

During the Cretaceous, thrust faults of the Sevier orogenic belt cut the area west and northwest of the Hurricane fault and Pine Valley Mountains (figures 1 and 2) (Armstrong, 1968; Cowan and Bruhn, 1992). Moderate folding and warping of Jurassic and older rocks occurred during this orogeny. Inconsistencies pervade the literature concerning the naming of the timing of this folding; some workers in the area prefer the term Laramide orogeny (i.e., Gardner, 1941; Kurie, 1966), which took place between the late Cretaceous and Middle Eocene, and others prefer the Sevier orogeny, occurring between early Cretaceous and Campanian time (i.e., Armstrong, 1968). The preferred designation for contractional structures in this discussion is Sevier for several reasons. Obviously, overlapping orogenic events may have occurred, but the Laramide predominately affected areas north and east of the Colorado Plateau (Dickinson and Snyder, 1978) and regional structures in southwestern Utah appear to parallel documented Sevier thrust belt frontal structures. Also, the structural style differs between the Sevier and the Laramide; the Sevier orogenic belt consists of thin-skinned thrust belts, in contrast, the Laramide orogeny resulted in large basement uplifts involving reverse to steeply dipping thrust faults. A major regional fold pair, the Virgin anticline and the Pine Valley syncline, occurs in the vicinity (figure 1) (E. Cook, 1957;

K. Cook and Hardman, 1967; Blank and Kucks, 1989). The Virgin anticline crops out within the study area (figures 1 and 3) and is within the hanging wall of the Hurricane fault. The folds may be footwall folds related to Sevier thrusting (Armstrong, 1968) or related to extension formed during flexure of this block (Buck, 1988; Wernicke and Axen, 1988). Footwall folding commonly accompanies extensional deformation (Spencer, 1984, 1990; Wernicke and Axen, 1988; Turner and Glazner, 1990; Yin, 1991) whereas hanging wall flexure may be related to non-planar fault geometry (Hamblin, 1965; Gibbs, 1984; Bruhn and others, 1987).

During the early and into middle Tertiary the study area underwent a period of tectonic quiescence (Cook, 1957). Early and middle Tertiary erosion of the thrust belt resulted in deposition of sediments of the late Paleocene to Oligocene Claron Formation (Gregory, 1951; Mackin, 1960; Bowers, 1972; Goldstrand, 1990; Taylor, 1993). Major regional magmatism occurred in the area during the Oligocene and Miocene, with volcanism beginning at about 33 Ma just north of the Pine Valley Mountains and migrating southward in time (e.g., Rowley and others, 1979; Best and Grant, 1987; Best and others, 1989). Between ~20 and 22 Ma the Pine Valley laccolith and other intrusions were emplaced (Armstrong, 1963; Nelson and others, 1992). Extension began in the Oligocene north of the Pine Valley Mountains and in the Miocene in the vicinity of the Pine Valley Mountains (Gardner, 1941; Cook, 1952; 1957; Mackin; 1960; Taylor and Bartley, 1992; Axen and others, 1993). Extension continued from the Miocene into the Quaternary in the vicinity of the Pine Valley Mountains.

The age of first motion of the Hurricane fault is unknown. Based on stratigraphic and structural relationships some workers suggest an initiation age of Miocene (Gardner, 1941; Averitt, 1964; Hamblin, 1970), contemporaneously with laccolith emplacement (Cook, 1957), and others suggest Pliocene or Pleistocene for some sections of the fault (Anderson and Mehnert, 1979; Anderson and Christenson, 1989). Anderson and Mehnert (1979) assert that only up to 850 m of total displacement

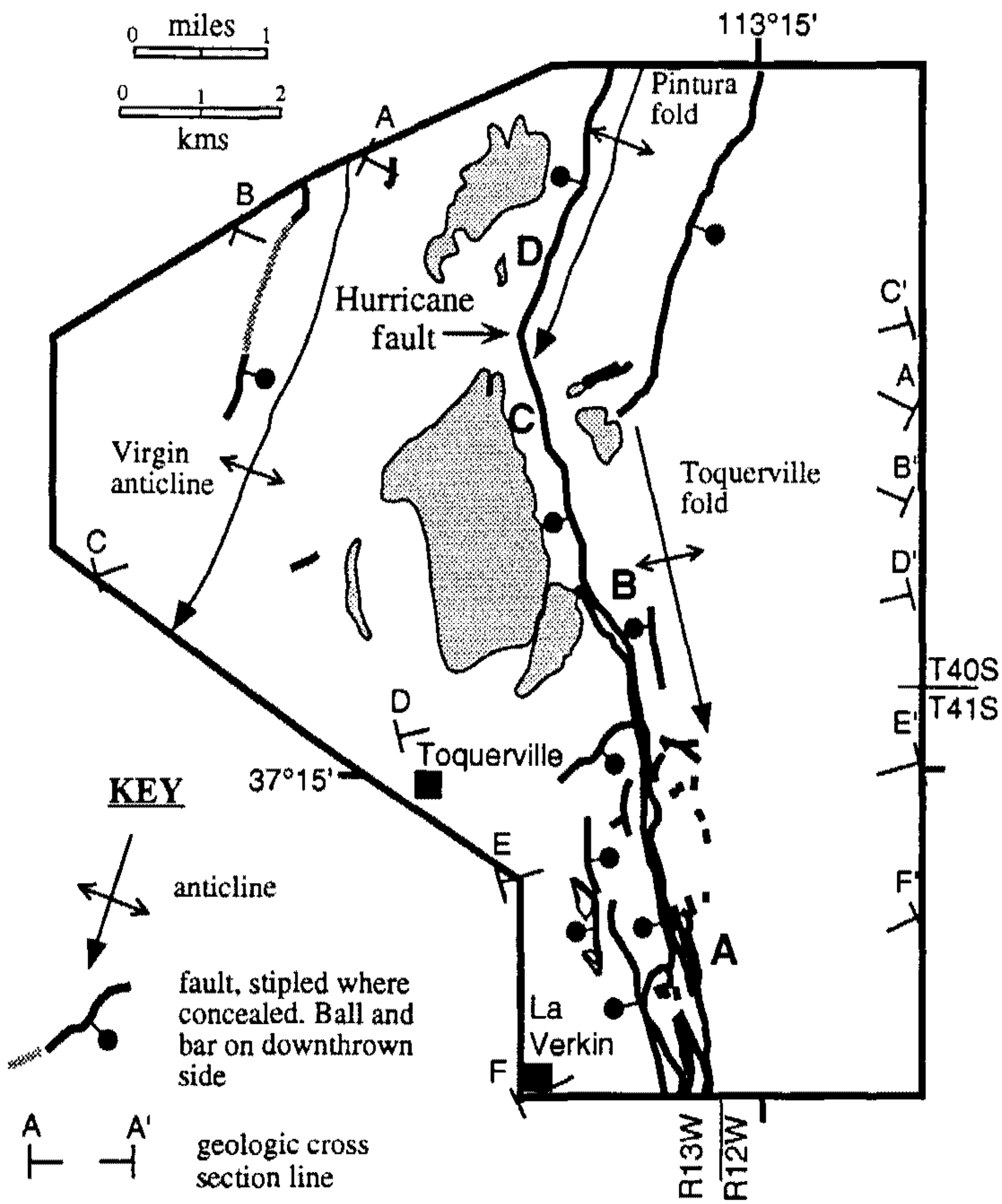


Figure 3. Simplified structure map of the Hurricane fault field area in Utah. Cenozoic basalt fields are stippled. The Virgin anticline, the Pintura fold and the Toquerville fold are shown. Fault sections are labeled with large, bold A, B, C, and D are referred to in the text. Cross sections A-A' through F-F' are shown constructed in figures 8A to 8F.

occurred along the fault based on the structural level of the top of the Navajo Sandstone in the St. George basin compared to the same contact on the Colorado Plateau. Near Toquerville, Utah, this study documents 450 m (1500 ft) of stratigraphic separation of Quaternary (?) basalt and a total stratigraphic separation of up to 2070 m (6800 ft). Because the Quaternary (?) basalt is offset less than older units, motion on the Hurricane fault initiated prior to basaltic volcanism and is likely to have begun as early as Late Miocene or Early Pliocene. However, the basalt in this area has not been dated, so rates of slip cannot be defined.

Although the age of onset of motion along the Hurricane fault is unknown, the fault is known to still be active. Recent seismicity on the Hurricane fault indicates that it is still active (Arabasz and others, 1992a; 1992b; Pechmann and others, 1992), and my new mapping of fault scarps provides evidence of Holocene and Quaternary surface motion.

Field and Instrumental Methods

Employing standard geologic mapping techniques, a base map scale of 1:12,000 from enlarged 1:24,000 scale U.S. Geological Survey topographic maps was used to generate a more detailed database than was currently available. The stratified rocks and major structures in the 92 km^2 (35 mi^2) study area were mapped during three months in the summer of 1993.

A total of thirteen Quaternary (?) basalt samples were analyzed to determine whether lava flows in the footwall of the Hurricane fault were the same as the flow rocks in the hanging wall. If these are the same flows, then a slip vector and amount of Quaternary offset can be measured because the flows are essentially wide but linear features that form piercing points. Samples were collected from the footwall and the hanging wall of the Hurricane fault in three stratigraphic sections and analyzed for trace and major elements (Table 1). The trace and major element analyses were determined by X-ray fluorescence spectrometry by Shirley A. Morikawa at the University of Nevada, Las Vegas. Detailed methods are listed in Appendix I.

Balanced cross sections were constructed along six different lines perpendicular to the strike of the Hurricane fault to analyze for along-strike variation. A discussion of the techniques used is in Appendix II.

CHAPTER 2

STRATIGRAPHY

The rocks exposed in the field area are predominately Paleozoic and Mesozoic sedimentary units typical of the cratonal section of the Colorado Plateau (figure 4). The formations are briefly discussed here. Detailed descriptions can be found in Appendix III.

The oldest unit cropping out in the study area is the Permian dolomite of the Pakoon Formation (McNair, 1951) that underlies Permian quartz sandstone of the Queantoweap Formation (McNair, 1951). The Toroweap Formation (McKee, 1938) overlies the Queantoweap Formation and comprises a lower gypsiferous member, a middle limestone member, and an upper gypsiferous member. The Permian Kaibab Limestone (Darton, 1910; Reeside and Bassler, 1922; Noble, 1928) conformably overlies the Toroweap Formation.

Lying disconformably above the Kaibab Limestone is the Triassic Moenkopi Formation, composed largely of gypsiferous sandy mudstone with intercalated limestone beds (Ward, 1901; Reeside and Bassler, 1922; Gregory and Williams, 1947; Gregory, 1950). Disconformably above the Moenkopi Formation is the Triassic Chinle Formation (Thomas and Taylor, 1946; Gregory, 1950). The basal Shinarump conglomerate member of the Chinle Formation is cross-bedded sandstone that contains varying amounts of rounded pebbles (Powell, 1873; Gilbert, 1875). Above the Shinarump conglomerate, the Chinle Formation consists of alternating beds of

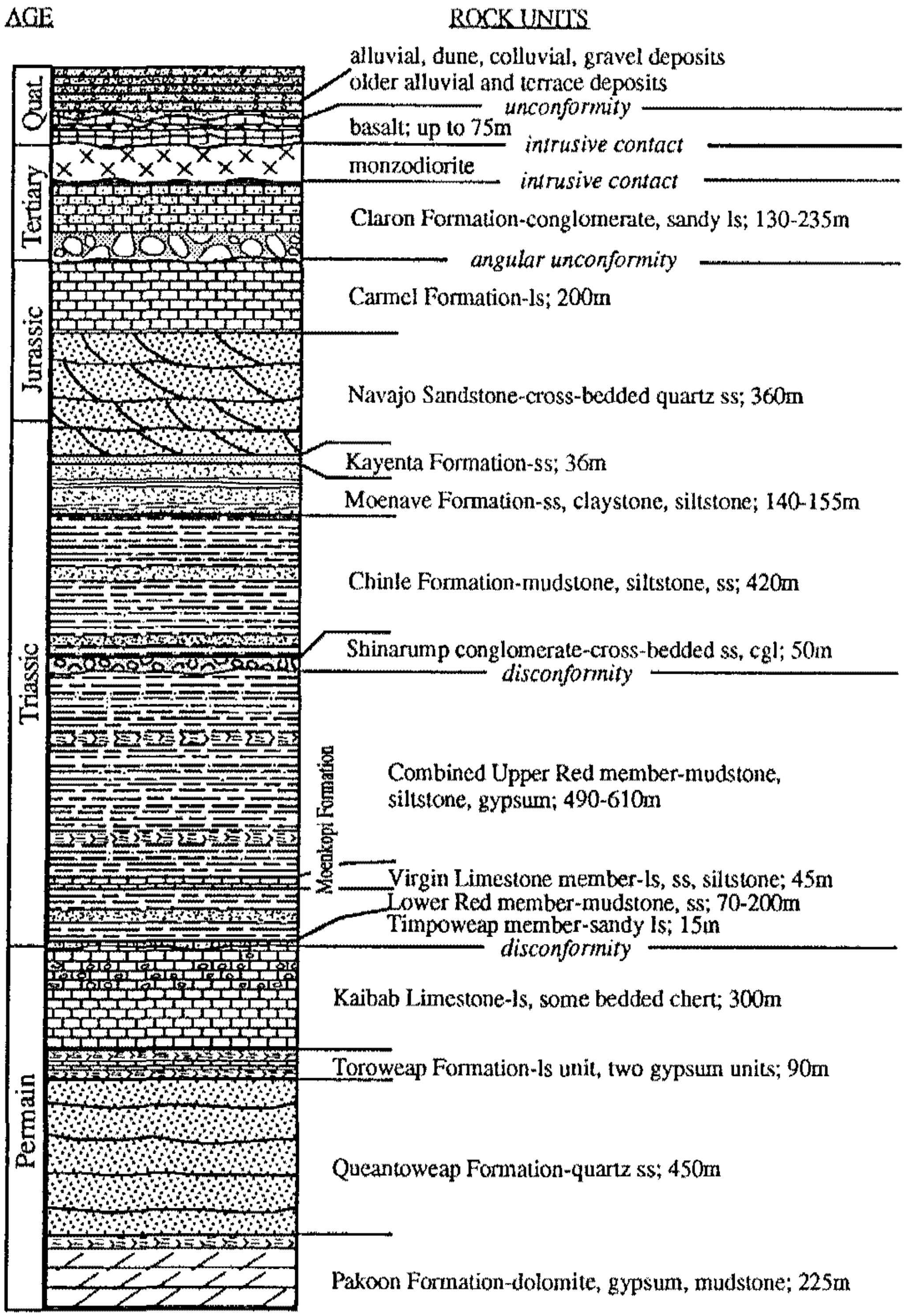


Figure 4. Stratigraphic column of rock units in the study area showing relative thicknesses of each unit. The Kayenta and Moenave Formations do not crop out in the field but are inferred to be present in the cross sections due to local occurrence of these units in well logs. Abbreviations: ss = sandstone, ls = limestone, cgl = conglomerate

sandstone and shale. Although it does not crop out in the study area, the Triassic Moenave Formation disconformably overlies the Chinle Formation and is composed of alternating sandstone, siltstone and claystone (Harshberger and others, 1957). A sandstone unit with some minor conglomerate, the Triassic Kayenta Formation (Thomas and Taylor, 1946; Gregory, 1950; Averitt and others, 1955) is not exposed in the field area but regionally overlies the Moenave Formation. The Triassic-Jurassic Navajo Sandstone overlies the Kayenta Formation and is a very thick bedded cross-bedded sandstone (Huntington and Goldthwait, 1904; Gregory and Williams, 1947; Williams, 1952). Comformably overlying the Navajo Sandstone is the Upper Jurassic Carmel Formation that consists of reworked Navajo Sandstone, gypsiferous shales, and arenaceous limestone (Gregory and Moore, 1931). In the study area, these Paleozoic and Mesozoic rock units have a total thickness of approximately 3230 m (10,600 ft).

Early Paleocene to Oligocene rocks of the Claron Formation were deposited in a continental basin formed following the Mesozoic Sevier orogeny and record a change from compressional tectonics to Oligocene volcanism and possibly earliest extension in the area (Appendix III) (Taylor, 1993). Tertiary igneous rocks in the area include small intrusions related to the Pine Valley laccolith (Cook, 1957 and Appendix III) and Quaternary (?) basalt. Intrusions are composed of gray monzodiorite. Four small Quaternary age basaltic cinder cones and flows crop out south of the area and one volcanic center occurs to the east (figure 2) (Hintze, 1963; Best and Brimhall, 1974; Hausel and Nash, 1977; Best and others, 1980; Hintze, 1980). These cones may have supplied the basalt that crops out within the study area. The stratigraphy of Quaternary (?) basalt flows occurring in both the footwall and the hanging wall of the Hurricane fault are an integral part of the study and are treated in detail below.

Unconsolidated or poorly consolidated sedimentary deposits of Quaternary age include older terrace deposits, older alluvium, older stream gravel, younger stream deposits, colluvium and alluvium. Older alluvium, with an unknown age, is faulted in three places along the Hurricane fault in the field area.

Quaternary (?) Extrusive Rocks

Basalt crops out in the hanging wall and footwall of the Hurricane fault and consists of five individual flows each from 3 to 9 m thick. The flows appear to have been extruded in a relatively brief time span because no evidence of soil formation between flows was observed. Surfaces are both pahoehoe and aa. The rocks have not been dated, but similar basalt in the vicinity was dated by the K/Ar method and falls between 0.3 and 1.1 Ma (Best and others, 1980).

Phenocryst composition in the basalt flows changes upsection. The lowest units are olivine-bearing basalt. Olivine crystals are 1-2 mm across, green and glassy. Upsection, the middle unit contains 1-4 mm blocky, acicular plagioclase crystals, and olivine crystals <1 mm across that commonly have an oxidation ring. The youngest basalt flow contains glomerocrysts of olivine 0.3 to 1 cm in size in a matrix of plagioclase laths. All flow surfaces are shiny black, typically with desert varnish and/or lichen. Fresh surfaces are gray-black for all flows. The total thickness of the basalt section is up to 75 m (250 ft).

Basalt from three locations was studied in thin section: AC (Ash Creek), T (Toquerville), and P (Pintura) (figure 5). For the purpose of correlating flows between the different sites two samples were collected at each of the three sites, one from the lowest flow and one from the youngest flow. At site P in the hanging wall of the Hurricane fault, the lowermost flow has a trachytic texture with aligned laths of plagioclase and subhedral olivine. There are two populations of plagioclase; xenocrysts up to 4 mm in diameter with highly corroded rims and acicular blades in the matrix, less than 1 mm in length. Euhedral olivine as long as 1.5 mm are altered to iddingsite and Fe-oxide and minor magnetite is present. The uppermost flow has a felty texture and is

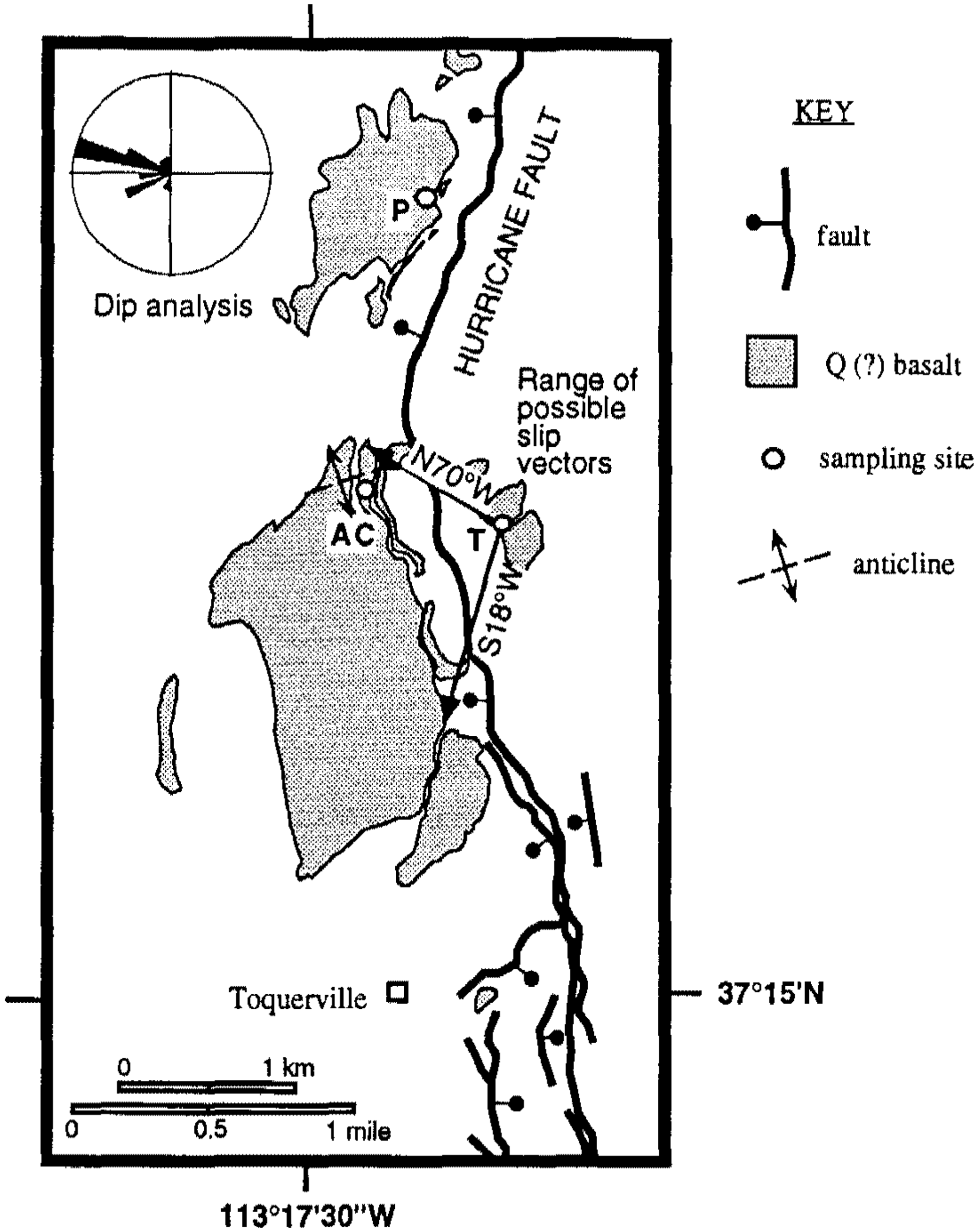


Figure 5. General location map of basalts in the study area in southwestern Utah. Circles indicate where sections were sampled. T=Toquerville, AC=Ash Creek, and P=Pintura. The range of possible slip vectors was determined by geochemically correlating basalt at T with basalt at AC using the X-ray fluorescence method and assuming that the basalt field that AC was collected from is homogeneous. The Rose diagram in the upper left corner is a dip analysis of the bedding attitudes of basalt in the hanging wall of the Hurricane fault (after Scott and others, 1994). The computed mean vector is N84°W and the median is N75°W. The data (n = 20) were plotted on an equal area net using R.W. Allmendinger's *Stereonet.*

composed of randomly oriented plagioclase and subhedral olivine. Acicular plagioclase crystals are up to 2 mm long. Euhedral olivine crystals up to 1.9 mm long and display alteration to iddingsite and Fe-oxide. Magnetite is present in minor amounts.

At site AC, also in the hanging wall, the lowermost flow is slightly vesicular and has a trachytic texture and contains plagioclase and subhedral olivine. Plagioclase crystals are up to 0.2 mm across. Olivine crystals are euhedral, up to 3.5 mm long and weakly altered to iddingsite. Minor amounts of magnetite are present. The upper flow at site AC has a trachytic flow fabric, a matrix composed of plagioclase and olivine, plagioclase crystals are up to 2 mm long, and olivine crystals as long as 1.1 mm. Olivine rims are commonly altered to iddingsite and Fe-oxide. Magnetite is present in minor amounts.

In the footwall at site T, the lowest flow has a semi-trachytic matrix of plagioclase and subhedral olivine. No plagioclase phenocrysts were observed. Olivine crystals, up to 0.8 mm in length, are highly corroded and altering to iddingsite. The rock contains small amounts of magnetite and minor amounts of calcite. The youngest flow at site T is vesicular and has a felty texture with a matrix of plagioclase and olivine. Plagioclase phenocrysts are as long as 1.8 mm and olivine phenocrysts are up to 1.2 mm long with a small amount of alteration to iddingsite and Fe-oxide. Magnetite in minor amounts is present.

From thin section analysis there is no clear correlation of the upper and lower flows belonging to sites T, AC, and P. All sampled locations have very similar mineral assemblages. Although glomerocrysts of olivine and plagioclase are easily identifiable in hand sample, none were observed in thin section.

Trace element composition of basalt is a fingerprint for determining chemical correlations. Therefore, X-ray fluorescence (XRF) was conducted on basalt samples collected from two locations in the hanging wall of the Hurricane fault and one location from the footwall to establish a chemical stratigraphy (figure 5 and Appendix I).

Samples were collected from corresponding stratigraphic intervals at: AC (Ash Creek), T (Toquerville), and P (Pintura). Flow structures such as pipe amygdules occur in basalt in the footwall (site T) indicating that the paleotopography was a valley during basalt extrusion. Care was taken to collect samples from the middle of this channel for the T sample. The trace element data (Table 1) were plotted versus stratigraphic position. The plotted data show striking positive correlations between flows at different outcrops (figures 6 and 7). The lowest flows at sites AC (in the hanging wall) and T (in the footwall) exhibit clear groupings in trace element plots suggesting that they are genetically related. The lowest unit at site P (also in hanging wall) is not related to the lowest unit at the two southern sampling sites (AC and T). Flows 2 to 5 at all three sampling locations appear to correlate. This agrees with mineral modes determined in hand specimen. The plot of Nb/Y (figure 7B), both highly incompatible elements in basalt, shows conclusively that flows two and above are related at all three sampling sites and the lowest flow at the T and AC locations is a separate unit. These data agree with Watson (1968) who observed that the basalt in the footwall and the hanging wall of the Hurricane fault at locations close to AC and T (figure 5) were the same based on petrographic analysis.

Tertiary-Quaternary Deposits

The Tertiary-Quaternary and Quaternary age sedimentary deposits are discussed in detail because three observations of offset in some of these units indicate the relative recency of displacement along the Hurricane fault. Additionally, the Quaternary deposits of colluvium, older alluvium, and sand dunes pose a hazard to structures and persons living in the area. Geologic hazard issues will be discussed in a later section.

Figure 6A

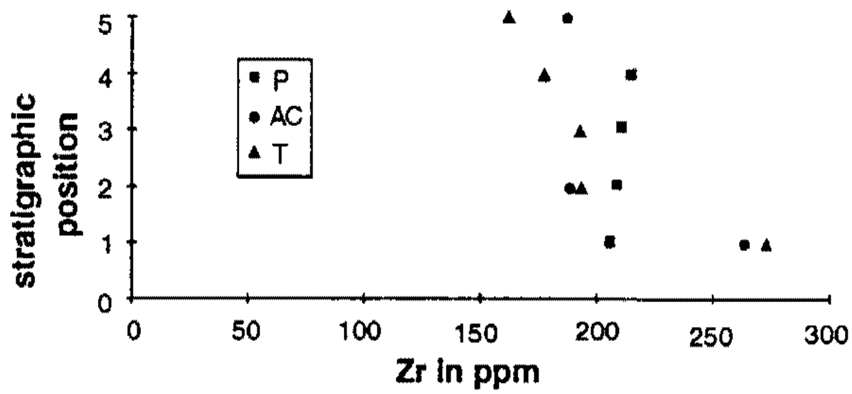


Figure 6B

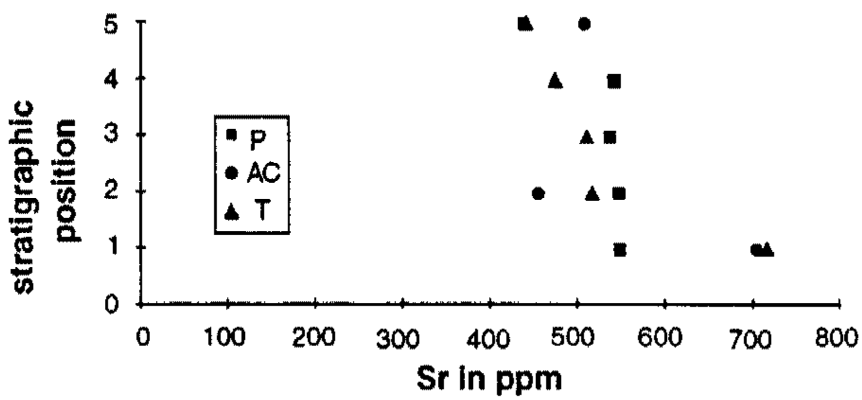


Figure 6C

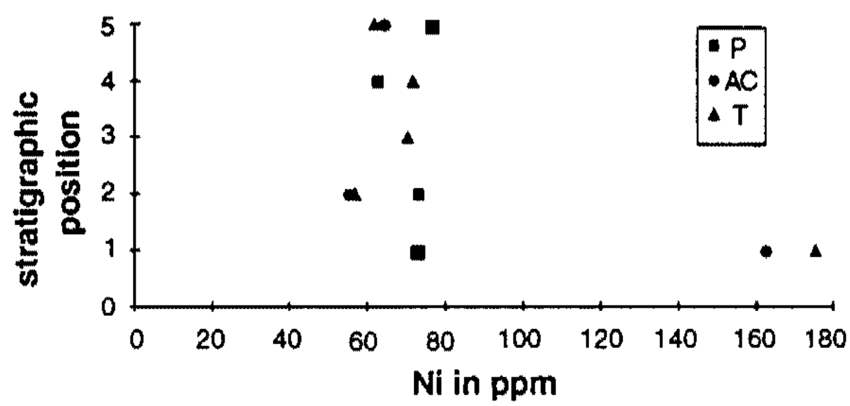


Figure 6. A shows a plot of Zr in ppm versus stratigraphic position for basalt flows collected at sites P, AC, and T which are labeled on figure 5. B is a plot for the element Sr and C is for the element Ni. The correlation of Ni is indicative of the presence of mafic minerals in constant proportions in flows two and above (stratigraphic positions 2 to 5).

Figure 7A

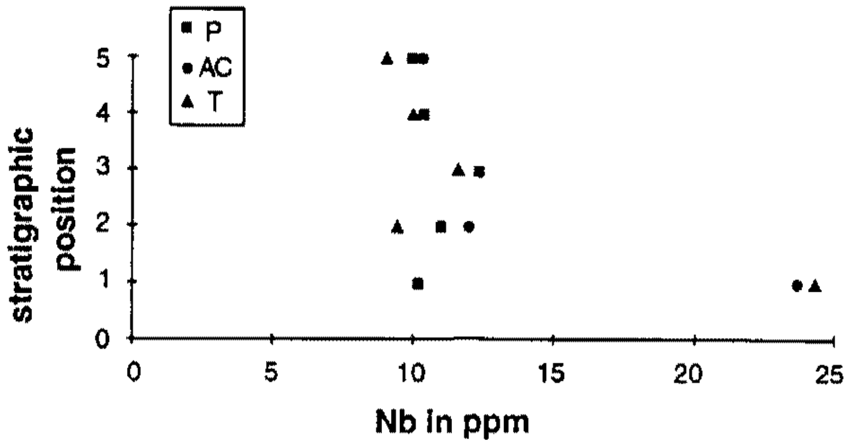


Figure 7B

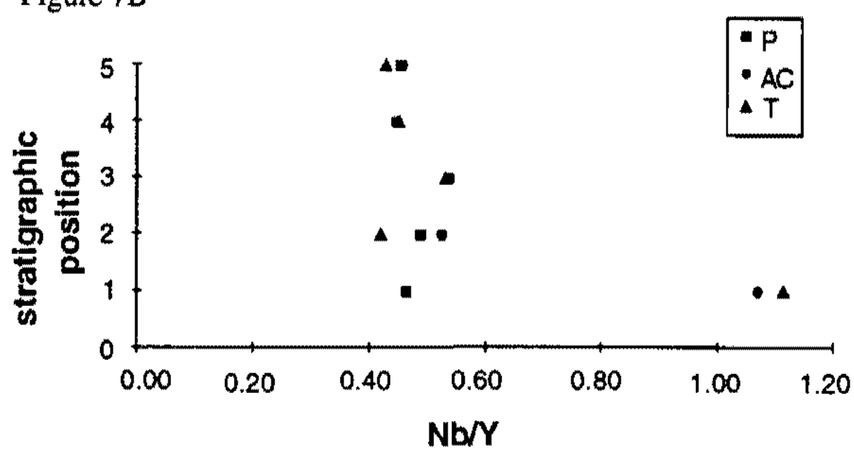


Figure 7. A shows a plot of the incompatible element Nb in ppm versus stratigraphic position for basalt flows at sites P, AC, and T which are labelled on figure 5. B is a ratio of incompatible elements Nb and Y versus stratigraphic position for basalt flows at sites P, AC, and T.

Alluvial Deposits

Unconsolidated alluvial deposits contain well-rounded boulders of monzodiorite similar to the Pine Valley laccolith, up to 4 m in diameter, as well as cobbles of well-rounded light gray fossiliferous limestone, chert, bedded yellow and brown quartzite, sandstone (Navajo), and clasts of Claron Formation. These deposits lie on top of and in cuts into Quaternary (?) basalt. This alluvial deposit was called the Mohave Peneplain by Huntington and Goldthwait (1904) and has been interpreted to be the result of a considerable time period of erosion in the area (Gardner, 1941). The upper surface of this unit has a slope direction from west to east and is commonly planar.

Terrace Deposits

This unconsolidated deposit is composed largely of well-rounded boulders of Tertiary igneous rocks similar to the Pine Valley laccolith and minor amounts of well-rounded cobbles of Paleozoic-Mesozoic sedimentary and metamorphic rocks of unknown provenance. This unit has a relatively planar upper surface and a slope direction typically from west to east. Terrace deposits always occurs in the vicinity of a Tertiary igneous body.

Gravel

An unconsolidated to poorly consolidated stream channel deposit along La Verkin Creek, east of the Hurricane fault, occurs up to 6 m higher than the active stream deposit. The gravel unit contains well-rounded pebbles of limestone and sandstone and large boulders of basalt and Shinarump conglomerate. No metamorphic or monzodiorite clasts were observed in this unit. This gravel is up to 9 m (30 ft) thick.

Alluvium (Older)

This unit is a basin deposit that accumulated in the resulting depression adjacent the Hurricane fault. The alluvium is a red to light red mudstone to fine-grained sandstone, the red color is probably derived from weathered red members of the Moenkopi Formation. It is loosely compacted near the base. Deposits are up to 15 m (50 ft) thick and contain parallel laminated bedding.

Dunes

Adjacent to many Navajo Sandstone outcrops are orange to red-orange vegetation-anchored sand dunes. The dunes range from 15 cm to 1 m high and are composed of the weathered quartz sand grains of the Navajo Sandstone.

Colluvium

The colluvium predominately comprises broken up basalt talus deposits. The mapped colluvium deposits are always associated with basalt flows and are the angular debris shed from the basalt.

Alluvium

The youngest alluvial deposits include active stream channel deposits and debris fall material. Alluvium comprises angular to rounded clasts of Tertiary igneous rocks, basalt, limestone, sandstone, dolomite, and conglomerate. Clasts of Kaibab Limestone, Navajo Sandstone, Queantoweap Formation, and Shinarump Conglomerate formations were recognized. The clasts range in size from 3 m to 0.5 cm in diameter.

CHAPTER 3

STRUCTURAL GEOLOGY

Hurricane Fault Zone

The Hurricane fault in southwestern Utah and northwestern Arizona is a 250 km long normal fault (figure 1). The southern part of the fault lies within the transition zone between the Basin and Range province and the Colorado Plateau and the northern part lies along the eastern boundary of the Basin and Range province. Near the town of Toquerville, Utah (figures 2 and 3), the Hurricane fault was found to be: 1) a dip-slip fault; 2) a segmented fault; 3) locally a fault zone or locally a single fault strand; and 4) an active fault. In addition, the fault has a large stratigraphic separation.

The Hurricane fault has been called a normal dip-slip fault (Huntington and Goldthwait, 1904; Gardner, 1941; Cook, 1957; Averitt, 1962; Hamblin, 1965; 1970; Kurie, 1966), a reverse fault (Lovejoy, 1964), and Moody and Hill (1956) proposed that the Hurricane fault had a significant left-slip component along it. The theory that the fault is a left-slip fault has again been recently suggested (Anderson and Barnhard, 1993, fig. 22, p. 39). To determine the direction of slip across the fault in the Quaternary, samples of Quaternary (?) basalt were collected from two locations in the hanging wall of the fault and one location in the footwall (figure 5). The x-ray fluorescence (XRF) analyses suggest that all the basalt units in the footwall at sampling site T, and all basalt units at sampling site AC in the hanging wall, are geochemically the same. Trace element compositions of the lowermost flow at T and AC clearly correlate, whereas the lowermost flow at P, which is also in the hanging wall, geochemically does not group with T and AC (for example, figures 6-7). Evidence that motion on the Hurricane fault after basalt extrusion has been nearly perfect normal dip-slip is provided by the fact that the flows at sites T and AC are geochemically the same, are displaced nearly parallel to the fault dip direction, and the hanging wall site, AC, was downdropped relative to site T (figure 5). The flows at site AC and T were once adjacent to each other and now make up a large piercing point for motion on the Hurricane fault in the Quaternary. The magnitude of stratigraphic separation of the basalt is 450 m (1500 ft) (figure 8C; Plate 2-cross section C-C'). There is no evidence supporting a strike-slip sense of motion along the Hurricane fault in this location during the Quaternary.

Normal dip-slip displacement is corroborated by four measured slickenside lineations exposed on the Hurricane fault. The rakes of these lines of direction of last motion, found in four locations in this study, range from 74° to vertical (Plates 1A and 1B). Additional exposures of slickenlines were not observed. In addition, Kurie (1966) reported vertical slickenlines on the Hurricane fault near Pintura, Utah. From the P-wave first motions focal mechanism of the St. George, Utah, earthquake, that occurred on September 2, 1992, on a southern segment of the Hurricane fault, the rake of the shock was 89° (figure 9), indicating, as well, dip-slip movement for the fault (Lay and others, 1994).

Total stratigraphic separation on the Hurricane fault in the study area ranges from 1740 m (5700 ft) to 2070 m (6800 ft). Measurements are constrained by downdropped outcrops of Triassic-Jurassic Navajo Sandstone in the hanging wall of the fault and projected locations of the Navajo Sandstone in the footwall where it and the older units were eroded away based on stratigraphic thicknesses. In the hanging wall, Quaternary (?) basalt rests unconformably on Navajo Sandstone and in the footwall the

Qa		recent alluvium
Qc		recent colluvium
QTa		alluvium, weakly consolidated
Qb		basalt
Ti		monzodiorite
Tc		Claron Formation
JTRn		Navajo Sandstone
TRk		Kayenta Formation
TRmo		Moenave Formation
TRc		Chinle Formation
TRcs		Shinarump conglomerate
TRmu	Moenkopi Formation	upper red member(s)
TRmv	Moenkopi Formation	Virgin limestone member
TRmlr	Moenkopi Formation	lower red member
TRmt	Moenkopi Formation	timpoweap member
Pk		Kaibab Limestone
Pt		Toroweap Formation
Pq		Queantoweap Formation
Pp		Pakoon Dolomite
und		undifferentiated Paleozoic rocks and basement

Unit explanation for figures 8A through 8F and 15. Cross sections locations are shown on figure 3.

Geologic cross section along A-A'

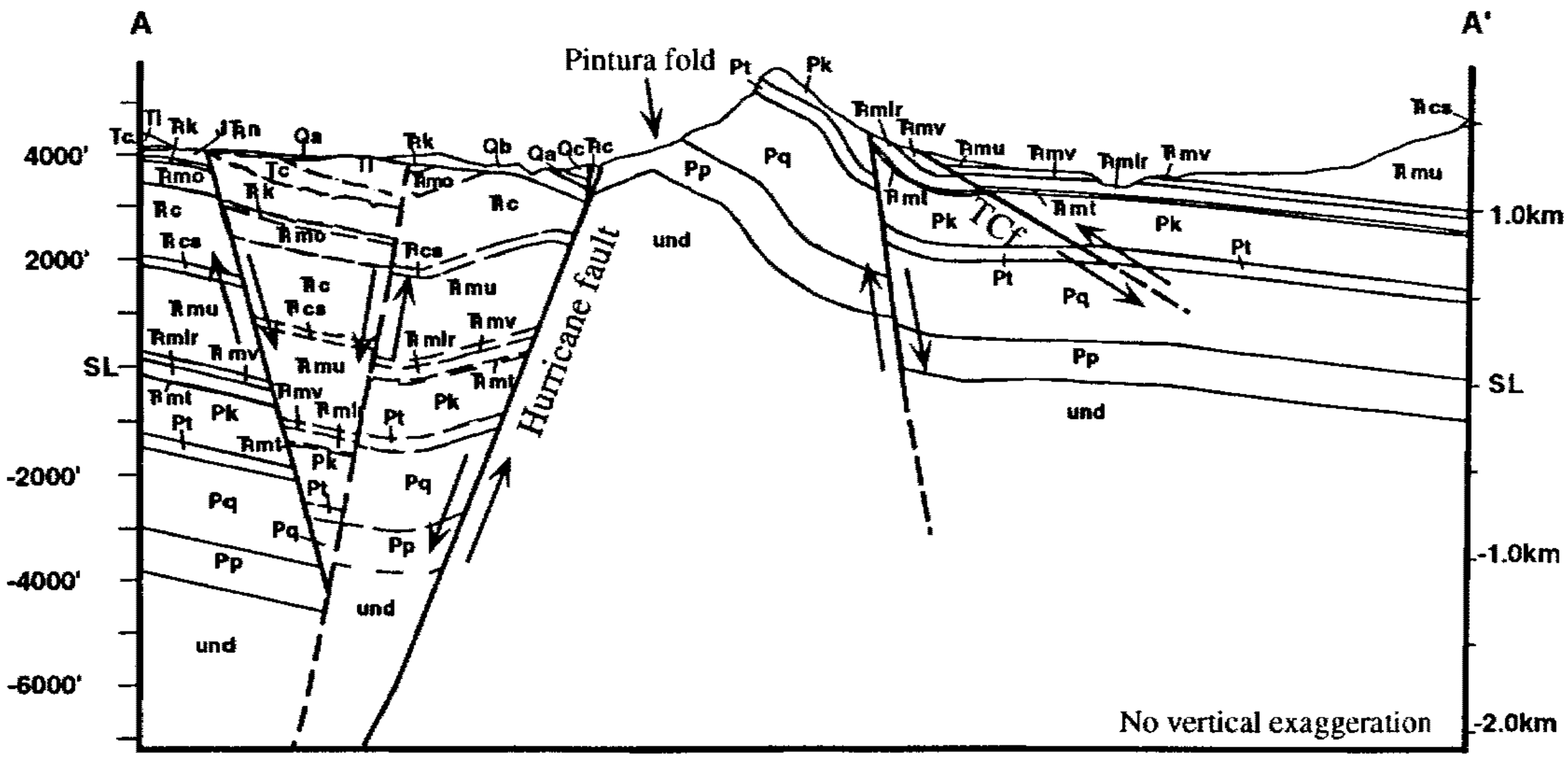


Figure 8A. Unit explanation on page 24. Hurricane fault and Pintura fold are labeled. TCf = Taylor Creek fault.

Geologic cross section along B-B'

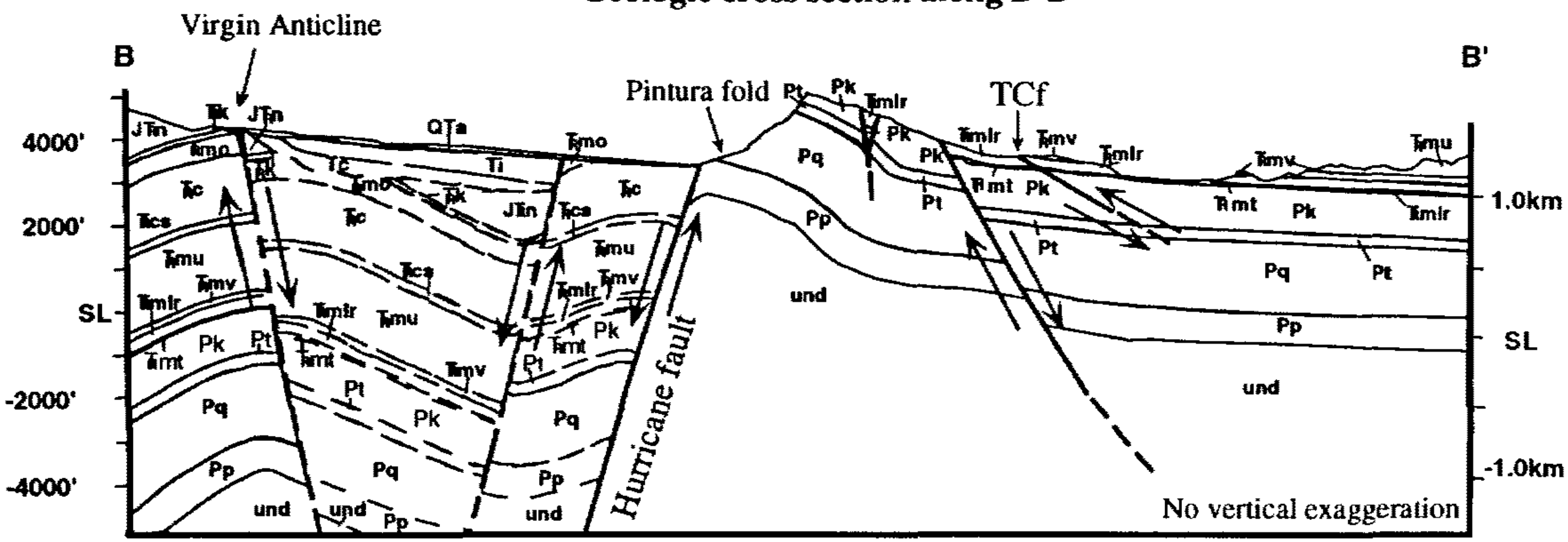


Figure 8B. Unit explanation on page 24. Hurricane fault, Virgin Anticline and Pintura fold are labeled. TCf = Taylor Creek fault.

Geologic cross section along C-C'

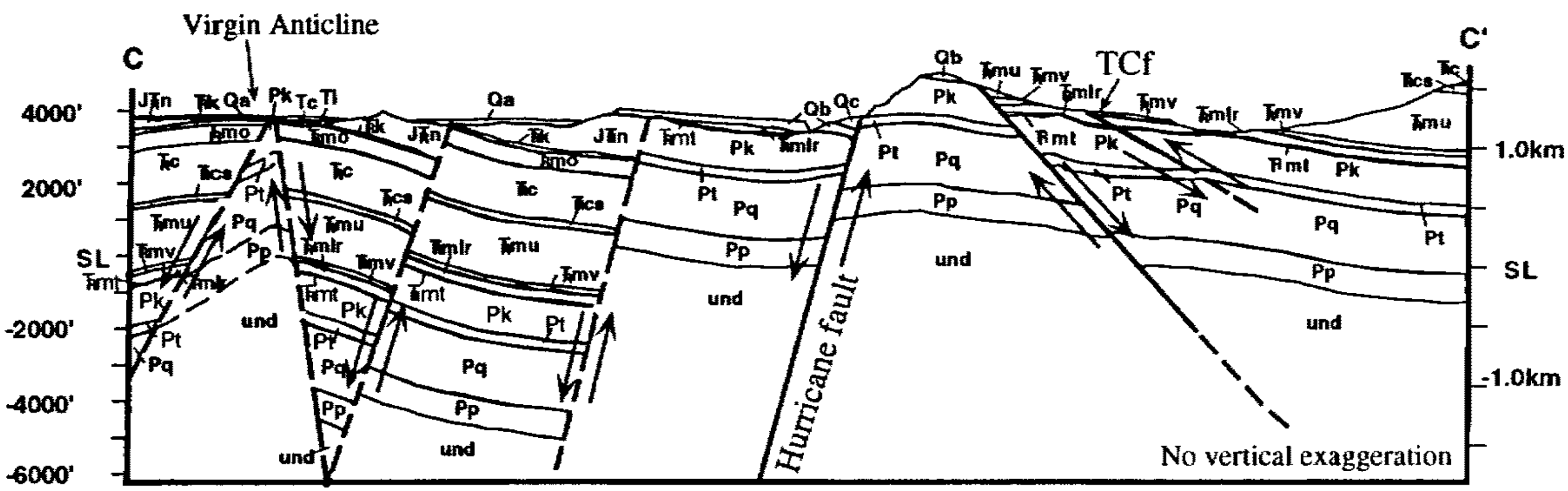


Figure 8C. Unit explanation on page 24. Hurricane fault and Virgin Anticline are labeled. TCf = Taylor Creek fault.

Geologic cross section along D-D'

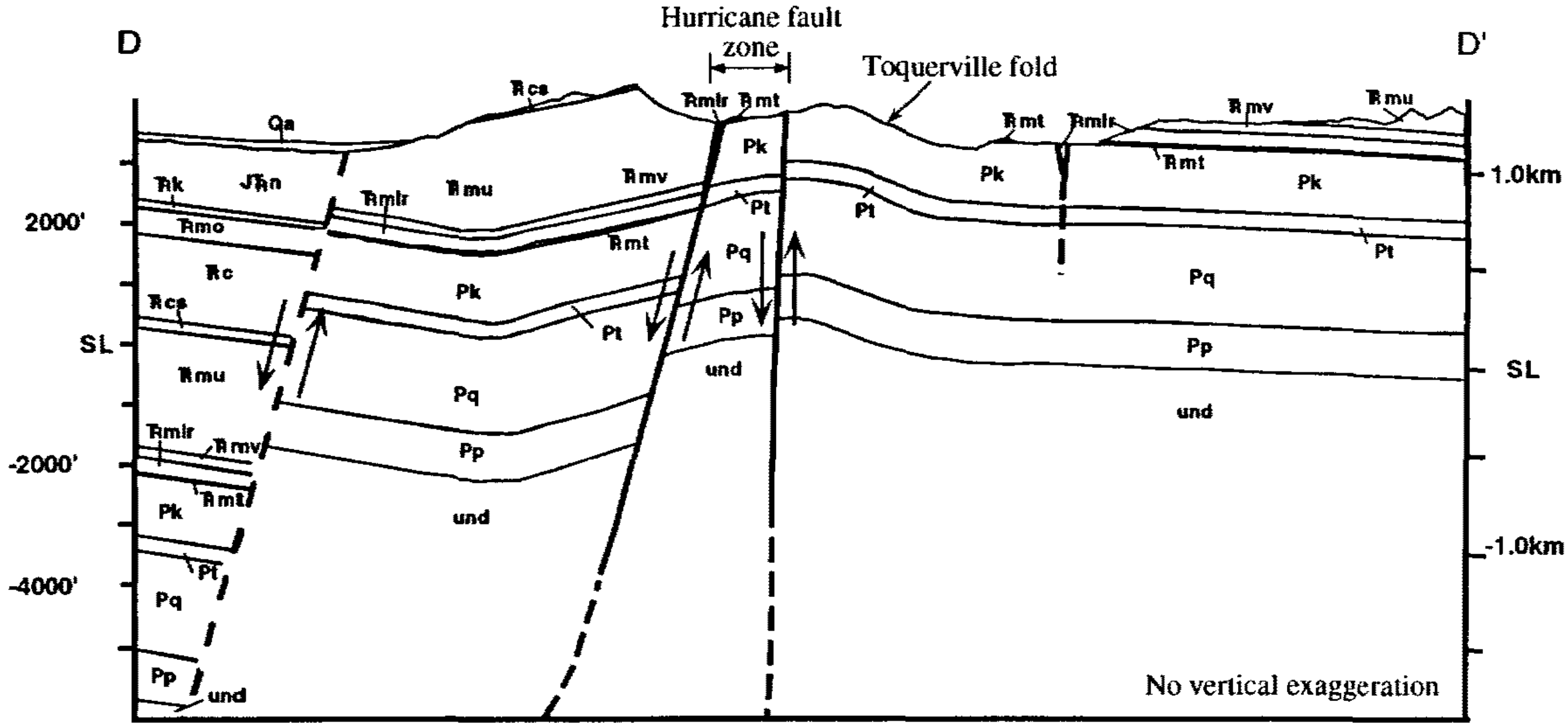


Figure 8D. Unit explanation on page 24. Hurricane fault zone and Toquerville fold are labeled.

Geologic cross section along E-E'

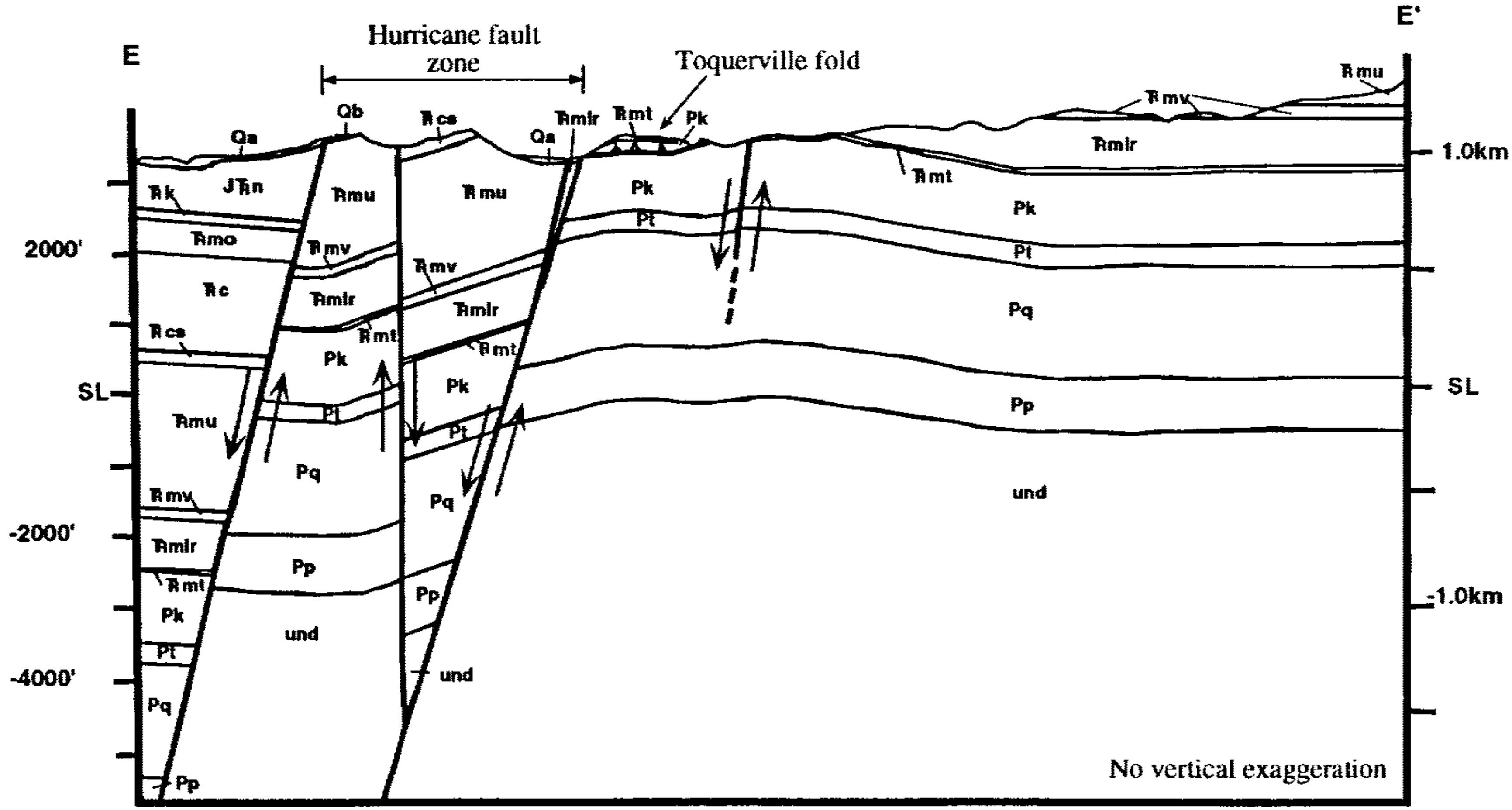


Figure 8E. Unit explanation on page 24. Hurricane fault zone and Toquerville fold are labeled.

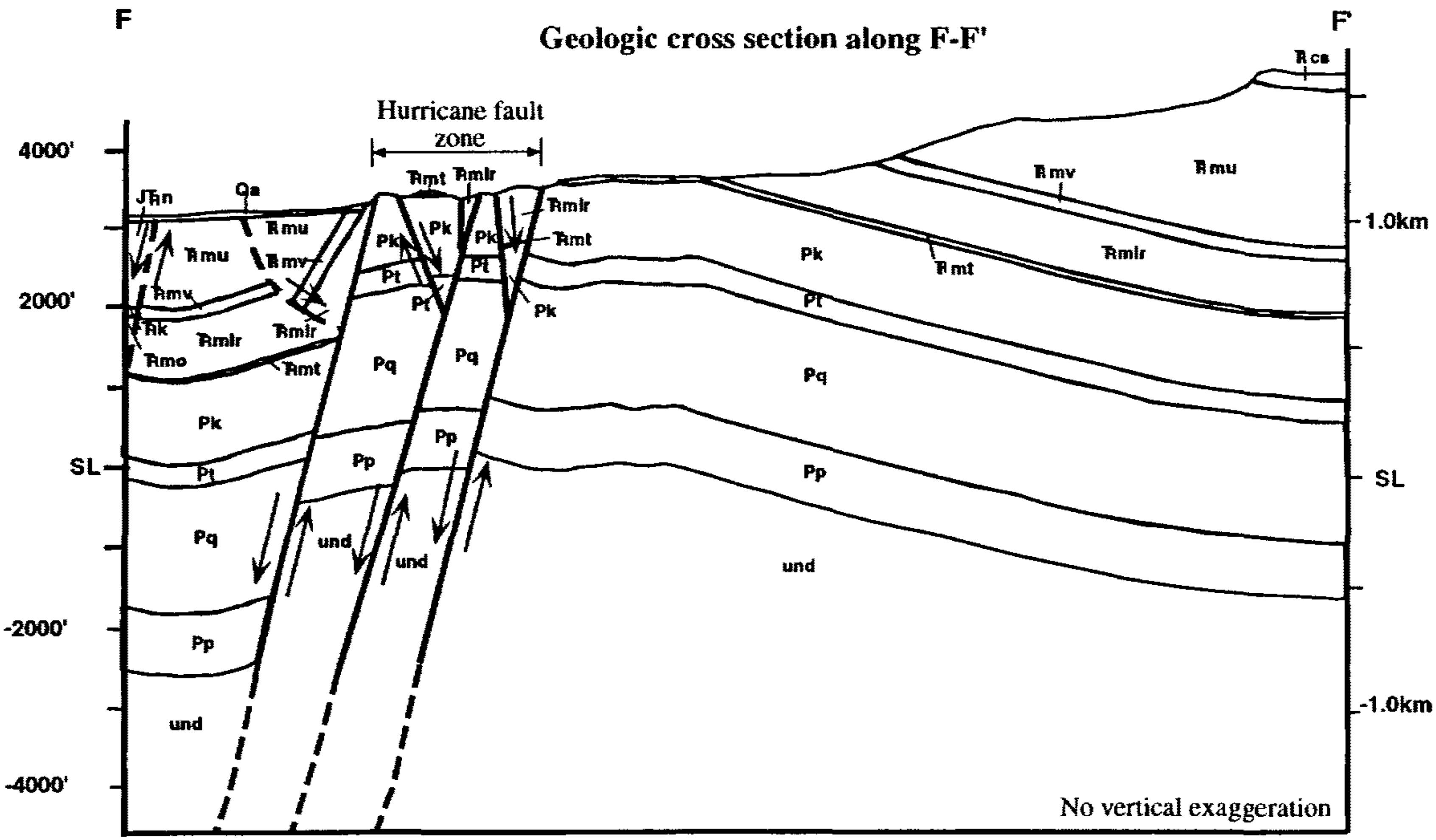


Figure 8F. Unit explanation on page 24. Hurricane fault zone is labeled.

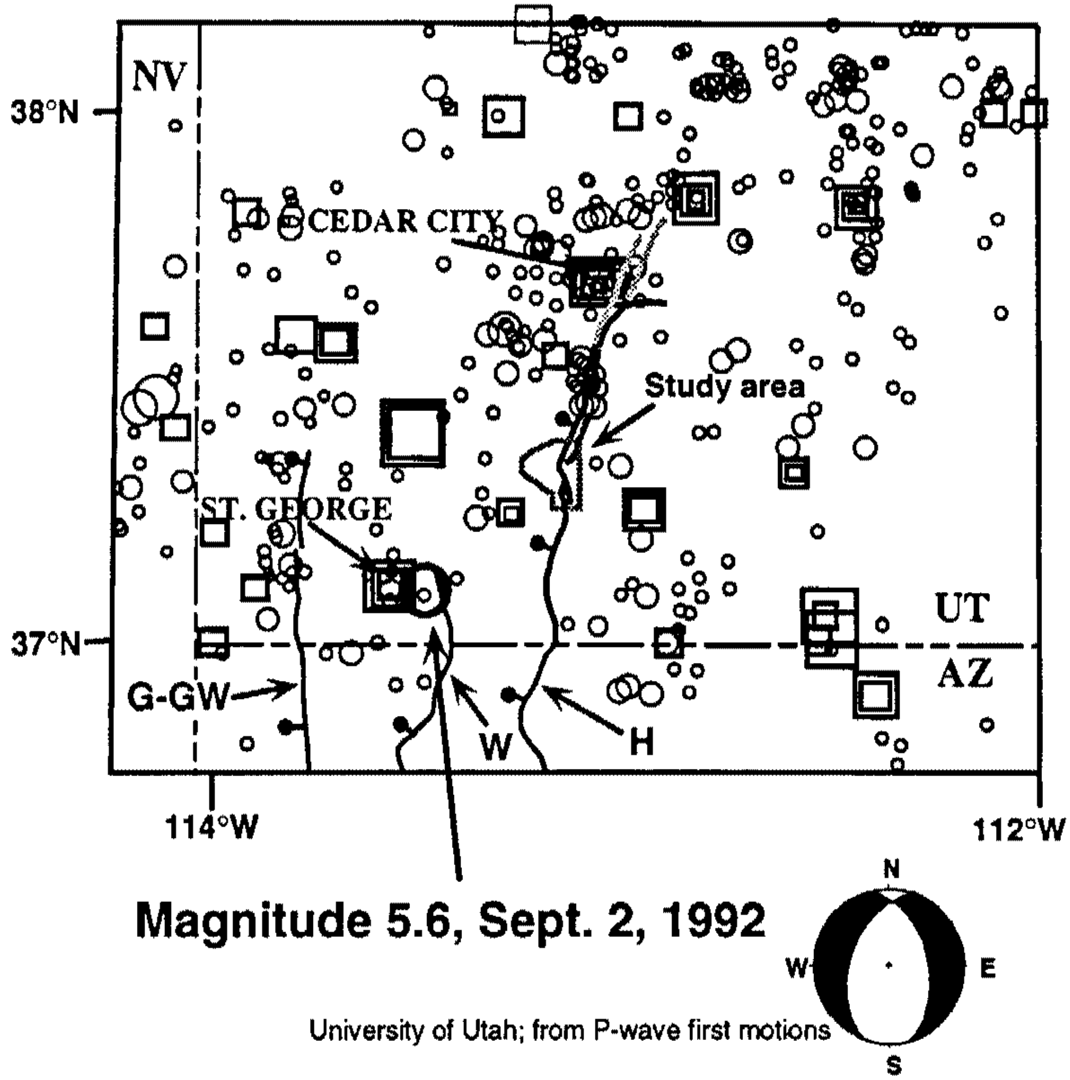


Figure 9. Earthquakes in southwestern Utah since 1850 [modified from Christenson and Nava (1992) and Arabasz and others (1992b)]. Normal faults shown (ball and bar on downthrown side) are G-GW = Gunlock-Grand Wash fault system, W = Washington fault, and H = Hurricane fault. Circles indicate instrumental locations for July, 1962, through September, 1992. Squares indicate primarily non-instrumental locations for earthquakes that occurred between 1850 and June, 1962. Epicenter size indicates approximate magnitude of shock. The smallest shown shocks are 2.0 and the largest is 6.3. The M5.6 St. George earthquake is shown with the P-wave first-motion focal mechanism (Pechmann and others, 1992). The average parameters for the quake are: strike, 188° ±10°; dip, 46° ±4°; rake, -89° ±14°; depth 15 ±5 km; and seismic moment, 2.2 ±0.6 x 10^{24} dyne-cm (Lay and others, 1994). The June 28-29, 1992, Cedar City swarm (Arabasz and others, 1992a) is also shown. The study area is outlined (same area as in figure 3) along the Hurricane fault.

geochemically identical basalt lies on Permian Kaibab Limestone. Total normal stratigraphic separation along the Hurricane fault is shown in cross sections A-A', B-B' and C-C' (figures 8A, B, and C; Plate 2). Assuming pure dip slip as indicated above, along the A-A' cross section line heave on the fault is 790 m (2600 ft) and throw is 2130 m (7000 ft), and along the C-C' line the heave of the fault is 240 m (800 ft) and the throw is 1030 m (3400 ft). A southward decrease in stratigraphic separation, heave and throw is suggested.

A minimum of two episodes of normal faulting exist along the Hurricane fault in this area. One episode faulted Navajo Sandstone against Kaibab Limestone. This episode was followed by erosion and then basalt extrusion. The subsequent episode displaces that basalt (figure 8C; Plate 2-cross section C-C').

The Hurricane fault is a segmented fault. In the study area, this is shown by changes in the strike of the fault along its length (figure 3). In the south, the fault strikes N12°W (near "A" on figure 3). The fault is also a 1.5 km wide zone with several separate fault strands at this location. Northward, the fault strikes N37°W (near "B" on figure 3), and further north it strikes N13°W (near "C" on figure 3). North of the town Toquerville (near "D" on figure 3), the fault changes strike to N21°E. The trend of the line of intersection of the segments at the bend between C and D is N85°W. In the vicinity of the bend in the fault between C and D (figure 3), there is a small scale anticline in the basalt (Plate 1A and figure 5) with a 1°, N72°E trending hinge zone that is normal to the fault, suggesting a segment boundary and a change in geometry of the fault (cf., Schlische, 1993).

Cropping out between A and B (figure 3) in the footwall of the Hurricane fault is a small magnitude thrust fault exposed in Permian Kaibab Limestone near La Verkin Creek (Plate 1B and figure 8E; Plate 3-cross section E-E'). This thrust has an attitude of approximately N56°W, 5°SW and a stratigraphic separation of up to 5 m. Although this thrust fault is cut by minor normal faults which have steep dips and strike between

N10°W and N20°W, it occurs in a structurally complex area. The thrust may be related to the presence of a restraining bend at a fault segment boundary. This point will be discussed further in the following section.

As previously stated, in the southern part of the study area, the Hurricane fault is a zone 1 to 1.5 km wide (Plate 1B; figure 10). Cross sections E-E' and F-F' (figures 8E and F; Plate 3) show the multiple fault strands in this area. In the central and northern part of the study area (figure 3), the Hurricane fault is a single surface as shown in cross sections A-A', B-B' and C-C' (Plate 2 ; figures 8A, B, and C).

The Hurricane fault is an active fault as indicated by: 1) offset Quaternary (?) basalt; 2) offset Quaternary alluvium; and 3) recent seismic activity, such as the June 28-29, 1992, earthquake swarm (Arabasz and others, 1992a), the September 2, 1992, earthquake (Arabasz and others, 1992b; Pechmann and others, 1992), as well as numerous small earthquakes that have occurred in the vicinity of the fault (Christenson and Nava, 1992; S. J. Nava, written communication, 1993). In three places along the Hurricane fault in the study area, unconsolidated Quaternary gravel or alluvium is offset (Plates 1A and 1B). The largest fault scarp in the alluvium has a scarp slope of 30° and a scarp height of 6 m; another scarp has a slope of 15° and a 3 m height. Scarp slopes were measured from the angle made by the horizontal surface in the footwall of the scarp to the middle of the steep face of the scarp slope (Bucknam and Anderson, 1979). At these two scarp sites, slip is apparently normal because down-dropped alluvium occurs in the hanging wall block. A third exposure of displaced Quaternary sediments is found in gravel in a narrow stream-cut channel near the town of La Verkin where two fault strands 3 m occur. There is 3 m of offset is along an 60°W dipping fault surface and 1.2 m of offset on a fault surface that dips 73°W. Exactly when fault motion created these scarps and offsets is unknown and it is not apparent whether motion was a single or multiple events.

The Hurricane fault lies within the Intermountain seismic belt (ISB) (Smith and Sbar, 1974) (figure 11). The ISB corresponds in part with the location of the transition zone between the thin crust of the Basin and Range province and the thicker crust of the Colorado Plateau and the Rocky Mountains and contains typical late Quaternary normal faults, small magnitude earthquakes with relatively shallow focal depths (15-20 km), and common earthquake swarm sequences (Arabasz and Smith, 1981). As is typical of seismicity in the ISB, epicenters and known active faults correlate only weakly (figure 9) (Arabasz and Smith, 1981).

From July, 1962, to September, 1993, the University of Utah Seismograph Stations recorded 776 earthquakes in southwestern Utah. Prior to July, 1962, there were 45 noninstrumentally reported earthquakes dating back to 1850. Most of the recorded quakes were M2.0 or less (S.J. Nava, written communication, 1993). A swarm of more than 60 earthquakes occurred on the Hurricane fault near Cedar City, Utah, on June 28-29, 1992, with the largest shock registering M4.1 (Arabasz and others, 1992a). This swarm happened within an hour of the Landers, California, M7.3 quake, which is 490 km to the southwest of Cedar City (Hill and others, 1993). The cause of the marked increase in seismic activity after but relatively far from the Landers event is believed to be due to dynamic stresses associated with the passage of seismic waves and the critical loading of faults in a heterogeneous crust (Hill and others, 1993).

The September 2, 1992, M5.6 earthquake, the largest temblor felt in Utah and surrounding areas since 1975 (Lay and others, 1994), occurred near the town of St. George, southwest of this area (figure 9) (Arabasz and others, 1992b). The quake occurred at 15 km depth and the surface projection of the west-dipping nodal plane lies close to the surface trace of the Hurricane fault which suggests, but is not conclusive evidence, that the main shock resulted from buried slip on the Hurricane fault (Pechmann and others, 1992). Also, the focal mechanism solutions indicate normal dip-slip for this quake (figure 9) (Lay and others, 1994).

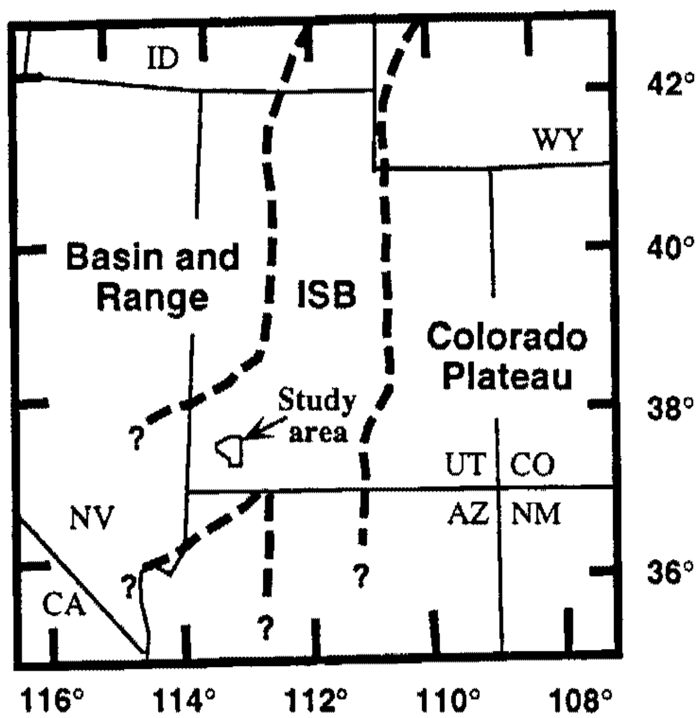


Figure 11. Location of Intermountain seimic belt (ISB), delineated by dashed line, in Utah and surrounding states, with the study area oulined in the southwestern corner of Utah. The ISB is characterized generally by: (1) normal faulting, with earthquake maximums of M7.5; (2) diffuse seismicity with weak correlations to major active faults; (3) relatively long average recurrence intervals for surface faulting; and (4) very few historical M>7.0 surface faulting earthquakes. Modified after Arabasz and Smith (1981).

Interpretations of Field Data Along the Hurricane Fault Zone

This section discusses the faulting processes along the Hurricane fault based on field evidence. An emphasis is placed on kinematics and structures at fault segment boundaries. The fault was mapped for 13 km along strike, so processes discussed here may not be applicable for the entire fault length of over 250 km.

Most previous studies of the Hurricane fault have indicated that the fault is a normal dip-slip fault. Based on slickenlines, the rake of the St. George earthquake, and the separation of Quaternary (?) basalt, it is without question that in the Quaternary the Hurricane fault is predominantly a dip-slip fault. The four slickenside lineations provide evidence of last motion on the fault being normal dip-slip. From the first motions focal mechanism for the St. George earthquake, the rake of the quake was 89°, which indicates the slip on the fault caused by the quake was normal dip-slip. The separation of the basalt in the footwall, which was sampled in the middle of a paleochannel, relative to geochemically identical basalt in the hanging wall is nearly perfect dip-slip.

The basalt in the footwall at site "T" was determined by XRF analysis to be the same package of rocks as at site "AC" (figure 5). Basalt samples were not analyzed to the south of AC, but if it is assumed that the basalt field that the AC samples were collected from is homogeneous, then the slip vector could be between N70°W and S18°W in the Quaternary (?).

Scott and others (1994) propose a dip analysis method for evaluating fault geometry and fault kinematics in the absence of geophysical data or field kinematic indicators by using the dip direction of the synrift strata in the hanging wall block of a fault. Theoretically, if the sense of motion on a fault is purely dip-slip, then the hanging wall dip direction will be exactly opposite to the dip of the fault. Therefore, dip analysis provides a mean direction of transport (Scott and others, 1992). Emphasizing that dip analysis is intended for regional studies, Scott and others (1994) developed the method by using two apparent dips along two intersecting seismic profiles collected in a rift basin. A potential drawback with using the dip analysis technique in this study is that enough data points (n=20) may not have been available to produce a regional transport direction. However, locally this method is applicable to the discussion of direction of transport. Dip analysis is not intended here or used here as a stand-alone technique. Bedding attitudes collected from the basalt in the hanging wall of the fault were plotted on a Rose diagram for fault motion direction analysis (figure 5). The Rose diagram indicates that a large number of basalt dip direction data plot between N70°W and N80°W. The median direction of motion of the hanging wall relative to the footwall is N75°W and the mean direction of motion is N84°W. In the basalt fields where dip data were collected, the fault strikes N13°W (near "C" on figure 3) and N21°E (near "D" on figure 3), so along these fault strands a mean direction of motion of N75°W would further indicate a normal sense of motion on the Hurricane fault in the Quaternary (?).

Using the vector information interpreted from the offset basalt, from N70°W to S18°W, in conjunction with the hanging wall dip data collected on basalt and plotted as a Rose diagram (figure 5), all attitudes measured in the basalt field indicate a median vector of motion of about N75°W. If N75°W is the direction of motion along the entire fault length in this study area, then along the fault near site P, where the fault strikes N21°E, faulting is nearly pure dip-slip, and motion along the fault near sites AC and T, where the fault strikes N13°W, is also dip-slip but with a small dextral component. These data verify that in the Quaternary no significant strike-slip motion occurred. In strike-slip scenarios, oblique en echelon folds may form in a narrow zone adjacent the fault in the hanging wall (Sylvester, 1988) and none were observed. A N75°W vector agrees with stress field data based on earthquake focal mechanisms for the transition zone which indicate a S78°E-N78°W $\pm 21°$ orientation (figure 12) (Zoback and Zoback, 1980; Arabasz and Julander, 1986).

Previously, no major fault segments nor segment boundaries were documented on the Hurricane fault in Utah. Identification of fault segments is critical because fault segment boundaries may be the sites of significant amounts of accumulated strain and may influence localization of earthquakes (Bruhn and others, 1990). A long (>200 km) normal slip fault such as the Hurricane fault will rupture along only some fraction (perhaps ≤40 km) of its length during a surface faulting event and it is probable that segment boundaries control the location and extent of rupture (Schwartz and Coppersmith, 1984). Schwartz and Coppersmith (1984) identified fault segment boundaries along the Wasatch fault in central Utah, which is also a large displacement normal fault. By trenching and mapping along the Wasatch fault, they used variability of offset, timing of faulting events, scarp morphology, and fault geometry to define segment boundaries. In the present study, hanging wall and footwall shortening structures, scarp morphology, fault geometry, and increased complexity of faulting along the Hurricane fault are used as definitive evidence for the existence of a fault segment boundary and two fault segments along the Hurricane fault.

Where a fault surface is nonplanar some internal deformation in the hanging wall will occur (Scott and others, 1994). Along a segmented normal fault, anticlines that trend normal to the fault strike typically occur at or near fault segment boundaries (Schlische, 1993, fig. 11, p. 1038). A fault segment boundary may not necessarily be sharply defined and may be a zone up to a few kilometers in length (cf., Schwartz and Coppersmith, 1984). The occurrence of a small scale anticline in the basalt in the hanging wall near the bend between C and D (figure 3), which has an axial trend of 1°, N72°E (figure 5), is strong evidence for a fault segment boundary there. The fault segment north of this anticline is named the Ash Creek segment and south of the anticline the segment is named the Anderson Junction segment (figures 5 and 15). A segment boundary at this location is also suggested by the large change in strike of the

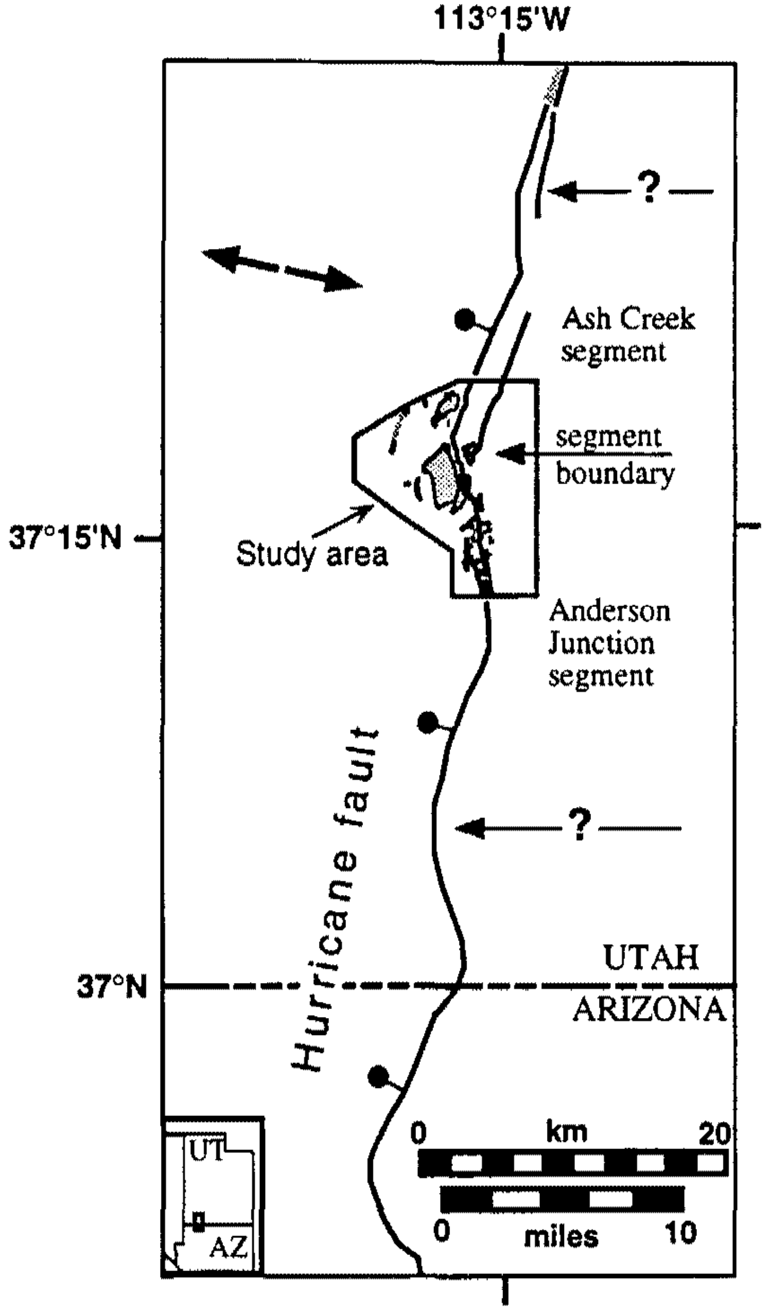


Figure 12. Map showing the locations of two fault segments, the Ash Creek segment and the Anderson Junction segment, along the Hurricane fault (with the field area outlined along it). Light weight arrows with ? indicates possible segment boundaries. The northern boundary of the Ash Creek segment and southern boundary of the Anderson Junction segment are hypothesized from map view geometry (cf., Hintze, 1980). Thick, opposing arrows indicate regional stress field direction for the transition zone, N78°W-S78°E, ±21° (Zoback and Zoback, 1980; Arabasz and Julander, 1986). Stippled areas in study area show basalt fields. Location of figure shown in inset map.

Hurricane fault here; along the Anderson Junction segment the fault strikes N13°W and along the Ash Creek segment the fault strikes N21°E (figure 12).

Antithetic and synthetic faults crop out along the Anderson Junction segment where the Hurricane fault is a zone as wide as 1.5 km (figures 8E and F; Plate 3-cross sections E-E' and F-F'). Antithetic faulting in the hanging wall occurs to fill space on a non-planar fault just as reverse drag fills space (Hamblin, 1965; Gibbs, 1984). A slight dextral component in slip on this fault segment might explain the complexity in geology and faulting in this area as compared to other sections of the field area. This complexity might be caused by the slight pushing to the north of the hanging wall block. The fault bend between the Ash Creek segment and the Anderson Junction segment (figure 12) may essentially be a slight restraining bend where the hanging wall is moving towards the bend.

A restraining bend at the fault segment intersection requires creation of new faults and/or a change in the volume of rock. At this restraining bend is a nonconservative barrier whereby the multiple fault strands in the southern part of the field area accommodate slip along the fault that cannot be taken up solely on the main Hurricane fault. A nonconservative barrier occurs along segmented faults where the slip vector is not parallel to the line created by the intersection of fault segments, effectively creating space along the fault (cf., King, 1986). The trend of the line of intersection between the Ash Creek segment and the Anderson Junction segment is approximately N85°W which roughly parallels the median vector of transport determined from dip analysis (N75°W) and lies within the range of vectors determined from offset basalt (N70°W to S18°W). This approximate parallelism would suggest a conservation of space across the fault plane, but field data suggest that there is, at least in part, some nonconservation of slip. Likewise, the N85°W trend of the line of intersection between the fault segments does not parallel the axial trend of the small scale anticline in the footwall (1°, N72°E), further indicating the existence of a nonconservative barrier.

A small thrust fault, which has an attitude of approximately N56°W, 5°SW and a stratigraphic separation of up to 5 m, is exposed in Permian Kaibab Limestone in the footwall of the Hurricane fault near La Verkin Creek (Plate 1B and figure 8E; Plate 3-cross section E-E'). Although this thrust fault is cut by minor normal faults, it is possible that, given the slight dextral component of motion on the fault in this vicinity and the northward push of the hanging wall block, this thrust is related to extension. The thrust's formation would be caused by compression at a fault segment boundary. This small thrust fault exists in the vicinity of a structurally complex area (between "A" and "B" on figure 3), although, structures of this nature were not observed elsewhere in locations that are equally complex, such as further south. It is also possible, however, that the thrust fault is related to a smaller bend in the fault rather than the large strike change at the documented segment boundary; the fault strikes N12°W near "A" on figure 3 and further north, and north of the thrust, the strike of the fault is N37°W (near "B" on figure 3). This again suggests that the thrust is related to extension and local compression at a fault bend.

Scarps in Quaternary alluvium are observed at two locations along the Ash Creek segment (Plate 1A). One scarp has a slope of 15° and is 3 m high, the larger scarp has a height of 6 m and a slope of 30°. The two scarps along the Ash Creek segment were plotted as maximum scarp-slope angle versus scarp height to determine a broad approximation of timing of faulting (figure 13). Over time a scarp will degrade and its slope will decrease (Nash, 1980). The scarp-slope data points fall between the 1,000 y.o. Fish Springs scarps regression line and the 15,000 y.o. Bonneville shoreline scarps regression line which were determined from previous scarp-slope studies in central Utah (Bucknam and Anderson, 1979), suggesting that the timing of faulting along the Ash Creek segment can be approximated to within 1,000 and 15,000 years ago. Clearly, scarp lay back angles are controlled by multiple variables (Pierce and

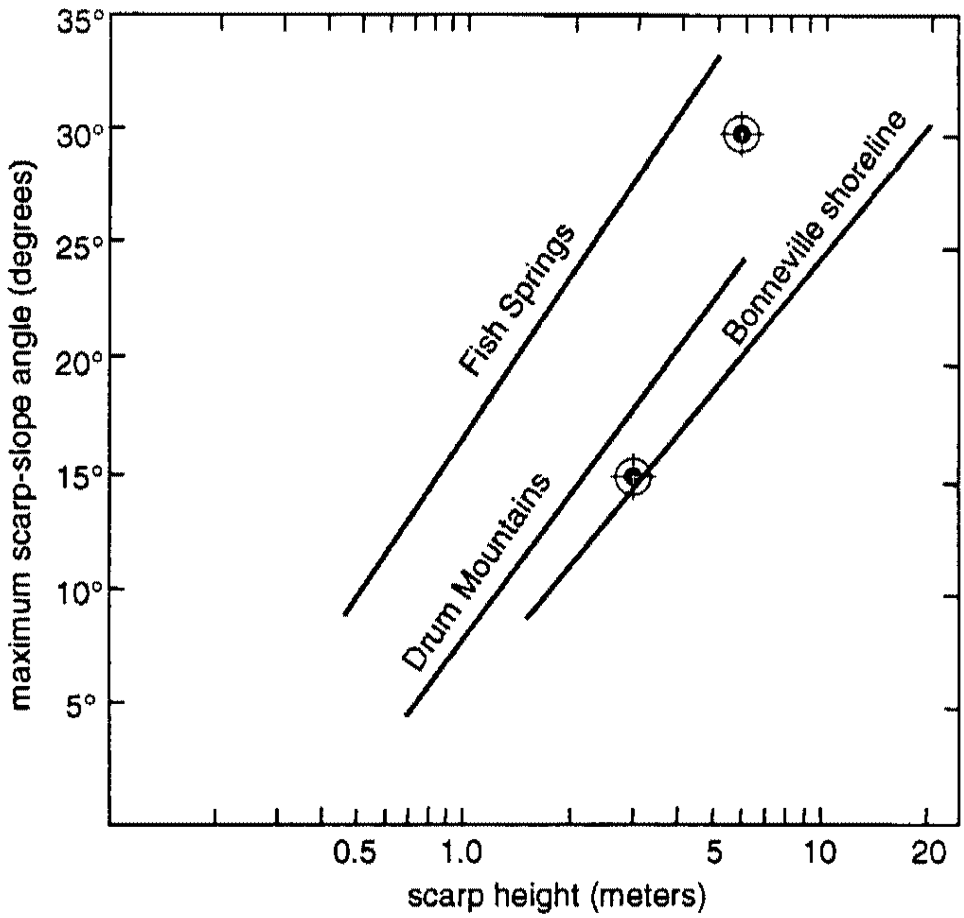


Figure 13. Plot of maximum scarp-slope angle versus the scarp height for two scarps in the alluvium on the Hurricane fault in the field area (indicated by circle and cross symbols). The labeled regression lines are from scarp-slope data from the approximately 1,000 y.o. Fish Springs scarps, the 10,000 y.o. Drum Mountains scarps, and the 15,000 y.o. Bonneville shoreline scarps, all located in Utah, from Bucknam and Anderson (1979).

Colman, 1986). Such factors as alluvial cementation, slope aspect, vegetation, and microclimate were considered to be uniform on Holocene fault scarps in this study.

At one location along the Anderson Junction segment, offset in Quaternary gravel is exposed in a stream-cut channel near the town of La Verkin (Plate 1B). Faulting occurred along two fault strands 3 m apart. On the more western strand there is 3 m of offset in the gravel and the fault surface dips 60°W. The eastern strand displays 1.2 m of displacement and the fault dips 73°W and strikes N12°W. This exposure does not form scarps so was not plotted in figure 13. The smaller amount of stratigraphic separation in the Quaternary sediment along the Anderson Junction segment compared to the Ash Creek segment suggests that the two segments have differing faulting histories, which is expected along a segmented fault. The lack of scarps along the Anderson Junction segment suggest the last surface rupture along it occurred before that of the Ash Creek segment.

The fault segments along the Hurricane fault can be further broken up into smaller fault sections. Within the field area the Anderson Junction segment (figure 12) comprises three fault sections, each with differing strikes (A, B, and C of figure 3). Along strike the Anderson Junction segment is not continuously curved, but has discrete sections of nearly constant strike. The total length of the Anderson Junction segment may be at least 25 km long or at most 49 km long, based largely on map view geometry and the major changes in the strike of the Hurricane fault (cf., Hintze, 1980). However, the epicenter of the September 2, 1992, St. George earthquake coincides with a large bend in the fault (figure 9), thus making the 25 km segment length more likely. Additionally, a 49 km fault segment length for the Anderson Junction segment is longer than general maximum segment lengths (cf., Jackson and White, 1989; DePolo and other, 1991). The Ash Creek segment may be as long as 19 km based on the same geometric criteria as above. A more detailed database of smaller scale mapping and trench studies along the Hurricane fault could help to better identify the fault's other major fault segments and boundaries. Additionally, close attention to the bedding attitudes in the synrift sediments and basalt will aid in clarifying other segment boundaries (cf., Schlische, 1993; Scott and others, 1994).

The timing of first motion on the fault is difficult if not impossible to calculate with the available data. If it is assumed that the basalt in the field area is from 0.3 to 2 Ma and has been displaced 450 m, then it is possible considering the total stratigraphic separation of up to 2520 m to back calculate an age of faulting to Pleistocene to Late Miocene. This, however, is highly conjectural and assumes a constant strain rate.

The discussion thus far has been confined predominantly to the utilization of attitudes in the Quaternary (?) basalt to address fault kinematics, which only provides a relatively short time period of observed motion along the Hurricane fault, the time after extrusion of the basalt to the present. It is obvious that the fault existed as a normal fault before the basalt was erupted because in the footwall, basalt flowed on to Permian rocks and in the hanging wall those same flow rocks lie on Triassic-Jurassic strata. No other clear kinematic indicators were found for the time period before the lava flows, so the sense of motion on the Hurricane fault prior to basalt extrusion is not as simply defined as the Quaternary motion. Additionally, no evidence was found for the Hurricane fault being a reactivated reverse fault as has been noted along other normal faults in the Basin and Range province and the transition zone (e.g., Royse and others, 1975; MacDonald, 1976; Allmendinger and others, 1983; Villien and Kligfield, 1986). If the Hurricane fault was active as a reverse fault, faulting would have occurred during the Sevier orogeny in the Cretaceous period. However, no stratigraphic evidence exists in this location that may provide a kinematic indicator on the fault for that time. Lastly, there are no exposures to support or refute the theory of the Hurricane fault being an even older structure, such as Precambrian in age (cf., Huntoon, 1990).

Virgin Anticline

The Virgin anticline is a regional fold (figure 1) that is exposed in Triassic-Jurassic Navajo Sandstone within the hanging wall of the Hurricane fault in the study area (Plate 1A; figure 10). The fold is exposed for 45 km along strike (Hintze, 1980). Hintze (1986) termed this fold the Bloomington-Washington-Harrisburg anticline, perhaps because Dobbin (1939) notes three domes with those names along strike of the fold, but most workers refer to this fold as the Virgin anticline (Dobbin, 1939). Near Hurricane, Utah, the Virgin anticline is a beautifully exposed, doubly plunging anticline.

In the field area, the anticline is upright, gently-plunging, open, and the fold axis orientation is 5°, S21°W (figures 14 , 8B and C; Plate 2-cross sections B-B' and C-C'). Beds in the western limb of the Virgin anticline strike from N-S to N50°E and dip from 10° to 30° to the west. Bedding dips on the eastern limb of the anticline range from 10°E near the hinge to 41°E on the limb. The strike of beds on the eastern limb range from N12°E to N35°E.

Pintura Fold

The Pintura fold is an anticline exposed within the footwall of the Hurricane fault (Plate 1A and figures 3 and 10) with a total along-strike length of approximately 23 km (Anderson and Mehnert, 1979). Some workers (i.e., Gregory and Williams, 1947; Anderson and Mehnert, 1979) call this anticline the Kanarra fold and others (i.e., Gardner, 1941; Neighbor, 1952) refer to the structure as the Pintura fold. From the literature the terms "Kanarra" and "Pintura" refer to the same fold and here the term Pintura fold is used because of the fold's proximity to the town of Pintura, Utah.

The fold axis of the Pintura fold is oriented 8°, S24°W (figure 14) and Permian rocks of the Pakoon, Queantoweap, and Toroweap Formations and Kaibab Limestone are exposed in the fold (figures 8A and B; Plate 2-cross sections A-A' and B-B'). Beds in the western limb of the Pintura fold strike from N10°E to N42°E and dips range from 14°W near the hinge to 75°W close to the Hurricane fault. The eastern limb of the

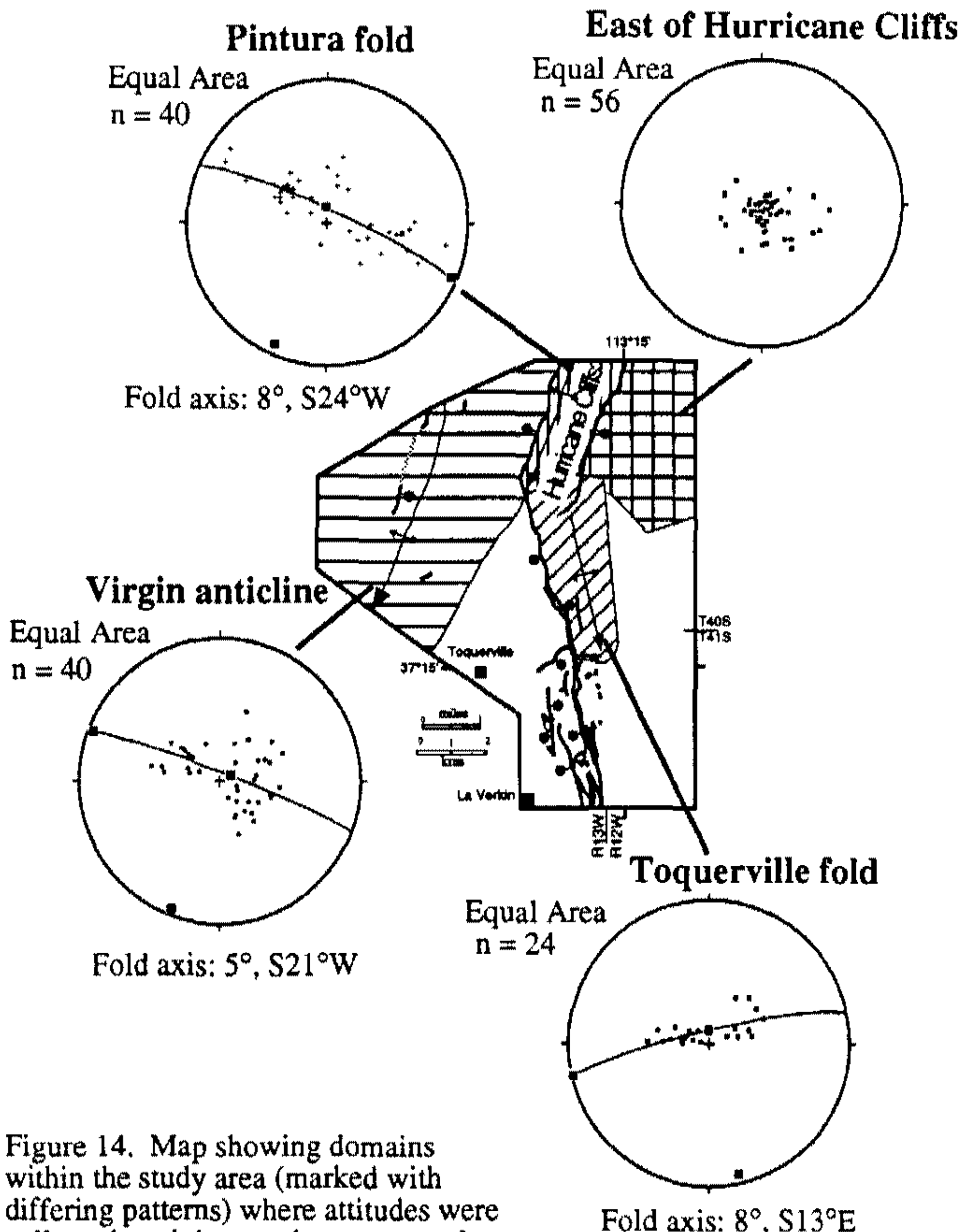


Figure 14. Map showing domains within the study area (marked with differing patterns) where attitudes were collected, and the equal area stereoplots of poles to bedding for domains. Great circles are best-fit great circles through the poles picked by the Bingham axial distribution analysis using *Stereonet* by R.W. Allmendinger.

fold contains beds that dip from 10° to 41° to the east and strike from N12°E to N35°E. The Pintura fold is an upright, gently-plunging to horizontal, open anticline. The shape of the fold may be distorted as a result of movement on the Hurricane fault; the effect of drag would be that beds in the western limb of the Pintura fold dip more steeply now than prior to faulting.

Toquerville Fold

The Toquerville fold (Lovejoy, 1964) is a gently-plunging upright anticline that roughly parallels the strike of the Hurricane fault and lies within the footwall of the fault (Plate 1A and figures 8D and E; Plate 3-cross sections D-D' and E-E'). The Toquerville fold appears to be unrelated to either the Virgin anticline or the Pintura fold. The fold is exposed in the Permian Kaibab Limestone and the Triassic Moenkopi Formation. The attitude of the fold axis is 8°, S13°E (figure 14). Bedding dips in the western limb of the fold range from 11°W to 35°W and strikes range from N10°W to N34°W. The beds in the eastern limb strike between N18°W and N52°E and dip from 10°E near the axis to 36°E away from the axis.

Discussion of the Major Folds and Age of Folding

The age of formation of the Virgin anticline is unclear but has been suggested to be a result of Laramide-age contraction (Gardner, 1941), Sevier contraction (Armstrong, 1968; Grant, 1987), emplacement of the Miocene Pine Valley laccolith (Cook, 1952), or Cenozoic extension (cf., Buck, 1988; Wernicke and Axen, 1988). The related Pine Valley syncline (Dobbin, 1939) exposed to the west of the Virgin anticline (figure 1), folds the Tertiary Claron Formation (Cook, 1957), suggesting that folding continued into the Tertiary. The shape of the Pine Valley syncline is broader and only roughly parallels the Virgin anticline indicating perhaps the occurrence of an overprinting event whereby the intrusion of the Pine Valley laccolith emplaced preferentially or coincidentally within the Pine Valley syncline and may have instigated folding of the underlying Claron Formation. In the field area, small laccolithic intrusions are commonly localized at or near the Virgin anticline hinge (Plate 1A; figure 10). In the Pine Valley Mountains, Cook (1957, fig. 46, pg. 95) mapped Cretaceous rocks immediately below the Tertiary Claron Formation with dips greater than the Claron and interpreted the Pine Valley syncline to be a re-depressed Laramide downwarp. The scenario preferred here is that the Pine Valley syncline and the Virgin anticline formed during the Sevier orogeny, based in part on parallelism to Sevier-age structures, and then the laccolith intruded the Pine Valley syncline and deformed the Tertiary Claron Formation.

The Pintura fold is truncated by the Hurricane fault near a fault segment boundary (between C and D on figure 3). This truncation was also noted by Watson (1968) and is evidence that the fold is older than the Hurricane fault. Armstrong (1968) placed the time of folding of the Pintura fold during the Sevier orogeny, which agrees with the overall parallel trend of the fold axis to Sevier structures.

From Bouger gravity anomaly data gathered along the Hurricane fault (Cook and Hardman, 1967-Plate 1), two apparent gravity highs occur on either side of the fault corresponding to the Virgin anticline and the Pintura fold. Between these two highs is a gravity low that is interpreted here as a syncline (figures 8B; Plate 2-cross sections B-B'). Figure 15 (Plate 4) is the restoration of cross section B-B' and shows both the Pintura fold and the Virgin anticline with a syncline between the two folds. Hamblin (1965, fig. 8, p. 1153) mapped a syncline along strike to the south. These two anticlines and the syncline, each having approximately similar wavelengths of about 10 km, apparently parallel each other for at least 65 km along trend. Also, the two anticlines have similarly trending fold axes; the Virgin anticline fold axis has an attitude of 5°, S21°W and the Pintura fold has a fold axis attitude of 8°, S24°W (figure 14). Therefore,

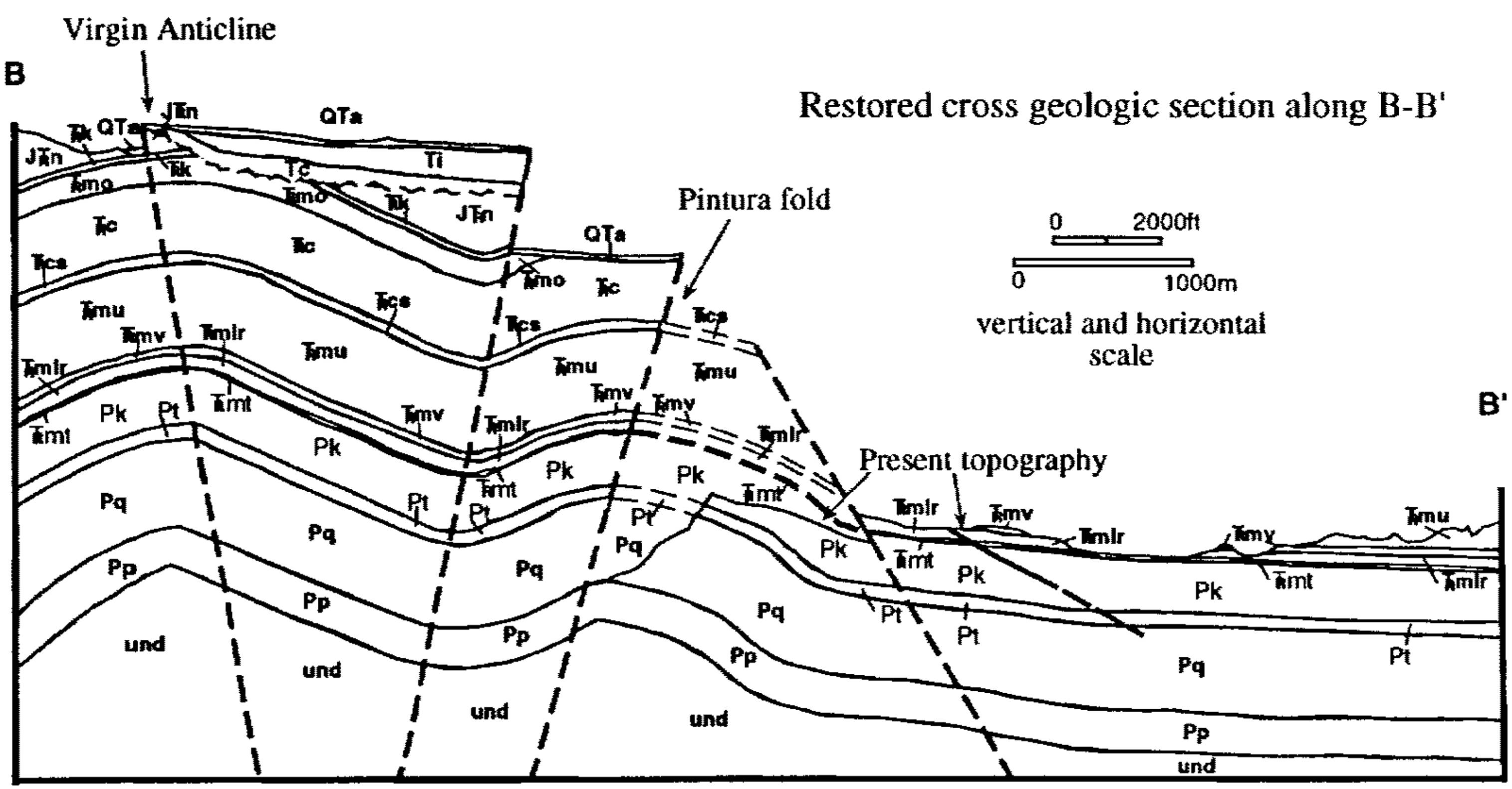


Figure 15. Unit explanation on page 24. Dashed lines are restored normal faults. Virgin Anticline and Pintura fold are labeled.

the folds are here interpreted to be genetically related. If the Pintura fold and the Virgin anticline are related anticlines, then the Pintura fold cannot be a monoclinal drape fold (cf., Davis, 1978) as is observed north of Cedar City, Utah (Threet, 1963). That fold, the Cedar City-Parowan monocline, is interpreted to have formed by Cenozoic normal faulting (Threet, 1963). Because the Pintura fold is cut by the Hurricane fault in the field area and the Washington fault cuts the Virgin anticline (figure 1) near Washington, Utah (Dobbin, 1939; Hamblin, 1970), these folds are both older than the active, extensional faulting in the area. Both the Virgin anticline and the Pintura fold generally parallel regional structures related to Sevier compression (cf., Armstrong, 1968) and are interpreted here to have formed during the early Cretaceous to late Cretaceous Sevier orogeny and are not related to extension.

The Toquerville fold, like the Pintura fold, is within the footwall of the Hurricane fault (Plate 1A; figure 10) and may have existed previously, but because the axial trends of the Toquerville fold and the Pintura fold are not parallel to each other they appear to be unrelated genetically (figure 14). The anticlines occur near fault sections with different strikes and have fold axes that parallel the strike of the fault, criteria required for extension related footwall flexure. One or both of these folds could be caused by footwall folding in a breakaway zone (Buck, 1988; Wernicke and Axen, 1988). However, as has already been interpreted, the Pintura fold is an older, pre-extensional structure. The Toquerville fold could be related to flexure of the footwall due to isostatic rebound of the footwall or lithospheric flexure accompanying the initial break of and motion along the Hurricane fault. With footwall flexure due to isostatic rebound, rotation can occur by motion of vertical footwall shear zones (Wernicke and Axen, 1988). In lithospheric flexure, normal faults are affected by anelastic behavior of the upper crust and the footwall bends in response (Buck, 1988). The Pintura fold, existing prior to faulting, may have been modified by footwall flexure but it is difficult if not impossible to determine if this is the case with the available data. The trend of the

Toquerville fold axis does not parallel regional Sevier structures (cf., Armstrong, 1968), further suggesting it is not a Sevier-age fold. Without further data such as continued detailed mapping to the south of this study area, an interpretation of the genesis of the Toquerville fold is equivocal.

Taylor Creek Fault

A small displacement thrust fault with an average strike of N15°E and a dip of 30°E crops out east of the Hurricane fault and east of the Hurricane Cliffs (Plate 1A). This thrust is the southern portion of the Taylor Creek fault (Lovejoy, 1964) and is considered a flank thrust to the Pintura fold (Grant, 1987; Noweir, 1990). The Taylor Creek fault may have formed in the Late Cretaceous or Early Tertiary during the Laramide orogeny (Kurie, 1966), but probably formed during Sevier compression because it generally parallels the trend of regional Sevier structures, such as the Pintura fold (8°, S24°W) and the Virgin anticline (5°, S21°W) (cf., Armstrong, 1968). In the study area, the Taylor Creek fault has a maximum displacement of 15 m (50 ft) (figures 8A, B, and C; Plate 2-cross sections A-A', B-B', and C-C'). Farther north near Zion National Park, the Taylor Creek thrust fault has more than 600 m (2000 ft) of vertical and 760 m (2500 ft) of horizontal displacement (Kurie, 1966).

CHAPTER 4

RELATIONSHIP OF THE HURRICANE FAULT TO NEARBY STRUCTURES

In southwestern Utah, two large displacement normal faults are exposed that accommodated Quaternary extension in the transition zone; the Hurricane fault and the Gunlock-Grand Wash fault system (figure 1). A third fault with less stratigraphic separation, the Washington fault, also lies in the transition zone. Because these faults have been active at about same time, have similar geometries and have similar amounts of offset, it is possible that these faults form a displacement transfer zone. A transfer zone is the overlapped ends of faults in which decreasing slip on one fault is compensated by increasing slip on the other (Dahlstrom, 1969). The transfer zone may form by a relay ramp structure (Larsen, 1988). By definition, a relay ramp requires that the two en echelon faults are connected at depth. This transfer zone may be the reason for the relatively wide width of the transition zone in this region (figure 16). For example, in southwestern Utah the transition zone is 130 km wide, however, in central Utah the transition zone is less than 1 km wide along the Wasatch fault. The Wasatch fault is a large displacement, active normal fault, similar to the Hurricane fault, but there is no paired, parallel normal fault near the Wasatch fault (e.g., Gilbert, 1928; Schwartz and Coppersmith, 1984; Arabasz and Julander, 1986; Bruhn and others, 1987). Consequently, adjacent to the Wasatch fault there is no displacement transfer zone and the transition zone is much narrower.

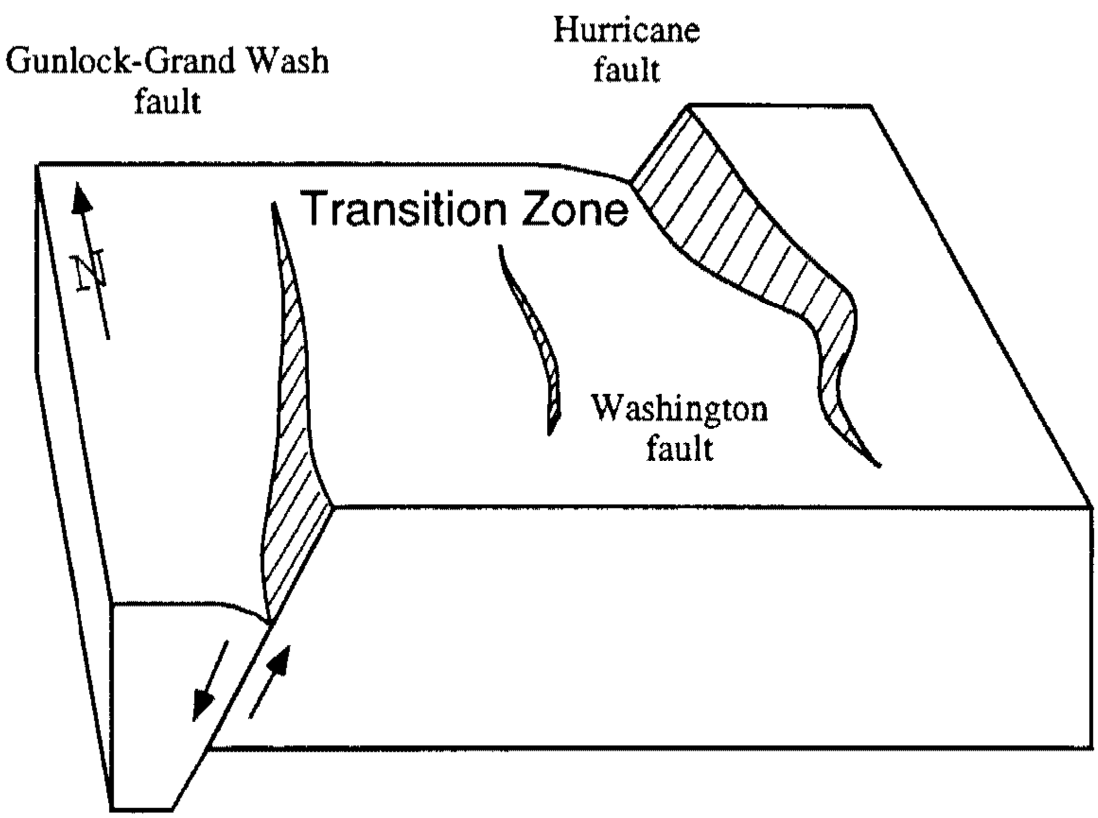


Figure 16. Schematic block diagram describing the displacement transfer zone relationship between the Gunlock-Grand Wash fault system, the Washington fault, and the Hurricane fault. Displacement dies out at the tip line of the Gunlock fault as displacement increases on the Hurricane fault, 50 km to the east. This relationship could be generating the relatively wide width of the Transition Zone in this region. The Basin and Range province is to the west of the Gunlock-Grand Wash fault and the Colorado Plateau is to the east of the Hurricane fault. Diagram is not to scale.

The Hurricane fault increases stratigraphic separation from south to north (Gardner, 1941). Near the south end of the fault (near "Z" on figure 1), there is less than 61 m of stratigraphic separation (Hamblin, 1970). At the Grand Canyon (near "Y" on figure 1) 450 m of stratigraphic separation was measured (Hamblin, 1970). Near the town of Toquerville, Utah, I documented 2070 m of total stratigraphic separation (figures 8A and B; Plate 2-cross sections A-A' and B-B'). Along its length the Hurricane fault displaces Quaternary basalt in at least seven locations (Gardner, 1952). In this study, 450 m of down-to-the-west stratigraphic separation of Quaternary basalt was mapped (Plate 1A; figure 10).

The Gunlock-Grand Wash fault system lies 50 km to the west of the Hurricane fault (figure 1) and is a large, 160 km long, down-to-the-west normal fault system (Moore, 1972). The Grand Wash fault was termed the Cedar Pocket Canyon fault in Utah by Dobbin (1939), but recent literature refers to the fault as the Grand Wash fault and that designation is used here. Stratigraphic separation on the Gunlock-Grand Wash fault system increases from north to south, opposite that of the Hurricane fault (Dobbin, 1939). South of Gunlock, Utah (figure 1), approximately 150 m of stratigraphic separation is documented (Anderson and Barnhard, 1993). Hamblin (1970) measured 450 m of stratigraphic separation near the Utah-Arizona state line. Lucchitta (1966) reported up to 4800 m of stratigraphic separation near the mouth of the Grand Canyon (near "V" on figure 1). This system, like the Hurricane fault, locally displaces Quaternary basalt (Anderson and Christenson, 1989). There are fourteen mapped scarps in alluvium along the Grand Wash fault (Pearthree and others, 1983). A reverse fault called the Reef Reservoir fault (Hintze, 1986) lies along strike between the Gunlock fault and the Grand Wash fault (figure 1); this fault was previously named the Shebit fault (Dobbin, 1939), but the name Reef Reservoir is the more recently used, name and is used here. Because of reverse slip along this up-on-the-west fault, Hintze (1986) suggested this structure is Laramide in age. Anderson and Barnhard (1993)

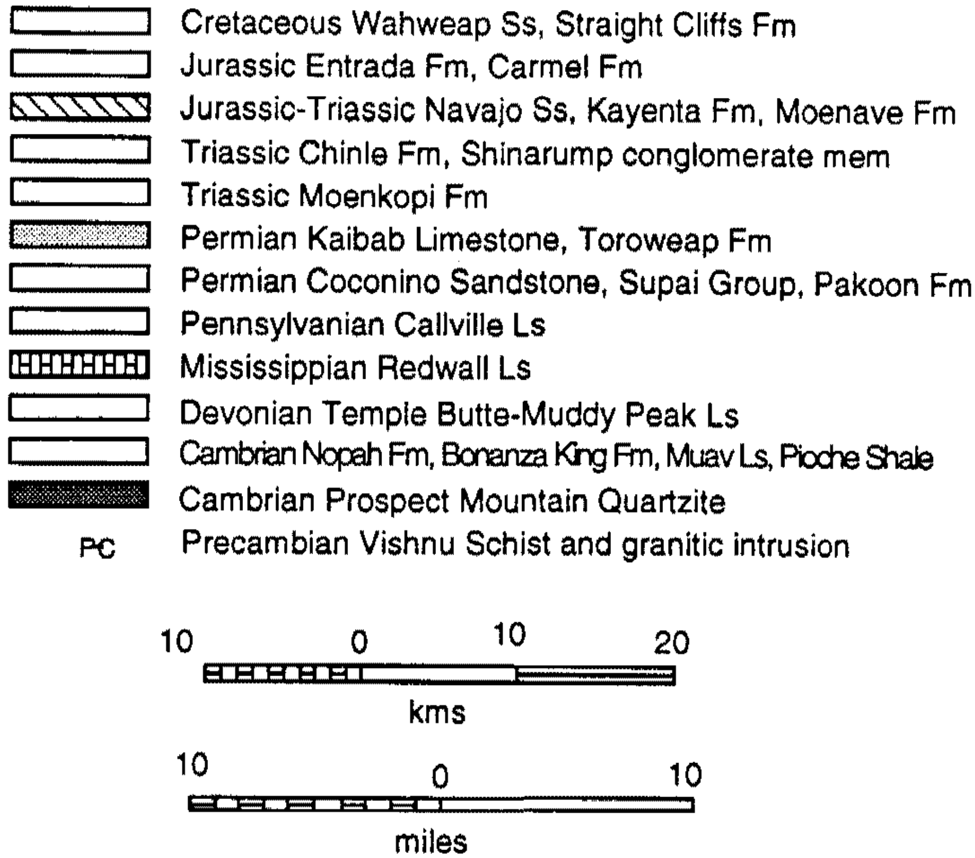
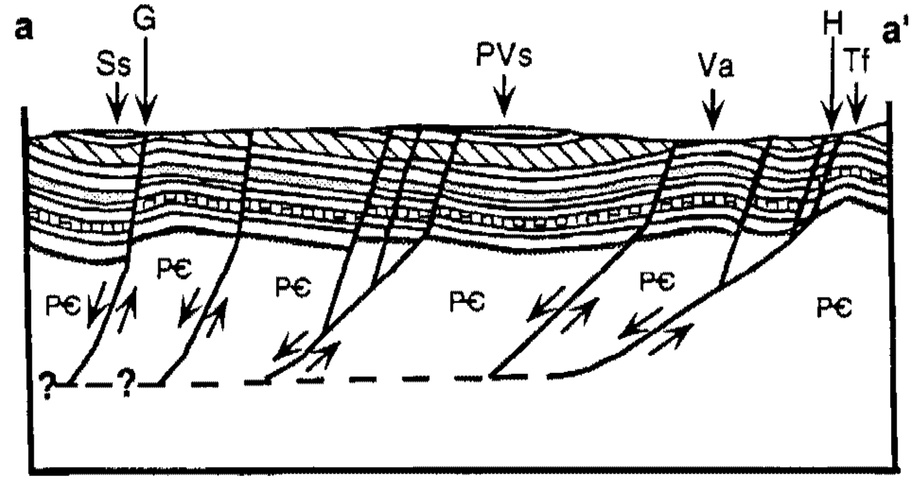
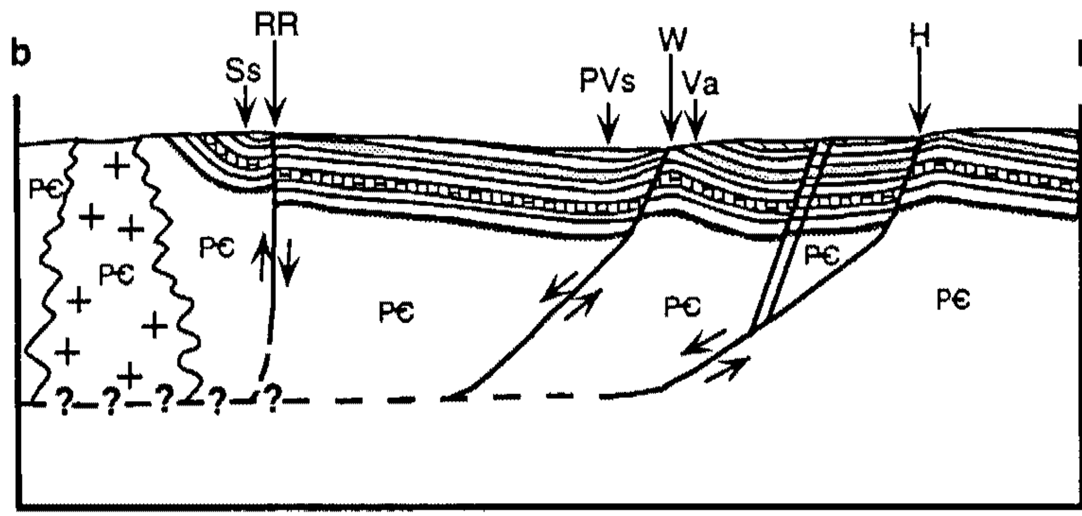
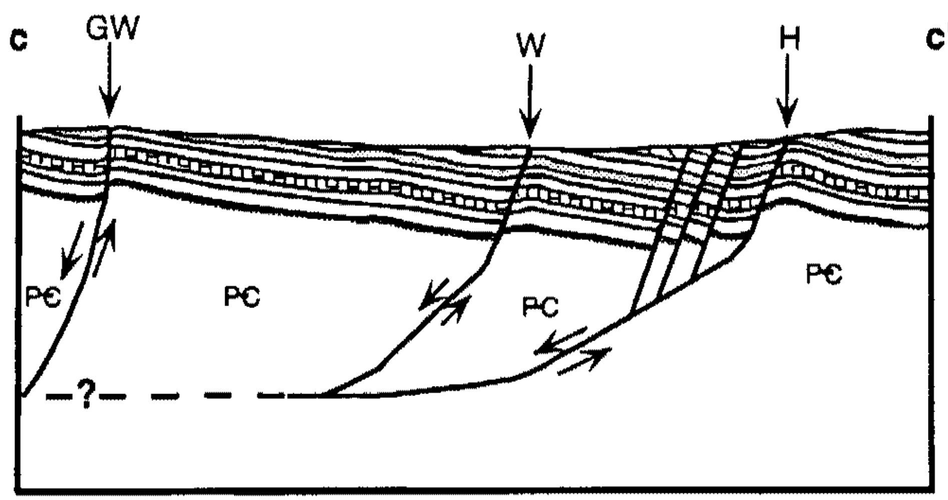


Figure 17. Unit and pattern explanation and scale for regional cross sections (following page) for lines a-a', b-b', and c-c' of figure 1. Major labeled faults are H = Hurricane, W = Washington, G = Gunlock, RR = Reef Reservoir, and GW = Grand Wash; labeled folds are Ss = Shivwitz syncline, PVs = Pine Valley syncline, Va = Virgin anticline, Tf = Toquerville fold. The surface geology and stratigraphic unit thicknesses are from Hintze (1980), scale 1:500,000. Mapping from the present study was incorporated into the structural geology along a-a' and consistency of structures was drawn along strike of the Hurriance fault. Regional structures were inferred from geophysical data of Cook and Hardman (1967). Question marks are drawn where the kinematics of the detachment fault are questioned. Other data that would be useful for defining the at-depth geometries of these faults would include more accurate earthquake location data, deep seismic profiles, and/or well data.


a
G
Ss
PVs
Va
H
a'
Tf
PЄ
PЄ
PЄ
PЄ
PЄ
PЄ
?
?


b
RR
Ss
W
PVs
Va
H
b'
PЄ
PЄ
PЄ
PЄ
PЄ
PЄ
PЄ
?
?
?
?
?


c
GW
W
H
c'
PЄ
PЄ
PЄ
PЄ
?

contend that because of the coincident strikes of the Gunlock, Reef Reservoir, and Grand Wash faults the faults are genetically related. They cite regional sinistral faulting in the Neogene as a factor for the opposing dip direction on the Reef Reservoir fault. The reverse polarity of dips in this fault system may be caused by linkage of sinusoidal border faults along a rift boundary creating an accommodation zone between the ends of the Grand Wash fault and the Gunlock fault (cf., Rosendahl and others, 1986, fig. 4, p. 33). The genetic relationship of the Reef Reservoir fault to the Gunlock-Grand Wash fault system is beyond the scope of this project and is not critical to the discussion of displacement transfer and so will not be considered further.

The Washington fault lies between the Hurricane fault and the Gunlock-Grand Wash fault system, about 20 km west of the Hurricane fault. It is exposed for 58 km along strike from Utah into Arizona (figure 1). Like the Gunlock-Grand Wash fault system, the Washington fault is a normal fault that dips to the west and increases stratigraphic separation from north to south (Dobbin, 1939). Petersen (1983) mapped 660 m of stratigraphic separation 6 km south of the Utah-Arizona state line (near "X" on figure 1) and observed normal displacement of Quaternary alluvium. In northern Arizona, the last motion on the Washington fault was less than 20,000-150,000 years ago, but a unit 5,000 years old is not offset (Menges and Pearthree, 1983). These data suggest that the Washington fault may have moved concurrently with the Hurricane fault and the Gunlock-Grand Wash fault system.

Seismic activity has been documented on all three faults, although the Hurricane fault has had the larger magnitude and more frequent earthquakes (figure 9). Rare seismicity has been documented along the Gunlock-Grand Wash system (i.e., Pearthree and others, 1983, fig. 2; Brumbaugh, 1990, fig .1, p. 436). A lack of earthquake data does not necessarily preclude a lack of activity because seismic monitoring stations are sparsely located throughout the transition zone in southwestern Utah and northwestern Arizona, with only five stations located within the area of figure 1 (Smith and Arabasz, 1991, fig. 8B, p. 196). This deficiency of stations greatly hinders thorough and accurate data collection and given that the majority of seismicity in the ISB is ≤ M2.0, many shocks probably go unobserved (Arabasz and Smith, 1981). However, recorded quakes scattered throughout southwestern Utah suggests that the Gunlock-Grand Wash fault system and the Hurricane fault are active.

Interpretations of the Relationship to Nearby Faults

The hypothesis that the Hurricane fault and the Gunlock-Grand Wash fault system are kinematically and structurally linked was discussed by Moore (1958) and is re-analyzed here. These two subparallel fault systems are of similar age. Stratigraphic separation increases in opposite directions suggesting that there may be displacement transfer between the Hurricane fault and the Gunlock-Grand Wash fault system (figure 16). Because the Gunlock-Grand Wash fault system and the Washington fault increase stratigraphic separation in the same direction and because the Washington fault has a smaller stratigraphic separation the discussion of the displacement transfer zone will be simplified by focusing on the Hurricane fault and the Gunlock-Grand Wash fault system.

In a displacement transfer zone, extension is accommodated across strike of two or more large en echelon faults. In addition, slip on one fault dies out at a tip line and is translated or transferred to increasing slip on another fault. These faults must be active concurrently. A relay ramp structure may be accommodating extension in the transfer zone, and if so, extension is transferred between the Hurricane fault and the Gunlock-Grand Wash fault system by movement along a subhorizontal fault or ductile shear zone at depth (Larsen, 1988). Along the Hurricane fault, the Gunlock-Grand Wash fault system and the Washington fault, Quaternary basalt are offset suggesting that all of these faults systems have been active in the Quaternary. Because the faults have been active in the Quaternary and remain active (figure 9) a transfer zone is chronologically possible.

A transfer zone may explain the relatively wide width of the transition zone in southwestern Utah. For instance, the Gunlock-Grand Wash fault system marks the eastern boundary of the Basin and Range province (figure 1), but at the tip line of this fault system, in the north, the boundary of the Basin and Range province makes a step-over to the Hurricane fault (figure 16), where stratigraphic separation on the fault is relatively increasing. Normal fault interactions between the en echelon Gunlock-Grand Wash fault system and the Hurricane fault accommodate extension and are probably generating the width of the transition zone in southwestern Utah and northwestern Arizona compared with the transition zone further north in central Utah along the Wasatch fault. The Wasatch fault has no en echelon fault and there the transition zone is only 1 km wide.

Across strike of the Hurricane fault, the Gunlock-Grand Wash fault, and the Washington fault the sums of stratigraphic separation are not equal. However, the difference could be due to a number of intervening smaller structures, such as mapped faults that were not included in the calculation, unexposed faults or extension-related compressional structures. The significance of these smaller faults can be observed in the regional cross sections (figure 17).

To test whether the Hurricane, Washington, and Gunlock-Grand Wash faults represent a linked fault system, a series of three balanced cross sections were constructed across the Hurricane fault, the Washington fault, and the Gunlock-Grand Wash fault system (figure 17) using the geologic map of Utah by Hintze (1980). The section lines were drawn normal to the strikes of the major faults. The cross section were drawn using the balanced cross section techniques of Gibbs (1983), and assuming that the three faults in question are hard linked by a subhorizontal detachment. The hypothesized depth to the detachment is drawn at approximately 15 km. This depth is based on typical deep earthquakes that occur in the Intermountain seismic belt, which are between 15 to 20 km (Arabasz and Smith, 1981), as well as on the epicenter depth of the September 2, 1992, St. George earthquake, which occurred at 15 km (Arabasz and others, 1992b; Pechmann and others, 1992). The curvature of the Hurricane fault at depth is interpretive. However, the epicenter for the St. George quake was approximately 16 km west of the Hurricane fault, thus if the quake occurred on the Hurricane fault, the fault must be curved. Curvature on the Washington fault and the Gunlock-Grand Wash fault system is also interpretative and has been drawn to mimic that of the Hurricane fault. Clearly, other scenarios may be possible for the faults at depth. A detachment fault is not necessary for the existence of a transfer zone by the Dahlstrom (1969) definition. However, if a detachment fault does link the Gunlock-Grand Wash and the Hurricane faults, then the detachment would probably have to continue to the west, as shown on the cross sections (figure 17), to be volumetrically feasible. Alternatively, the faults may die out downward and mechanical and geometric continuity is accomplished through internal strain of the block between the faults.

On the basis of: 1) the series of regional cross sections (figure 17); 2) the reverse symmetry of stratigraphic separation on the Hurricane fault and the Gunlock-Grand Wash fault; 3) the similar timing of faulting along all faults including stratigraphic separation of Quaternary basalt; and 4) recent earthquake activity, a displacement transfer zone accommodated by a relay ramp is a reasonable hypothesis in southwestern Utah. This structural link between the Gunlock-Grand Wash fault, the Washington fault, and Hurricane fault is very likely generating the wide width of the transition zone in this region relative to other parts of the transition zone.

CHAPTER 5

GEOLOGIC HAZARDS

Southwestern Utah experienced rapid population growth over the past decade which increased urban and rural development in a geologically hazardous area. The study area is located between the cities of St. George (population 32,700) and Cedar City (population 13,443) as well as several small towns (combined population 6757) (figure 3). This section focuses on the general geologic hazards expected in southwestern Utah and specifically on hazards near the towns of La Verkin and Toquerville. These hazards include, but are not limited to, earthquakes, landslides and rock falls, poor soil conditions, and active sand dunes.

Earthquakes and Other Seismically-induced Hazards

The Gunlock fault, the Washington fault, and the Hurricane fault are major, active, normal faults that lie within the Intermountain seismic belt (ISB) in southwestern Utah (figure 11), a belt of recent seismicity that poses the greatest seismic risk in southwestern Utah (Christenson and Nava, 1992). Because the ISB is an extensive zone of pronounced intraplate earthquake activity (Smith and Sbar, 1974), earthquake hazards in the area include ground shaking, surface rupture, liquefaction, and rock falls (Christenson, 1992).

Although most of the seismic activity in the ISB in southwestern Utah has been M2.0 or less (S.J. Nava, written communication, 1993), a few shocks of greater magnitude have been recorded. Most notably, a M6.0 occurred in the Pine Valley Mountains in 1902 (Arabasz and Smith, 1981) and a M5.6 quake occurred on September 2, 1992, east of St. George, Utah (Arabasz and others, 1992b). In fact, based on previous late Quaternary scarp-forming earthquakes, the occurrence of a M≥ 7.0 earthquake is reasonably likely on one of these faults (Arabasz and Smith, 1981). In the event of a M6.0 earthquake, which has an estimated recurrence interval of 200-300 years in the ISB, an estimated one foot of surface offset could occur across any of these faults (Christenson, 1992). Additionally, the tectonic stress patterns of the ISB tend to produce earthquake swarms (Arabasz and Smith, 1981). One such swarm of over 60 shocks occurred on the Hurricane fault on June 28-29, 1992, near Cedar City, with the largest temblor measuring M4.1 (Arabasz and others, 1992a). Many of these small quakes were felt by people living in the area.

Along strike, the Hurricane fault is a segmented fault. When an earthquake and surface rupture occurs on a long normal fault, such as the Hurricane fault, the fault will rupture for some fraction of its length (Schwartz and Coppersmith, 1984). Commonly, this limited surface rupture distance is related to fault segment barriers and boundaries; segment boundaries will act as a barrier to rupture propagation in the event of an earthquake and may be the site of accumulated strain (Bruhn and others, 1987). Within the study area, there is one fault segment boundary and two fault segments (figure 12) indicating that surface rupture is possible along the Hurricane fault in the study area.

Although historic surface offsets on the Gunlock, Washington, or Hurricane faults have not been documented, there is abundant evidence for surface rupture during the Quaternary on each fault (Christenson, 1992). In this study, three scarps or offset in Quaternary sediments are documented. Along the northern fault segment there are two scarps in alluvium (Plate 1A), the largest is 6 m in height, has a scarp slope of 30°, and has a broad potential age of surface offset of between 1,000 years and 15,000 years (figure 13). A third offset in Quaternary gravel is located on the southern fault segment and has a maximum of 3 m of separation (Plate 1B). Following the characteristic earthquake model of Schwartz and Coppersmith (1984) which suggests that a fault will have typical or characteristic magnitude events or amounts of slip, the two fault segments appear to have separate faulting histories and it can be expected that similar rupture events along these discrete segments will recur.

Liquefaction, the loss of soil bearing strength in poorly graded sands and silts, will result from ground shaking in areas with a shallow water table. Such a shallow water table (less than 3 m) is found in unconsolidated deposits along stream flood plains in southwestern Utah (Christenson, 1992). Although liquefaction susceptibility for southwestern Utah has not been quantified locally, it is a potential hazard on flood plains and adjacent lowlands (Christenson and Nava, 1992). Ash Creek lies north and west of Toquerville and the creek channel is 450 m wide. The water table is probably relatively close to the surface, which poses a site for high liquefaction potential. Near La Verkin the confluence of La Verkin Creek with Ash Creek widens the flood plain to 1200 m. Highway 17 and at least 15 homes are constructed near this creek confluence (Plate 1B) and those structures could be adversely effected in the event of ground shaking and liquefaction. Damage to Highway 17, one of two main roads leading into Zion National Park from the west, could decrease park visitation as well as inconvenience or strand local residents.

Landslides and Rock Falls

Slope-failure or landslides are a common geologic hazard in southwestern Utah (Harty, 1991). Landslides, driven by gravity, commonly result from heavy precipitation, earthquakes, or over-irrigation. In arid southwestern Utah, rain-induced landslides are not common, but in urban areas, over-watering of lawns that are on hill tops and that are underlain by clay-rich material can induce slope-failure. As urbanization increases in areas such as St. George, development on hill slopes will continue (Harty, 1991; 1992).

The geologic unit most prone to landsliding in the region is the clay-rich Chinle Formation (Harty, 1992), which crops out extensively near St. George (Hintze, 1980) but occurs sparsely in the study area. Rock slides, however, occur in the area; there are two talus slides mapped by Harty (1991) near the town of Toquerville as well as a pair of small, deep-seated landslides near La Verkin.

Earthquakes commonly trigger landslides. For instance, the 1992 M5.6 St. George earthquake caused a massive, destructive, landslide near Springdale, Utah, that blocked the highway into Zion National Park, 60 km northeast of the epicenter (Arabasz and others, 1992b). In this seismically active area, earthquakes near mesas that are capped by resistant rock, such as the Shinarump conglomerate or basalt, can trigger major rock falls (Christenson, 1992).

Eight colluvial rock falls that consist primarily of basalt boulders are labeled Qc on Plates 1A and 1B of this study. Toquerville Hill contains 1 km^2 of rock fall material that lies in the town of Toquerville where a number of homes are built and more are down slope of a potential fall. Highway 17 is built along the base of Toquerville Hill and could be blocked by a boulder landslide. Areas that may experience rock falls in the future would include the base of the Hurricane Cliffs near Toquerville due to loosening of basalt material at the top of the cliffs, and near Toquerville Hill, where previous falls have occurred.

Soil Conditions

In southwestern Utah, a number of hazards exist arising from soil conditions. These problem soils include: 1) expansive and collapsible soil caused by swelling clays;

2) gypsum and gypsiferous soils prone to dissolution and chemical attack of concrete; and 3) limestone susceptible to karst or solution collapse (Mulvey, 1992).

Foundation problems caused by poor soil conditions exist in southwestern Utah where structures have been built directly on the Chinle or Moenkopi formations. These fine-grained, clay-rich, units typically produce an overlying expansive soil (Christenson, 1992). Calcareous formations such as the Kaibab Limestone and the Pakoon Dolomite are also common throughout southwestern Utah and increase the likelihood of sinkholes or karst collapse locally (Mulvey, 1992).

In the study area, gypsiferous and expansive soils may cause problems near the town of La Verkin, east of Highway 17, where at least 2 km^2 of a Quaternary sediment (labeled Qa2 on Plate 1B) is derived from erosion of the Moenkopi Formation. This deposit is in some locations 20 m thick. Expansive clays occur in the Moenkopi Formation (Averitt, 1962) and the formation is prone to piping, or localized subsurface erosion (Christenson, 1992). Because Qa2 is composed of fine-grained, clay-rich, gypsiferous soil, the mapped area is probably highly susceptible to sink holes and/or foundation instability. A thorough, quantitative soil-foundation investigation will be required to measure the extent of this hazard. At the close of the field season in 1993 grading had begun for future development of this area near La Verkin. Many trailer parks and camp grounds already exist in the area because of the close proximity to Zion National Park.

Sand Dunes

In this study, dune fields (labeled Qd on Plate 1A) comprise over 7.5 km^2 and are located near Toquerville and east and west of Interstate 15 . These dune fields are typically stabilized with vegetation and are inactive. Some hazards arising from urbanization in or near sand dune fields include the likely reactivation of the dune field due to removal of, or damage to, vegetation. This increases wind blown sand and allows sand dune migration over roads and into irrigation channels. Another hazard associated with dune fields is the probable contamination of ground water from the disposal of wastewater into the highly permeable material (cf., Mulvey, 1992).

CHAPTER 6

CONCLUSIONS

The Hurricane fault in southwestern Utah, near the town of Toquerville (figure 3), is an active high-angle normal fault. Normal faulting formed up to 2070 m of stratigraphic separation prior to extrusion of Quaternary (?) basalt. Following basaltic volcanism, there was an additional 450 m of stratigraphic separation for a total stratigraphic separation of 2520 m. Unconsolidated Holocene gravels were displaced up to 6 m. From measurement of displaced basalt (figure 8C; Plate 2-cross section C-C'), slickenlines, and basalt dip analysis (figure 5), the relative motion for the northern portion of the fault in the field area, named the Ash Creek fault segment, is nearly perfect dip-slip. The relative motion in the southern section, termed the Anderson Junction segment, is dominantly dip-slip but has a slight dextral component to it.

Between the Ash Creek and Anderson Junction fault segments, a small scale anticline crops out in the hanging wall. This anticline trends normal to the fault and suggests a segment boundary in the vicinity of a large change in fault strike (Schlische, 1993). This segment boundary is a nonconservative barrier and faulting in the hanging wall may be accommodating slip along the fault (cf., King, 1986). The Anderson Junction segment has three fault sections within the field area (figure 3), although there may be more along strike. The Ash Creek segment is probably 19 km long and the Anderson Junction segment is at least 25 km long (figure 12).

The Hurricane fault may form a displacement transfer zone with the Gunlock-Grand Wash fault and the Washington fault (figure 16). The Hurricane fault increases stratigraphic separation from south to north while the Gunlock-Grand Wash fault, 50 km to the west, increases stratigraphic separation from north to south. This information, along with the similarity of the fault ages, and recent seismic activity on both faults, suggests that a displacement transfer exists between the two faults. Balanced cross sections constructed perpendicular to the strikes of these faults suggest that a displacement transfer zone is possible with the depth to the detachment at approximately 15 km (figure 17). The transfer zone probably generates the 40+ km width of the transition zone in this region (figure 1).

Two large scale anticlines, the Virgin anticline and the Pintura fold, crop out in the study area. The Virgin anticline is cut by the Washington fault and the Pintura fold is truncated by the Hurricane fault. Based on these cross cutting relationships, the restored cross section along B-B' (figure 15; Plate 4), and Bouger gravity evidence for the existence of a syncline paralleling and between the Virgin anticline and the Pintura fold (Cook and Hardman, 1967), these folds are interpreted to be genetically related to each other and are older than extensional faults. Because the anticlines parallel nearby Sevier-age structures they are interpreted to be Sevier-related folds. It may be possible that the Virgin anticline, the Pintura fold, and the regionally related Pine Valley syncline, are compressional structures and that the Pine Valley syncline was reactivated by emplacement of the Pine Valley laccolith.

Another large fold in the area, the Toquerville fold, has a fold axis trend that does not parallel either the Virgin anticline or the Pintura fold (figure 14). The Toquerville fold is probably unrelated to those two folds, and consequently, may not be related to Sevier contraction. Where this fold crops out, the fold axial trend parallels the strike of the Hurricane fault along the Anderson Junction segment. The Toquerville fold may be caused by isostatic uplift of the footwall created by normal fault motion.

However, the fold does not appear to trend the length of the fault segment, so footwall flexure may only in part explain this footwall anticline.

Southwestern Utah contains several small but growing urban centers. With increased encroachment and development upon geologically unstable areas, such as hard rock capped mesas, flood plains, and regions that have previously experienced land slides, major damage to property and structures can be expected. Earthquakes commonly occur in the area and large earthquakes will trigger hazards which include liquefaction, ground shaking, surface rupture, and rock falls. Other geologic hazards to be expected include problems presented by poor soil conditions and migrating sand dunes.

APPENDIX I

XRF LABORATORY METHODS

The following analytical methods are modified from Morikawa (1993). These are the standard methods employed at the University of Nevada, Las Vegas.

Approximately 1-1.5 kg of fresh, unweathered sample were collected for each analysis. Samples were initially pulverized to <100 mesh in a Dyna Mill Supercollider air suspended impact attrition mill. A geochemical split (approximately 300 ml in volume) was separated from each pulverized sample and powdered to <200 mesh using a Pulverisette automated agate mortar and pestle.

Samples were processed into fused glass disks for major element analysis by heating 1.0 g sample, 9.0 g lithium tetraborate, and 0.16 g ammonium nitrate to 1100°C in gold-platinum crucibles and pouring the resultant melt into heated Au-Pt molds (Noorish and Hutton, 1969; Mills, 1991). Samples for trace element analysis were prepared by mixing 2.5 g sample with 0.5 g methyl cellulose, enclosing this mixture with a rim and backing of additional methyl cellulose, and compressing to 10,000 psi in a Buehler specimen mount press to form a disk (Hutchison, 1974). All samples and reagents were weighted to ± 0.0002 g. All prepared samples were stored in dessicators prior to analysis.

X-ray fluorescence analyses of major and trace elements were completed using the Rigaku 3030 X-ray fluorescence Spectrometer at the University of Nevada, Las Vegas.

sample #	P-0-93	P-1-93	P-2-93	P-3-93	P-4-93	AC-1-93	AC-2-93	AC-3-93	T-1-93	T-2-93	T-3-93	T-4-93	T-5-93	BIR-1 Precision	BIR-1 Accuracy
WT %															
SiO2	49.5	51.8	51.2	51.7	51.7	50.2	50.4	50.4	49.5	51.3	50.5	48.9	48.9	0.32	0.06
TiO2	1.6	1.5	1.5	1.5	1.6	1.9	1.9	1.6	2.0	1.6	1.7	1.8	1.6	0.84	1.04
Al2O3	16.6	16.2	15.2	16.0	16.2	16.1	15.8	16.1	15.8	16.2	16.1	15.8	16.3	0.54	2.40
Fe2O3	10.7	9.9	9.9	9.8	10.4	10.0	12.0	11.3	10.6	11.2	11.3	12.6	12.0	0.47	0.26
MnO	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	2.91	3.89
MgO	6.2	5.5	5.6	5.5	6.5	8.2	6.3	6.7	8.0	6.6	6.6	7.4	7.4	* 1.82	* 2.99
CaO	10.4	9.1	9.3	9.3	9.1	8.1	9.7	9.5	8.4	9.4	9.7	10.1	10.1	2.86	2.12
Na2O	2.7	2.8	2.7	2.8	3.4	3.8	3.4	3.3	3.5	3.4	3.4	3.2	3.1	1.36	1.90
K2O	0.7	1.0	0.9	1.1	1.1	1.4	0.9	0.9	1.4	1.0	0.9	0.7	0.6	0.22	0.59
P2O5	0.3	0.3	0.3	0.3	0.3	0.5	0.3	0.3	0.5	0.3	0.3	0.3	0.3	* 2.50	* 15.18
Total wt. %	98.6	98.2	96.8	98.1	100.3	100.3	100.7	100.3	99.9	101.3	100.6	100.8	100.5		
														BHVO-1	
ppm														Precision	Accuracy
Rb	10.0	18.0	11.9	19.8	20.3	16.9	18.6	18.5	17.3	18.8	17.3	13.3	8.7	2.04	2.42
Ba	395	644	758	635	745	519	444	551	538	546	540	427	384	7.34	78.96
Nb	9.9	10.1	10.9	12.3	10.3	23.6	11.9	10.3	24.3	9.4	11.6	10.0	9.0	8.22	19.62
Sr	436	547	545	534	539	703	453	505	715	515	508	473	439	0.66	3.96
Zr	162	206	210	212	215	263	188	187	272	193	192	177	162	1.82	1.71
Y	21.9	21.9	22.4	22.9	23.1	22.2	22.8	22.6	21.8	22.4	21.8	22.1	21.1	1.53	21.27
Cr	214	227	334	370	259	93	148	185	217	295	193	208	146	5.65	5.33
Ni	76	72	73	70	63	162	55	64	175	56	70	71	62	31.82	5.19

Table 1. Major and trace elements determined by the XRF technique for basalt samples. Sample number (P, AC, T) corresponds to locations shown in figure 5. Analytical precision and accuracy in % are compared with the standard BIR-1 (* indicates comparison with GSP-1) for major elements and BHVO-1 for trace elements. All are USGS standards.

APPENDIX II

CROSS SECTION CONSTRUCTION TECHNIQUE

Structural and stratigraphic relationships observed in the field, as well as by previous workers, were employed to construct balanced cross sections for the area (figures 8A-F ; Plates 2 and 3). All cross sections were drawn perpendicular to the strike of the fault to analyze for along-strike variation. Cross sections were constructed assuming plane strain meaning no material moved in or out of the cross section plane. Bed-length balancing was employed and consistency between hanging wall and footwall cut-off lengths across the fault(s) for individual cross sections was maintained (Rowan and Kligfield, 1989; Groshong, 1989). Volume is assumed to remain constant during deformation (Dahlstrom, 1969). Constant thickness (in the east-west direction) was maintained along an individual section. Where noted, some unit thicknesses increased to the south. Most structural features such as fault dip(s), hanging wall structures and inferred, unmapped, faults were assumed to maintain lateral continuity and were constructed consistently between cross sections.

APPENDIX III

STRATIGRAPHY AND IGNEOUS ROCKS

Paleozoic Sedimentary Formations

Permian Pakoon Formation

The lowest stratigraphic unit in the map area is the Permian dolomite of the Pakoon Formation. The type locality is near Grand Wash, Arizona (McNair, 1951).

The top of the Pakoon is gypsiferous silty mudstone that is recessive, red, yellow and tan. Gypsum layers from 1 mm to 2 m thick are common and interbedded limestone, dolomite and mudstone are from 1-10 cm thick. Below the mudstone is dolomite that is yellow-tan to gray-brown weathered, and gray-tan to light gray fresh, with 5-30 cm thick beds and some bedded chert. The base of the Pakoon is not exposed in this area so the local thickness is uncertain, however, 225 m (740 ft) of Pakoon was logged in a well drilled west of Pintura, Utah (Drilling Records for Oil and Gas in Utah, 1965).

Permian Queantoweap Formation

The Queantoweap Formation, named for exposures in Queantoweap (Whitmore) Canyon near the Grand Canyon (McNair, 1951), is a quartz sandstone that is buff to white to light orange colored on both fresh and weathered surfaces, well-sorted, and fine- to medium-grained. Locally parallel laminations, high- and low-angle cross bedding, and iron staining along bedding occurs. The Queantoweap has a calcareous cement, is porous, but is a resistant unit. The total thickness is 457 m (1500 ft).

Permian Toroweap Formation

The Toroweap Formation stratigraphically overlies the Queantoweap Formation. The type section is found in Toroweap Valley, Mohave County, Arizona (McKee, 1938). It is formally divided into the basal Seligman Member, the middle Brady Canyon Member, and the upper Woods Ranch Member, but in this study the Toroweap Formation was mapped as a single unit.

The base of the Toroweap is a slope forming sandstone with interbedded gypsum layers. The sandstone is composed of well-rounded, medium-sized quartz grains and is tan to yellow-tan in color, but grades to white with increased amounts of gypsum. The resistant middle portion of the Toroweap is composed of dolomite and limestone and contains chert layers about 0.5 m thick and limestone beds 1.5 to 1.8 m thick. The recessive upper section of the Toroweap is 50% white to dark gray laminated gypsum and 50% tan gypsiferous siltstone and thin-bedded dolomite. Total thickness for the Toroweap is 91 m (300 ft).

Permian Kaibab Limestone

The Kaibab Limestone (Darton, 1910) conformably overlies the Toroweap Formation. Type locations include the northern Kaibab Plateau, Utah (Noble, 1928) and the Virgin River Valley, Utah (Reeside and Bassler, 1922).

This resistant limestone is gray, tan, red and yellow on weathered surfaces and gray to tan on fresh. Bedded chert layers are common, as are criniod fragments and brachiopods. The matrix is micrite. Some outcrops contain a basal conglomerate. The Kaibab is commonly brecciated where faulted. Regionally, the thickness of the Kaibab is approximately 305 m (1000 ft) measured in Virgin Valley, south of the field area by Reeside and Bassler (1922).

Mesozoic sedimentary formations

Triassic Moenkopi Formation

Lying disconformably above the Kaibab Limestone is the Moenkopi Formation. The type locality is in the Grand Canyon east of Arizona (Ward, 1901). The Moenkopi Formation is formally subdivided into six members: the Timpoweap member (Gregory and Williams, 1947; Gregory, 1950), the Lower Red member (Gregory, 1950), the Virgin Limestone member (Reeside and Bassler, 1922), the Middle Red member (Gregory, 1950), the Shnabkaib member (Reeside and Bassler, 1922), and the Upper Red member (Gregory, 1950). In this study, the Middle Red, Shnabkaib, and Upper Red members were combined and mapped as a single unit, but are still called and labeled the upper red member (see Plate 1).

Timpoweap Member

The lowermost member of the Moenkopi Formation is the Timpoweap member. This limestone unit is very nonresistant and commonly occurs as rolling hills overlying the very resistant Kaibab Limestone. The Timpoweap member is a fine-grained limestone and shale that is yellow to tan and breaks in platy fragments. Total thickness of the Timpoweap is 15 m (50 ft).

Lower Red Member

Overlying the Timpoweap member is the Lower Red member which is composed of finely-laminated mudstone to thin beds of sandstone. The color is red to brown red with 1-10 cm thick layers of gray mudstone. Thin interbeds of gypsum are common. The slope-forming Lower Red member varies in thickness from 70 m (230 ft) in the north part of the study area to 213 m (700 ft) in the south.

Virgin Limestone Member

Above the Lower Red member is the Virgin Limestone member. This unit forms a resistant ledge, light in color, between two nonresistant red members. The Virgin Limestone member comprises interbedded limestone, sandstone, and siltstone. The limestone beds are 3 to 6 m thick. The sandstone beds are from 1.5 to 9 m thick, are gray to tan on both fresh and weathered surfaces, contain calcite cement, and are porous. On weathered surfaces the limestone is yellow-tan to light gray and on fresh surfaces is yellow-gray and crystalline. Total thickness of the Virgin Limestone is 45 m (150 ft).

Combined Upper Red Member

The combined upper red member of the Moenkopi Formation as used in this study comprises red to maroon to gray-white mudstone beds 1 cm to 1 m thick that form slopes. Gypsum layers, 5-15 cm thick, form slightly more resistant white-gray layers. There is a conspicuous white to gray band of gypsiferous mudstone and siltstone (the Shnabkaib member) that has gradational contacts above and below between the two red members (the Middle Red member and the formal Upper Red member). The uppermost portion of the combined upper red member is red-brown to maroon mudstone. Total thickness of the combined upper red member is from 490 m (1600 ft) to 610 m (2000 ft).

Triassic Chinle Formation

The Chinle Formation contains a basal sandstone, the Shinarump conglomerate member (Gilbert, 1875), which overlies the Moenkopi disconformably. The type locality for the Shinarump conglomerate is in the Kanab area of Kane County, Utah (Powell, 1873). The Shinarump is conformable with the overlying part of the Chinle Formation (Thomas and Taylor, 1946; Gregory, 1950). The Chinle Formation type locality is in eastern Iron County, Utah (Gregory, 1950).

The Shinarump conglomerate is a cross-bedded sandstone composed of angular quartz grains and silica cement. Commonly forming a caprock, the Shinarump is very weather resistant and has a sugary appearance. On weathered surfaces the Shinarump is light gray to yellow and on fresh it is white to light gray. Pebbles make up 0-80% of the unit. The pebbles are well-rounded metamorphic rocks, 0.5-5 cm in diameter. Petrified wood occurs in minor amounts. Total thickness of the Shinarump is 49 m (160 ft).

The Shinarump grades upward into the nonresistant mudstones, siltstones, and sandstones of the Chinle Formation. The color ranges from light gray to gray-red, but generally there is a distinctive purple cast to the Chinle. Petrified wood is common. The upper contact with the Moenave Formation is not exposed in the field area. Cook (1957) reported 420 m (1380 ft) of Chinle Formation, not including the Shinarump conglomerate, from a well-log drilled two miles west of Pintura.

Triassic Moenave Formation

The alternating sandstone, claystone and siltstone of the Moenave Formation (Harshberger and others, 1957), although not exposed in the study area, regionally disconformably overlies the Chinle Formation. The type locality for the Moenave is on the Navajo Indian Reservation in northern Arizona (Harshberger and others, 1957). Regionally, the Moenave is 140 to 155 m (460 to 510 ft) thick (Averitt, 1962).

Triassic Kayenta Formation

A sandstone unit with some minor conglomerate, the Kayenta Formation (Thomas and Taylor, 1946; Gregory, 1950), unconformably overlies the Moenave. The type location is at the Red Hill north of Coal Creek, Utah (Averitt and others, 1955). The Kayenta does not crop out in the field area so is not here described. However, regionally the thickness is 36 m (118 ft) (Gregory, 1950).

Triassic-Jurassic Navajo Sandstone

The Navajo Sandstone, which forms the spectacular cliffs in Zion National Park, Utah, overlies the Kayenta (Huntington and Goldthwait, 1904; Gregory and Williams, 1947; Williams, 1952). Composed of well-sorted, subangular to angular quartz grains with minor feldspar and black flecks of magnetite and biotite, the Navajo Sandstone is a resistant formation. Large cross beds are ubiquitous. The Navajo contains silica cement, is very porous and typically friable. On fresh and weathered surfaces the color can be white, orange, pink or red. Due to fracturing and faulting related to the Hurricane fault the Navajo exposed in the study area does not form large cliffs. The regional total thickness is 366 m (1200 ft) (Gregory, 1950).

Jurassic Carmel Formation

The Carmel Formation was named by Gregory and Moore (1931) for an exposure near the town of Mount Carmel in Kane County, Utah. This unit comprises a thin-bedded, micritic limestone that is light gray to light yellow on both fresh and weathered surfaces. Limestone beds are 15 to 60 cm thick, with some rare thin interbeds of mudstone. Some thick beds are resistant but generally the Carmel is a friable, platey, slope forming unit. No fossils were observed. The upper contact did not crop out in the study area so the thickness can not be calculated, however, Cook (1952) measured 206 m (675 ft) of Carmel Formation in the nearby Pine Valley Mountains.

Tertiary Sedimentary Formations

Early Paleocene to Oligocene Claron Formation

The Claron Formation was named by Leith and Harder (1908) for Mount Claron near Iron Mountain, Utah. Where exposed in the field area, the base of the Claron Formation is faulted.

The Claron is composed of a red basal conglomerate overlain by red-orange sandy limestone and mudstone and gray to white fresh water limestone upsection. The upper and lower contacts of the Claron are not exposed in the study area. In many locations, a clastic unit overlies the limestone, but that unit is missing in this area. Thicknesses of 128 m (420 ft) at Leeds Creek near Leeds, Utah and 235 m (770 ft) in the Pine Valley Mountains are reported (Taylor, 1993).

Tertiary Igneous Rocks

There are four small stocks of monzodiorite that may be related to the Pine Valley laccolith (Cook, 1957), a very shallow intrusion. The monzodiorite is 50% gray cryptocrystalline to fine-grained groundmass, and 50% phenocrysts of plagioclase 2-5 mm in diameter, augite, hypersthene, euhedral biotite, hornblende, and minor amounts of magnetite and ilmenite. On fresh and weathered surfaces the monzodiorite is gray. The surface is well-weathered and jointing is common.

REFERENCES CITED

Allmendinger, R.W., Sharp, J.W., Von Tish, D., Serpa, L., Brown, L., Kaufman, S., Oliver, J., and Smith, R., 1983, Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic-reflection data: Geology, v. 11, p. 532-536.

Anderson, R.E. and Barnhard, T.P., 1993, Heterogeneous Neogene strain and its bearing on horizontal extension and horizontal and vertical contraction at the margin of the extensional orogen, Mormon Mountains area, Nevada and Utah: U.S. Geological Survey Bulletin 2011, 43 p.

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

Anderson, R.E. and Mehnert, H., 1979, Reinterpretation of the history of the Hurricane fault in Utah: Rocky Mountain Association of Geologists-Utah Geological Association, 1979 Basin and Range Symposium, p. 145-173.

Arabasz, W.J. and Smith, R.B., 1981, Earthquake prediction in the Intermountain seismic belt-An interplate extensional regime, Simpson, D.W. and Richards, P.G., eds., Earthquake prediction--An international review: American Geophysical Union, Maurice Ewing Series 4, p. 238-258.

Arabasz, W.J. and Julander, D.R., 1986, Geometry of seismically active faults and crustal deformation within the Basin and Range-Colorado Plateau transition of Utah, *in* Mayer, L., ed., Extensional tectonics of the southwestern United States--A perspective on processes and kinematics: Geological Society of America Special Paper 208, p. 43-74.

Arabasz, W.J., Nava, S.J., and Pechmann, J.C., 1992a, Earthquakes near Cedar City, Utah, June 28-29, 1992: University of Utah Seismograph Stations, Preliminary Earthquake Report, 5 p.

Arabasz, W.J., Pechmann, J.C., and Nava, S.J., 1992b, The St. George (Washington County), Utah, earthquake of September 2, 1992: University of Utah Seismograph Stations, Preliminary Earthquake Report, 6 p.

Armstrong, R.L., 1963, K-Ar ages of volcanics in southwestern Utah and adjacent Nevada, *in* Guidebook to geology of southwestern Utah: Intermountain Association of Petroleum Geologists Annual Field Conference Guidebook, p. 79-80.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p.429-458.

Averitt, P., Detterman, J.S., Harshbarger, J.W., Repenning, C.A., and Wilson, R.F., 1955, Revisions in correlation and nomenclature of Triassic and Jurassic formations in southwestern Utah and northern Arizona: American Association of Petroleum Geologists Bulletin, v. 39, no. 12, p. 2515-2524.

Averitt, P., 1962, Geology and coal resources of the Cedar Mountain quadrangle, Iron County, Utah: U.S. Geological Survey Professional Paper 389, 72 p.

Averitt, P., 1964, Table of post Cretaceous geologic events along the Hurricane fault near Cedar City, Iron County, Utah: Geological Society of America Bulletin, v. 75, p. 901-908.

Axen, G.J., Taylor, W.J., and Bartley, J.M, 1993, Space-time patterns and tectonic controls of Tertiary extension and magmatism in the Great Basin of the western United States: Geological Society of America Bulletin, v. 105, p. 56-76.

Bally, A.W., 1981, Atlantic type margins, *in* Bally, A.W. and others, eds., Geology of passive continental margins: American Association of Petrololeum Geologists Educational Course Note Series 19, p. 1-48.

Best, M.G., and Brimhall, W.H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geological Society of America Bulletin, v. 85, p. 1677-1690.

Best, M.G., McKee, E.H., and Damon, P.E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1035-1050.

Best, M.G. and Grant, S.K., 1987, Stratigraphy of the volcanic Oligocene Needles Range Group in southwestern Utah: U.S. Geological Survey Professional Paper 1433-A, p. 3-28.

Best, M.G., Christiansen, E.H., and Blank, R.H., Jr., 1989, Oligocene caldera complex and calc-alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and Utah: Geological Society of America Bulletin, v. 101, p. 1076-1090.

Bjarnason, I.T. and Pechamann, J.C., 1989, Contemporary tectonics of the Wasatch Front region, Utah, from earthquake focal mechanisms: Bulletin of the Seismological Society of America, v. 79, p. 731-755.

Blank, H.R., Jr., and Kucks, R.P., 1989, Preliminary aeromagnetic, gravity, and generalized geologic maps of the USGS Basin and Range - Colorado Plateau transition zone study area in southwestern Utah, southeastern Nevada, and northwestern Arizona (the "BARCO" project): U.S. Geological Survey Open-file Report 89-432, 16 p.

Bowers, W.E., 1972, The Canaan Peak, Pine Hollow, and Wasatch Formations in the Table Cliff region, Garfield County, Utah: U.S. Geological Survey Bulletin 1331-B, 39 p.

Bruhn, R.L., Gibler, P.R., and Parry, W.T., 1987, Rupture characteristics of normal faults: an example from the Wasatch fault zone, Utah, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extensional tectonics: Geological Society Special Publication No. 28, p. 337-353.

Bruhn, R.L., Yonkee, W.A., and Parry, W.T., 1990, Structural and fluid-chemical properties of seismogenic normal faults: Tectonophysics, v. 175, p. 139-157.

Brumbaugh, D.S., 1990, Earthquake and seismicity of the Grand Canyon region, *in* Beus, S.S., and Morales, S.M., eds., Grand Canyon geology: Oxford University Press, Museum of Northern Arizona Press, p. 435-442.

Buck, W.R., 1988, Flexural rotation of normal faults: Tectonics, v. 7, p. 959-974.

Buck, W.R., Steckler, M.S. and Cochran, J.R., 1988, Thermal consequences of lithospheric extension: pure and simple: Tectonics, v. 7, p. 213-234.

Bucknam, R.C. and Anderson, R.E., 1979, Estimation of fault-scarp ages from a scarp-height-slope-angle relationship: Geology, v. 7, p. 11-14.

Christenson, G.E., 1992, Geologic hazards of the St. George area, Washington County, Utah, *in* Harty, K.M., ed., Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, Field Symposium, p. 99-108.

Christenson, G.E. and Nava, S.J., 1992 Earthquake hazards of southwestern Utah, *in* Harty, K.M., ed., Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, Field Symposium, p. 123-138.

Cook, E.F., 1952, Geology of the Pine Valley Moutains, A preliminary note: Guidebook to the Geology of Utah, Utah Geological and Mineralogical Survey, n. 7, p. 92-100.

Cook, E.F., 1957, Geology of the Pine Valley Mountains, Utah: Utah Geological and Mineralogical Survey Bulletin 58, 111 p.

Cook, K.L. and Hardman, E., 1967, Regional gravity survey of the Hurricane fault area and Iron Springs district, Utah: Geological Society of America Bulletin, v. 78, p. 1063-1076.

Cowan, D.S. and Bruhn, R.L., 1992, Late Jurassic to Early Late Cretaceous geology of the U.S. Cordillera, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordillera orogen: Conterminous U.S.: Boulder, Colorado, The Geological Society of America, Decade of North American Geology, v. G3, p. 169-204.

Dahlstrom, C.D.A., 1969, Balanced cross sections: Canadian Journal of Earth Sciences, v. 6, p. 743-757.

Darton, N.H., 1910, Reconnaissance of parts of northwest New Mexico and northern Arizona: U.S. Geological Survey Bulletin, v. 435, p. 1-88.

Davis, G.H., 1978, Monocline fold pattern of the Colorado Plateau, *in* Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: The Geological Society of America Memoir 151, p. 215-233.

DePolo, C.M., Clark, D.G., Slemmons, D.B., and Ramelli, A.R., 1991, Historical surface faulting in the Basin and Range province, western North America: implications for fault segmentation: Journal of Structural Geology, v. 13, no. 2, p. 123-136.

Dickinson, W.R. and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny,*in* Matthews, V., III, ed., Laramide folding associated with basement block faulting in the western United States: The Geological Society of America Memoir 151, p. 355-366.

Dobbin, C.E., 1939, Geologic structure of St. George district Washington County, Utah: American Association of Petroleum Geologists Bulletin, v. 23, p. 121-144.

Drilling Records for Oil and Gas in Utah, 1965, Heylmun, E.B., Cohenour, R.E., and Kayser, R.B., compilers: Utah Geological and Mineralogical Survey Bulletin 74, p. 497-502.

Gardner, L.S., 1941, The Hurricane fault in southwestern Utah and northwestern Arizona: American Journal of Science, v. 239, p. 241-260.

Gardner, L.S., 1952, The Hurricane fault: Guidebook to the Geology of Utah, Utah Geological and Mineralogical Survey, n. 7, p. 15-21.

Gibbs, A.D., 1983, Balanced cross-section construction from seismic sections in areas of extenional tectonics: Journal of Structural Geology, v. 5, p. 153-160.

Gibbs, A.D., 1984, Structural evolution of extensional basin margins: Journal of the Geological Society of London, v. 141, p. 609-620.

Gilbert, G.K., 1875, Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872 and 1873: U.S. Geographical and Geological Surveys, West of the 100th Meridian Report (Wheeler), v. 3, p. 17-187.

Gilbert, G.K., 1928, Studies of Basin-Range structure: U.S. Geological Survey Professional Paper 153, 92 p.

Goldstrand, P.M., 1990, Stratigraphy and ages of the basal Claron, Pine Hollow, Canaan Peak, and Grapevine Wash Formations, southwest Utah: Utah Geological and Mineralogical Survey Open File Report, 188 p.

Grant, S.K., 1987, Kolob Canyons, Utah: Structure and stratigraphy: Geological Society of America Centennial Field Guide-Rocky Mountain Section, p. 287-290.

Gregory, H.E. and Moore, R.C., 1931, The Kaiparowits region, a geographic and geologic reconnaissance of parts of Utah and Arizona: U.S. Geological Survey Professional Paper 164, 161 p.

Gregory, H.E. and Williams, N.C., 1947, Zion National Monument: Geological Society of America Bulletin, v. 58, p. 211-244.

Gregory, H.E., 1950, Geology and geography of the Zion Park region, Utah and Arizona: U.S. Geological Survey Professional Paper 220, p. 200.

Gregory, H.E., 1951, The geology and geography of the Pansaugunt region, Utah: U.S. Geological Survey Professional Paper 226, 116 p.

Groshong, R.H., 1989, Half-graben structures: Balanced models of extensional fault-bend folds: Geological Society of America Bulletin, v. 101, p. 96-105.

Hamblin, W.K., 1965, Origin of "reverse drag" on the downthrown side of normal faults: Geological Society of America Bulletin, v. 76, p. 1145-1164.

Hamblin, W.K., 1970, Structure of the westen Grand Canyon region, *in* Hamblin, W.K. and Best, M.G, eds., Guidebook to the geology of Utah: Utah Geological Society, p. 3-19.

Harshberger, J.W., Repenning, C.A., and Irwin, J.H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo Country: U.S. Geological Survey Professional Paper 291, p. 1-74.

Harty, K.M., 1991, Landslide map of Utah: Utah Geological and Mineral Survey Map 133, scale 1:500,000, 28 p.

Harty, K.M., 1992, Landslide distribution and hazards in southwestern Utah, *in* Harty, K.M., ed., Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, Field Symposium, p. 109-118.

Hausel, W.D. and Nash, W.P., 1977, Petrology of Tertiary and Quaternary volcanic rocks, Washington County, southwestern Utah: Geological Society of America Bulletin, v. 88, p. 1831-1842.

Hill, D.P., and 30 others, 1993, Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake: Science, v. 260, p. 1617-1623.

Hintze, L.F., 1963, Geologic map of southwestern Utah: Brigham Young University, Utah State Land Board, scale 1:250,000.

Hintze, L.F., 1975, Geologic highway map of Utah: Brigham Young University Geology Studies Special Publication 3, scale 1:1,000,000.

Hintze, L.F., 1980, Geologic map of Utah: Utah Geological and Mineral Survey, scale 1:500,000.

Hintze, L.F., 1986, Stratigraphy and structure of the Beaver Dam Mountains, southwestern Utah, *in* Griffen, D., and Phillips, W.R., eds., Thrusting and extensional structures and mineralization in the Beaver Dam Mountains, southwestern Utah: Utah Geological Association Publication 15, p. 1-36.

Huntington, E. and Goldthwait, J.W., 1904, The Hurricane fault in the Toquerville district, Utah: Harvard College Museum Comp. Zoology Bulletin, v. 42, p. 199-259.

Huntoon, P.W., 1990, Phanerozoic structural geology of the Grand Canyon, *in* Beus, S.S., and Morales, S.M., eds., Grand Canyon geology: Oxford University Press, Museum of Northern Arizona Press, p. 261-309.

Hutchison, C.S., 1974, Laboratory Handbook of Petrographic Techniques: New York, John Wiley and Sons, 527 p.

Jackson, J.A. and White, N.J., 1989, Normal faults in the upper continental crust: observations from regions of active extension: Journal of Structural Geology, v. 11, p. 15-36.

King, G.C.P., 1986, Speculations on the geometry of the initiation and termination processes of earthquake rupture and its relation to morphology and geological structure: Pure and Applied Geophysics, v. 124, p. 567-585.

Kurie, A.E., 1966, Recurrent structural disturbance of the Colorado Plateau margin near Zion National Park, Utah: Geological Society of America Bulletin, v. 77, p. 867-872.

Larsen, P-H, 1988, Relay structures in a Lower Permian basement-involved extension system, East Greenland: Journal of Structural Geology, v. 10, p. 3-8.

Lay, T., Ammon, C.J., Velasco, A.V., Ritsema, J., Wallace, T.C., and Patton, H.J., 1994, Near-real time seismology: Rapid analysis of earthquake faulting: GSA Today, v. 4, n. 5, p. 129-134.

Leith, C.K., and Harder, E.C., 1908, The Iron Springs district, southern Utah: U.S. Geological Survey Bulletin 316-E, p. 359-375.

Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1986, Application of the detachment fault model to the formation of passive continental margins: Geology, v. 14, p. 246-250.

Lovejoy, E.M.P., 1964, The Hurricane fault zone, and the Cedar Pocket Canyon-Shebit-Gunlock fault complex, southwestern Utah and northwestern Arizona: [Ph.D. Thesis] University of Arizona, 195 p.

Lucchitta, I., 1966, Cenozoic geology of the upper Lake Mead area adjacent to the Grand Wash Cliffs, Arizona: [Ph.D Thesis] Pennsylvania State University, 218 p.

MacDonald, R.E., 1976, Tertiary tectonics and sedimentary rocks along the transition, Basin and Range Province to Plateau and Thrust Belt Province, Utah, *in* Hill, J.G., ed., Symposium on Geology of the Cordilleran Hingeline: Rocky Mountain Association of Geology, p. 281-317.

Mackin, J.H., 1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: American Journal of Science, v. 258, p. 81-131.

McKee, E.D., 1938, The environment and history of the Toroweap and Kaibab formations of northern Arizona and southern Utah: Carnegie Institute, Washington Publication 492, 268 p.

McNair, A.H., 1951, Paleozoic stratigraphy of part of northwestern Arizona: American Association of Petroleum Geologists Bulletin, v. 35, p. 503-541.

Menges, C.M. and Pearthree, P.A., 1983, Map of neotectonic (latest Pliocene-Quaternary) deformation in Arizona: Arizona Bureau of Geology and Mineral Technology Open-File Report 83-22, 48 p.

Mills, J.G., 1991, The Timber Mountain Tuff, southwestern Nevada volcanic field: Geochemistry, mineralogy and petrogenesis: [Ph.D. Thesis] Michigan State University, 332 p.

Moody J.D. and Hill, M.J., 1956, Wrench-fault tectonics: Bulletin of the Geological Society of America, v. 67, p. 1207-1246.

Moore, R.T., 1958, Geology of northwestern Mohave County, Arizona: [Master's Thesis] University of Arizona, 81 p.

Moore, R.T., 1972, The geology of the Virgin and Beaverdam Mountains, Arizona: The Arizona Bureau of Mines Bulletin 186, 65 p.

Morikawa, S.A., 1993, The geology of the Tuff of Bridge Spring: Southern Nevada and northwestern Arizona: [Master's Thesis] University of Nevada, Las Vegas, 165 p.

Mulvey, W.E., 1992, Engineering geologic problems caused by soil and rock in southwestern Utah, *in* Harty, K.M., ed., Engineering and environmental geology of southwestern Utah: Utah Geological Association Publication 21, Field Symposium, p. 139-144.

Nash, D.B., 1980, Morphologic dating of degraded normal fault scarps: Journal of Geology, v. 88, p. 353-360.

Neighbor, F., 1952, Geology of the Pintura structure Washington County, Utah: Guidebook to the Geology of Utah, Utah Geological and Mineralogical Survey, n. 7, p. 79-80.

Nelson, S.T., Davidson, J.P., and Sullivan, K.R., 1992, New age determinations of central Colorado Plateau laccoliths, Utah: Recognizing disturbed K-Ar systematics and re-evaluating tectonomagmatic relationships: Geological Society of America Bulletin, v. 104, p. 1547-1560.

Noble, L.F., 1928, A section of the Kaibab limestone in Kaibab Gulch, Utah: U.S. Geological Survey Professional Paper 150, p. 40-60.

Noorish, K. and Hutton, J.T., 1969, An accurate X-ray spectrographic method for the analysis of a wide range of geological samples: Geochimica et Cosmochimica Acta, v. 33, p. 431-453.

Noweir, M.A., 1990, Structural analysis of the Overthrust Belt (OTB) of southwest Utah: [Ph.D. Thesis] University of Missouri-Rolla, 141 p.

Pearthree, P.A., Menges, C.M., and Mayer, L., 1983, Distribution, recurrence, and possible tectonic implications of late Quaternary faulting in Arizona: Arizona Bureau of Geology and Mineral Technology Open-File Report 83-20, 36 p.

Pechmann, J.C., Arabasz, W.L., and Nava, S.J., 1992, The St. George, Utah, earthquake of September 2, 1992: A normal-faulting earthquake with very weak aftershock activity: Eos (Transactions, American Geophysical Union), v. 73, p. 399.

Petersen, S.M., 1983, The tectonics of the Washington fault zone northern Mohave County, Arizona: Brigham Young University Geology Studies, v. 30, p. 83-94.

Pierce, K.L. and Colman, S.M., 1986, Effect of height and orientation (microclimate) on geomorphic degradation rates and processes, late glacial terrace scarps in central Idaho: Geological Society of America Bulletin, v. 97, p. 869-885.

Powell, J.W., 1873, Some remarks on the geological structure of a district of a county lying to the north of the Grand Canyon of the Colorado: American Journal of Science, 3rd Series, v. 5, p. 456-465.

Reeside, J.B. and Bassler, H., 1922, Stratigraphic sections in southwestern Utah and northwestern Arizona: U.S. Geological Survey Professional Paper 129-D, p. 53-77.

Reynolds, S.J., 1988, Geologic map of Arizona: Arizona Geological Survey, scale 1:1,000,000.

Rosendahl, B.R., Reynolds, D.J., Lorber, P.M., Burgess, C.F., McGill, J., Scott, D., Lambiase, J.J., and Derksen, S.J., 1986, Structural expressions of rifting: lessons from Lake Tanganyika, Africa, *in* Frostrick, L.E., and others, eds., Sedimentations in the East African Rifts: Geological Society Special Publication, no. 25, p. 29-43.

Rowan, M.G. and Kligfield, R., 1989, Cross section restoration and balancing as aid to seismic interpretation in extensional terranes: American Association of Petroleum Geologists Bulletin, v. 73, p. 955-966.

Rowley, P.D., Steven, T.A., Anderson, J.J., and Cunningham, C.G., 1979, Cenozoic stratigraphic and structural framework of southwestern Utah: U.S. Geological Survey 1149, 22 p.

Royse, F., Warner, M.A., and Reese, D.L., 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho-northern Utah, *in* Symposium on Deep Drilling Frontiers in the Central Rocky Mountains: Rocky Mountain Association of Geologists, p. 41-54.

Schlische, R.W., 1993, Anatomy and evolution of the Triassic-Jurassic continental rift system, eastern North America: Tectonics, v. 12, p. 1026-1042

Schwartz, D.P., and Coppersmith, K.J., 1984, Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas fault zones: Journal of Geophysical Research, v.89, no. B7, p. 5,681-5,698.

Scott, D.L., Etheridge, M.A., and Rosendahl, B.R., 1992, Oblique-slip deformation in extensional terrains: A case study of the Lakes Tanganyika and Malawi rift zones: Tectonics, v. 11, p. 998-1009.

Scott, D.L., Braun, J., and Etheridge, M.A., 1994, Dip analysis as a tool for estimating regional kinematics in extensional terranes: Journal of Structural Geology, v. 16, p. 393-401.

Smith, R.B. and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the Intermountain seismic belt: Geological Society of America Bulletin, v. 85, p. 1205-1218.

Smith, R.B. and Arabasz, W.J., 1991, Seismicity of the Intermountain eismic belt, *in* Slemmons, D.B., Engdahl, E.R., Zoback, M.D., and Blackwell, D.D., eds., Neotectonics of North America: Boulder, Colorado: Geological Society of America, Decade of North American Geology Map Volume 1, p. 185-228.

Spencer, J.E., 1984, Role of tectonic denudation in warping and uplift of low-angle normal faults: Geology, v. 12, p. 95-98.

Spencer, J.E., 1990, Late Cenozoic extensional and compressional tectonism in the southern and western Arawatz Mountains, southeasten California, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 317-333.

Susong, D.D., Janecke, S.U., and Bruhn, R.L., 1990, Structure of a fault segment boundary in the Lost River Fault Zone, Idaho, and possible effect on the 1983 Borah Peak earthquake rupture: Bulletin of the Seismological Society of America, v. 80, p. 57-68.

Sylvester, A.G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, p. 1666-1703.

Taylor, W.J. and Bartley, J.M., 1992, Prevolcanic extensional breakaway fault and its geologic implications for eastern Nevada and western Utah: Geological Society of America Bulletin, v. 104, p. 255-266.

Taylor, W.J., 1993, Stratigraphic and lithologic analysis of the Claron Formation in southwestern Utah: Utah Geological and Mineralogical Survey Miscellaneous Publication 93-1, 52 p.

Threet, R.L., 1963, Structure of the Colorado Plateau margin near Cedar City, Utah *in* Heylmun, E.B., ed., Intermountain Association of Petroleum Geologists Guidebook to the geology of southwestern Utah, 12th Annual Field Conference: Utah Geological and Mineralogical Survey, p. 104-117.

Thomas, H.E. and Taylor, G.H., 1946, Geology and groundwater resources of Cedar City and Parowan Valleys, Iron County, Utah: U.S. Geological Survey Water-Supply Paper 993. 210 p.

Turner, R.D. and Glazner, A.F., 1990, Miocene volcanism, folding, and faulting in the Castle Mountains, southern Nevada and eastern California, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 23-35.

Villien, A. and Kligfield, R.M., 1986, Thrusting and synorogenic sedimentation in central Utah, *in* Peterson, J.A., ed., Paleotectonics and sedimentaion: American Association of Petroleum Geologists Memoir 41, p. 281-307.

Ward, L.F., 1901, Geology of the Little Colorado Valley: American Journal of Science, 4th Series, v. 12, p. 401-413.

Watson, R.A., 1968, Structural development of the Toquerville-Pintura segment of the Hurricane Cliffs, Utah: Brigham Young University Geology Studies, v. 15, p. 67-76.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range Province-Nappe tectonics in an extending orogen: Nature, v. 291, p. 645-648.

Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108-125.

Wernicke, B. and Axen, G.J., 1988, On the role of isostacy in the evolution of normal fault systems: Geology, v. 16, p. 848-851.

Williams, N.C., 1952, Jurassic stratigraphy of southwestern Utah: Guidebook to the Geology of Utah, Utah Geological and Mineralogical Survey, n. 7, p. 61-68.

Yin, A., 1991, Mechanisms for the formation of domal and basinal detachment faults; a three-dimensional analysis: Journal of Geophysical Research, v. 96, p. 14,577-14,594

Zoback, M.L. and Zoback, M.D., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, p. 6113-6156.