Fault segmentation, fault linkage, and hazards along the Sevier fault, southwestern Utah

Ilsa M Schiefelbein
University of Nevada, Las Vegas

Follow this and additional works at: https://digitalscholarship.unlv.edu/rtds

Repository Citation
Schiefelbein, Ilsa M, "Fault segmentation, fault linkage, and hazards along the Sevier fault, southwestern Utah" (2002). UNLV Retrospective Theses & Dissertations. 1393.
https://digitalscholarship.unlv.edu/rtds/1393

This Thesis is brought to you for free and open access by Digital Scholarship@UNLV. It has been accepted for inclusion in UNLV Retrospective Theses & Dissertations by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48108-1346 USA
800-521-0600
NOTE TO USERS

Page(s) not included in the original manuscript are unavailable from the author or university. The manuscript was microfilmed as received.

62

This reproduction is the best copy available.
FAULT SEGMENTATION, FAULT LINKAGE, AND HAZARDS ALONG
THE SEVIER FAULT, SOUTHWESTERN UTAH

by

Ilia M. Schiefelbein
Bachelor of Science
University of Wisconsin - Milwaukee
1998

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science Degree
Department of Geoscience
College of Sciences

Graduate College
University of Nevada, Las Vegas
August 2002
The Thesis prepared by

Ilisa M. Schiebelbein

Entitled

Fault Segmentation, Fault Linkage, and Hazards along the Sevier Fault, Southwestern Utah

is approved in partial fulfillment of the requirements for the degree of

Master of Science

Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

Fault Segmentation, Fault Linkage, and Hazards along the Sevier Fault, Southwestern Utah

by

Ilsa M. Schiefelbein

Dr. Wanda J. Taylor, Examination Committee Chair
Associate Professor of Geology
University of Nevada, Las Vegas

Theoretically, short normal faults link to form long faults and salients develop in the linkage zones. This project provides new data and interpretations on (1) normal fault linkage zones; (2) earthquake and landslide hazards; and (3) fold formation along the active Sevier fault, Utah. Geologic mapping, geometric analyses, geochronology, landslide evaluation, and stream history led to five conclusions. (1) Six principal faults linked to form the Orderville salient and connect the Mt. Carmel and Spencer Bench segments. Four relay ramps formed between overlapping faults. This multipartite linkage zone implies that simple models only imperfectly represent natural examples. (2) Two relay ramps contain rarely analyzed fault-parallel folds. These folds accommodate a downward decrease in space between faults. (3) Fluvial deposits indicate three downcutting stages of a south-flowing stream. Some slip along the Sevier fault occurred after the first two stages and tilted the deposits. (4) 570 ka basalt is offset ~3 m. Thus, the young slip rate is 0.018 mm/yr. (5) Mechanical weathering processes or seismicity induced 14 landslides and similar future slope failures are likely.
# TABLE OF CONTENTS

ABSTRACT ................................................................................................................................iii

LIST OF FIGURES......................................................................................................................v

ACKNOWLEDGEMENTS .......................................................................................................vi

CHAPTER 1  INTRODUCTION ............................................................................................1

CHAPTER 2  CONCEPTUAL MODELS ............................................................................3
  Introduction ..............................................................................................................................3
  Fault Linkage Models .............................................................................................................3
  Displacement vs. Distance Diagrams ...................................................................................9
  Relay Ramps ..........................................................................................................................11
  Segment Boundaries ..............................................................................................................14

CHAPTER 3  REGIONAL TECTONIC BACKGROUND ...............................................17
  Introduction ............................................................................................................................17
  Evolution of the Transform Boundary ...............................................................................18
  Regional Tectonics of Southwestern Utah .........................................................................19
  Mesozoic Sevier Orogeny ....................................................................................................19
  Laramide Orogeny ................................................................................................................20
  Cenozoic Volcanism .............................................................................................................20
  Late Cenozoic Basin and Range Style Extension ............................................................21
  Definition of Provinces in Southern Utah .........................................................................23
    Basin and Range Province .............................................................................................23
    Colorado Plateau .............................................................................................................23
    Utah Transition Zone .......................................................................................................24
    High Plateaus subprovince of the Colorado Plateau ....................................................25

CHAPTER 4  STRATIGRAPHY ........................................................................................26
  Mesozoic Stratigraphy .........................................................................................................26
  Cenozoic Stratigraphy .........................................................................................................27

CHAPTER 5  STRUCTURAL DESCRIPTIONS ..................................................................29
  Introduction ...........................................................................................................................29
  Sevier Fault ...........................................................................................................................29
  Southern Domain - Orderville Relay Ramp .....................................................................30
  Central Domain - Stewart Canyon Overlap Zone ............................................................31
  Spencer Bench Domain .......................................................................................................35

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Folding within the Study Area</td>
<td>38</td>
</tr>
<tr>
<td>CHAPTER 6 VIRGIN RIVER DEPOSITS</td>
<td></td>
</tr>
<tr>
<td>Introduction</td>
<td>39</td>
</tr>
<tr>
<td>Modern Fluvial Deposits</td>
<td>40</td>
</tr>
<tr>
<td>Young Fluvial Conglomerate</td>
<td>41</td>
</tr>
<tr>
<td>Older Fluvial Conglomerate</td>
<td>42</td>
</tr>
<tr>
<td>Interpretations</td>
<td>43</td>
</tr>
<tr>
<td>Discussion of the Virgin River Deposits</td>
<td>44</td>
</tr>
<tr>
<td>Faulting within the Quaternary Fluvial Deposits</td>
<td>44</td>
</tr>
<tr>
<td>CHAPTER 7 STRUCTURAL INTERPRETATIONS</td>
<td>47</td>
</tr>
<tr>
<td>Linkage</td>
<td></td>
</tr>
<tr>
<td>Examples of Fault Linkage</td>
<td>47</td>
</tr>
<tr>
<td>Fault Capture in the Orderville Area</td>
<td>48</td>
</tr>
<tr>
<td>Overlapping Faults in the Stewart Canyon Area</td>
<td>49</td>
</tr>
<tr>
<td>Eastern Stewart Canyon Overlap Zone</td>
<td>49</td>
</tr>
<tr>
<td>Central Stewart Canyon Zone</td>
<td>50</td>
</tr>
<tr>
<td>Western Stewart Canyon Zone</td>
<td>51</td>
</tr>
<tr>
<td>Folds within Relay Ramps</td>
<td>52</td>
</tr>
<tr>
<td>Summary</td>
<td>53</td>
</tr>
<tr>
<td>Stages of Relay Ramp Development in the Stewart Canyon Overlap Zone</td>
<td>53</td>
</tr>
<tr>
<td>Stages of Linkage Along the Central Sevier Fault</td>
<td>54</td>
</tr>
<tr>
<td>Segments and Segment Boundaries</td>
<td>56</td>
</tr>
<tr>
<td>Age Constraints for the Sevier Fault</td>
<td>57</td>
</tr>
<tr>
<td>Slip Rates</td>
<td>57</td>
</tr>
<tr>
<td>Fault Scarps</td>
<td>59</td>
</tr>
<tr>
<td>Folding along the central Sevier fault</td>
<td>60</td>
</tr>
<tr>
<td>CHAPTER 8 EARTHQUAKE AND LANDSLIDE HAZARDS</td>
<td>63</td>
</tr>
<tr>
<td>Earthquakes</td>
<td>63</td>
</tr>
<tr>
<td>Landslides</td>
<td>65</td>
</tr>
<tr>
<td>Identifying and Categorizing Landslides</td>
<td>65</td>
</tr>
<tr>
<td>Regional Slope Failures</td>
<td>67</td>
</tr>
<tr>
<td>Triggering Mechanisms for Long Valley Landslides</td>
<td>68</td>
</tr>
<tr>
<td>Classification of the Dry Wash Landslide</td>
<td>70</td>
</tr>
<tr>
<td>Ethical Assessment of Hazards</td>
<td>72</td>
</tr>
<tr>
<td>CHAPTER 9 REGIONAL TECTONIC INTERPRETATIONS</td>
<td>73</td>
</tr>
<tr>
<td>Introduction</td>
<td>73</td>
</tr>
<tr>
<td>Northern Termination of the Sevier Fault</td>
<td>73</td>
</tr>
<tr>
<td>Other Long Normal Fault Relationships</td>
<td>74</td>
</tr>
<tr>
<td>Sevier, Laramide, or Cenozoic Regional Folding within the Study Area</td>
<td>76</td>
</tr>
<tr>
<td>CHAPTER 10 PETROLEUM POTENTIAL</td>
<td>77</td>
</tr>
<tr>
<td>Normal Fault Linkage and Hydrocarbon Production</td>
<td>77</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Location Map</td>
<td>87</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Models of Types of Linkage</td>
<td>88</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Stress Field Diagram</td>
<td>90</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Displacement vs. Distance Models</td>
<td>91</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Relay Ramp Models</td>
<td>92</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Segment Boundary Models</td>
<td>93</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Tectonic Map</td>
<td>94</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Lower Stratigraphic Column</td>
<td>95</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Upper Stratigraphic Column</td>
<td>96</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Simplified Geologic and Location Map</td>
<td>97</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Basalt Isochrons</td>
<td>98</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Fault Trace Map</td>
<td>99</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Orderville Relay Ramp Fence Diagram</td>
<td>101</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Orderville and Glendale Relay Ramp Stereonets</td>
<td>102</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Geologic Map of Quaternary Units</td>
<td>103</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Stewart Canyon Overlap Zone Fence Diagram</td>
<td>104</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Photos of Different Aged Conglomerate</td>
<td>105</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Photos of Channels and Sandbars within the Conglomerate Unit</td>
<td>106</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Displacement vs. Distance Diagrams for the Central Sevier Fault</td>
<td>107</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Displacement vs. Distance Diagrams for the Overlap Zones</td>
<td>108</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Space Accommodation Diagram</td>
<td>109</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Stages of Linkage along the Central Sevier Fault</td>
<td>110</td>
</tr>
<tr>
<td>Figure 23</td>
<td>Fault Trace Maps of the Stages of Linkage within the Stewart Canyon Overlap Zone</td>
<td>111</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Types of Landslides</td>
<td>112</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Landslide Map of the Area</td>
<td>113</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Photo (A) Glendale Landslide (B) Dry Wash Landslide</td>
<td>114</td>
</tr>
<tr>
<td>Figure 27</td>
<td>Photos of Vegetation on the Dry Wash Landslide</td>
<td>115</td>
</tr>
<tr>
<td>Figure 28</td>
<td>Photos of Vegetation within and Surrounding the Dry Wash Landslide</td>
<td>116</td>
</tr>
<tr>
<td>Figure 29</td>
<td>Photos of the (A) Toe and (B) Head Scarp of the Dry Wash Landslide</td>
<td>117</td>
</tr>
<tr>
<td>Figure 30</td>
<td>Photo of Toe of Dry Wash Landslide</td>
<td>118</td>
</tr>
<tr>
<td>Figure 31</td>
<td>Relay Ramp Models for Petroleum Accumulation</td>
<td>119</td>
</tr>
<tr>
<td>Figure 32</td>
<td>Location Map of Oil Fields in Southwestern Utah</td>
<td>120</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

First and foremost, I would like to thank my parents, Rick and Kathy Schiefelbein, for their endless love, support, and encouragement and my brother for all the humorous phone conversations and just making me laugh. I would also like to thank my advisor and friend, Dr. Wanda J. Taylor, for all her support, patience, confidence boosting, understanding, thoughtfulness, and motivation. I could not have done it without her. Thanks goes to my committee, Dr. Gene Smith, Dr. Terry Spell, and Dr. Barbara Luke, for all their helpful reviews, encouragement, and meeting important deadlines. Additionally, thanks to Dr. Gene Smith for assisting me with sample collection, motivation in the field, and dealing with all my traumas throughout my final semester.

I would like to acknowledge the following sources of funding which helped make this project possible: American Association of Petroleum Geologists Grants-in-Aid, Geological Society of America Research Grant, Sigma Xi Grants-in-Aid of Research, Arizona/Nevada Academy of Science research grant, UNLV Graduate College Summer Session Scholarship, Bernada E. French Scholarship, UNLV Graduate Student Association Grant-in-Aid, Geological Society of America Travel Grants, Roy Shelmon Meeting Awards, and a UNLV PIA grant to Dr. Wanda J. Taylor and Dr. Margaret Rees.

I would like to thank my field assistant, Treasure Bailey, for helping me keep my sanity in the field for twelve weeks, input on geologically difficult areas, collecting
samples, friendship, and companionship. Thanks to all of the landowners, especially, the
Spencer family, Barry and Judith Ford, the Sorensen family, the Lamb family, the
Chamberlain family, the Heaton family, the Brinkerhoff family, the Cox family, and
Norman Carroll for access to and help navigating their property. I would also like to
thank Ellen Lamb, her family, and staff the Glendale KOA for their friendship, allowing
us to camp at a very reasonable rate in an enjoyable camping environment, allowing us to
store equipment, use the phone, and watching over us. Thanks for everything Ellen.
You, your family, and staff made summer fieldwork logistics easier and very enjoyable.
I acknowledge all the help and advice on land ownership from the staff at the Kanab
Bureau of Land Management office.

Thanks to each faculty and staff member in the UNLV Geoscience Department
for all the contributions and creating an enjoyable environment to work in. I would
particularly like to thank Dr. Timothy Lawton at New Mexico State University for his
helpful contributions and discussions of the geology of the area. Thanks to Kathy Zanetti
for all the help with understanding the process of dating, dating my samples, and reading
the results in the Nevada Isotope Geochronology Lab.

I would like to thank my friends and colleagues for creating an enjoyable learning
environment. I particularly would like to thank my friends Robyn Howley, Melissa
Hicks, Amy Brock, John VanHoesen, and Jason Smith for all their support both in and
out of the office, helpful reviews and comments, good times, and friendship.

Last, but certainly not least, I would like to thank my loving boyfriend Rob
Kerscher, for all his love, support, patience, encouragement, and being the scale in my
field photos. I could have never done it without him. Thanks again.
CHAPTER 1

INTRODUCTION

The purpose of this project is two-fold. First, conduct a detailed study of multipartite normal fault (several faults that link and form on long fault) linkage zones using the central Sevier fault, southwestern Utah as a case study (Fig. 1). Second, evaluate the earthquake and landslide hazards in the region.

Most published data and interpretations focus on simple linkage zones (e.g., Crone and Haller, 1991; Koukouvelas and Doutsos, 1996; Pavlides et al., 1998). Although multipartite linkage zones have been mapped in the past (e.g., Bowers, 1991; Billingsley, 1993, 1994; Barton et al., 1998; Zampieri, 2000; Ferrill and Morris, 2001), these sites have not been analyzed in detail. Linkage zones contain information important to understanding how long (10's–100's of km) faults form.

Linkage zones are also important to hydrocarbon exploration because active exploration is common within them (e.g., Gulf of Mexico). Understanding multipartite linkage zones will help determine where migration pathways and potential petroleum traps exist.

The Sevier fault is an ideal place to study fault linkage because (1) it is located in a relatively geologically simple region, (2) exposure is excellent, and (3) detailed work has not been done along the central Sevier fault. The new data document a multipartite linkage zone between Glendale and Orderville Utah, which separates two geometric
segments (Mt. Carmel and Spencer Bench segments). The linkage zone forms the Orderville salient (bend). This salient contains the linkage sites of several faults and four relay ramps (strain transfer zones). This number of faults and folds is greater than predicted in simple linkage models. Two of the relay ramps contain fault-parallel folds in one linkage area in addition to the ramp monoclines (Plates 1 and 2). Understanding the structure within relay ramps is necessary to fully describe linkage zones. However, fault-parallel folds within linkage zones are not commonly discussed because these folds are typically subtle and not recognized.

The second problem addressed in this project is the earthquake and landslide hazards for the region. Evaluating earthquake and landslide hazards is important because the area is popular with summer tourists and is populated by small (<250 people) towns and agricultural communities. However, little detailed work on seismic activity or landslides has been done along the central Sevier fault. The data presented here show that the central Sevier fault cuts ~570 ka basalt and tilts Quaternary stream terraces. Historic earthquakes have been felt and reported in the vicinity of the central Sevier fault trace, which indicates the central Sevier fault may have been active in the Holocene. In addition, many of the rock formations are weak and are prone to landslides. The landslides may be either gravity or seismically induced and may pose a risk to the residents.
CHAPTER 2

STRUCTURAL CONCEPTUAL MODELS

Introduction

Long (10's-100's km) normal faults cannot rupture as a whole during a single earthquake because earthquakes can not produce enough slip to rupture lengths greater than a few 10's of kilometers. This relationship suggests that long faults may have formed by linkage of several shorter faults. Fault linkage forms geometric segments (bends) that may or may not correlate to rupture segments (discussed later). Models for fault linkage and structures formed within the linkage zones are described below.

Fault Linkage Models

Fault segment linkage is the mechanical interaction between two separate fault segments (e.g., Peacock and Sanderson, 1991; Trudgill and Cartwright, 1994; Cartwright et al., 1995; Crider and Pollard, 1998; Crider, 2001; Ferrill and Morris, 2001). Linkage affects the slip distribution on each of the faults because as the faults interact, slip is transferred from one fault to the other fault (Crider and Pollard, 1998). The bounding faults in linkage zones have approximately parallel strikes and display opposite displacement gradients (Ferrill and Morris, 2001).

Two mechanically different styles of linkage are called “soft” and “hard” linkage. Soft linkage occurs when the fault geometry changes only because of the stress field
interactions (Gupta and Scholz, 2000; Taylor et al., 2001). During soft linkage, strain is
transferred between faults through the rock. In contrast, during hard linkage the faults
physically connect (Gupta and Scholz, 2000; Taylor et al., 2001), and faults cut relay
ramps (strain transfer zones) or blocks between the faults resulting in a single fault with
multiple bends (Young et al., 2001). To elucidate fault linkage and the structures formed
within linkage zones, a definition and explanation of radial propagation, linkage, and the
stress fields at fault tips is given below.

Geometrically simple faults tend to grow by radial propagation. Radial
propagation typically occurs when an individual fault extends in length and width, where
the fault has zero slip at the fault tips and the maximum slip is located in the middle 1/3
of the fault (Fig. 2) (Cowie and Shipton, 1998). This type of growth is accompanied by
increasing displacement (or displacement gradient) and along strike propagation of fault
tips (Fig. 2) (Wu and Bruhn, 1994). With increased slip along the fault, stress builds up
at the fault tip. Eventually when the stress at the fault tips exceeds the strength of the
surrounding rock, the surrounding rock will fail and the fault will grow in length (Scholz,
1990; Cartwright et al., 1995). In this type of fault growth, the footwall is not deflected
(Cartwright et al., 1995). Faults that grow by radial propagation follow a single growth
path provided the materials have constant material properties when the fault propagates
(Cartwright et al., 1995).

Radially propagating faults may grow according to a relationship between the
fault length and the maximum displacement, which is perpendicular to the fault trace
(Cartwright et al., 1995; Cladouhos and Marrett, 1996; Cowie and Shipton, 1998). This
relationship requires the maximum displacement to be equal to critical shear strain
multiplied by the maximum length (Cartwright et al., 1995). This relationship is typically used for faults with single growth paths because complex fault geometries will cause scatter in the displacement and length data (Cartwright et al., 1995).

Isolated normal faults typically have a gently curved or "shovel shape" in map view (Fig. 2). This geometry is caused by a variety of complex mechanisms (cf., Mandl, 2000). When an individual fault propagates along strike or dip, the strike according to the Mohr-Coulomb theory will be parallel to \( \sigma_2 \) (intermediate principal stress) (Mandl, 2000). The shovel shape is caused by the curving of the \( \sigma_2 \) trajectories (Mandl, 2000). The curved \( \sigma_2 \) trajectories may have existed prior to faulting or may have been induced by the initial propagation of the fault and the interaction of local stress fields at the fault tips (Mandl, 2000).

In contrast, long faults with salients (bends) tend to grow by radial propagation followed by segment linkage (Fig. 2). The initial faults may be en echelon or non-en echelon. Fault growth by segment linkage consists of propagation, local stress field interaction, and linkage of segments with or without deflection of the footwall (Cartwright et al., 1995; Ferrill and Morris, 2001).

Active normal faults have local stress fields located near the fault tips that are different from the regional stress field. These local stress fields exist because of a mechanical interaction between the fault tip and the surrounding rock. The local stress field along a single dip-slip normal fault has the greatest shear strength near the fault tip. The normal shear stresses increase beyond the local stress field and decreases near the center of the fault. The fault is more likely to rupture in the increased shear stress field than the decreased shear stress field (Fig. 3A) (Cowie and Shipton, 1998).
Local stress fields interact when two or more faults propagate and the tips lie close to each other. When the zones of relatively high shear stresses near two fault tips touch, the local stress fields begin to curve toward each other and interact (Fig. 3B). Crider and Pollard (1998) suggest that the local stress field at the fault tip is located in the footwall of the faults when the increased shear stresses interact (Fig. 3B-D). With continued slip, these stress fields will curve towards each other causing the faults to curve. When the local stress fields interact soft linkage exists between the two faults. The shear stresses also will increase in the future strain transfer zone (relay ramp) (Crider and Pollard, 1998). With continued slip, the local stress fields and faults will ultimately curve and physically connect (link), called hard linkage. The hard linkage is not pictured in Fig. 3 because this type of linkage has not been numerically modeled.

Two major types of segment linkage occur where fault tips: (1) underlap or (2) overlap. The overlapping-fault linkage type, contains two subtypes: (1) fault capture and (2) breakthrough or cross faults. These types and subtypes are discussed below.

Underlapping faults or fault tips are two or more individual faults, either en echelon or non-en echelon in map view, with the tips spatially separated such that they do not lie across strike from each other (Fig. 2A). The greatest amount of slip is typically in the center 1/3 of the fault and by definition the fault tips have zero slip. Toward the tip, the size of the local stress field will decrease rapidly because faulted and unfaulted rocks are adjacent to each other (Cowie and Shipton, 1998). This difference develops the local stress field at the fault tips. With continued slip along the faults, soft linkage will occur (Fig. 2A). This geometry can be viewed in the field as two or more subparallel faults curved towards each other with underlapping fault tips. However, after physical hard
linkage occurs, only one fault with one or more salients will be apparent in natural settings (Fig. 2A).

Overlapping faults are two or more individual subparallel faults with the tip of one fault across strike from the other fault(s) (Fig. 2). In the basic type of overlapping fault linkage, faults with a similar amount of slip propagate past each other and interaction between the local stress fields near the fault tips requires the faults to curve toward each other (Crider and Pollard, 1998; Ferrill et al., 1999; Crider, 2001; Ferrill and Morris, 2001; Taylor et al., 2001). A relay ramp, which accommodates strain transfer between the faults, forms in the fault overlap zone (discussed in a following section) (e.g., Larsen, 1988; Morley et al., 1990; Peacock and Sanderson, 1994; Trudgill and Cartwright, 1994; Crider and Pollard, 1998; Ferrill et al., 1999; Moore and Schultz, 1999; Walsh et al., 1999; Peacock et al., 2000; Zampieri, 2000; Crider, 2001; Ferrill and Morris, 2001; Reber et al., 2001). As the two faults continue to slip, strain is transferred between the faults and the faults may ultimately link into one long fault (Fig. 2B).

Fault capture is a subtype of linkage in which fault tips overlap. As the faults propagate in the direction of strike, one fault has more or a greater rate of slip than the other fault (Ferrill et al., 1999; Reber et al., 2001; Taylor et al., 2001). More slip along a fault may be related to one fault having more frequent and/or larger earthquakes than the other faults. Ultimately, the stress field developed around the tip of the more active fault interacts with that of the other fault. Then, only the larger slip or faster moving fault curves toward the other fault and the faults link. With additional slip, the faults ultimately transfer strain with or without the formation of a relay ramp (Fig. 2D). In the field, faults linked by fault capture are recognized by one curved fault that connects with
another fault with a comparatively straight trace. These faults, when linked, form a single fault. The end of the captured fault that lies across strike from the capturing fault (fault with more or more rapid slip) commonly is isolated in the hanging wall (or possibly the footwall) and no further slip occurs along it. The captured end may also be buried by the hanging wall-basin sediments. If a relay ramp formed in the overlap zone, it too may be down dropped in the hanging wall or isolated in the footwall after linkage (discussed in a later section).

A second subtype of overlapping fault linkage is breakthrough along connecting faults. Breakthrough along connecting faults occurs when the tips of two or more individual faults propagate past each other, overlap and new faults with a different strike form in the overlap zone (Cartwright et al., 1996; Ferrill et al., 1999; Ferrill and Morris, 2001). Generally, the new breakthrough faults form parallel to each other and at approximately $30^\circ$ to the bounding faults. Strain is transferred from one fault strand to the other fault strand along this newly formed fault set (Fig. 2D). The breakthrough fault set forms because of an increased displacement gradient in the overlap zone, which causes extension to increase (Ferrill et al., 1999). This extension produces additional faults (called breakthrough or cross faults) that allow slip transfer between the overlapping faults, and occurs where fault throw is disproportional to the fault tip propagation (Ferrill et al., 1999; Ferrill et al., 2001). If breakthrough faults propagate from both faults, then fault bounded blocks are formed within an anastomosing fault zone (Ferrill et al., 1999). In the field, linkage via breakthrough faults (or cross faults) is identified by two nearby faults with similar strikes, and between the two faults are one or more faults that strike at a moderate to high angle ($-30^\circ$) to the bounding faults. Upon
linkage, these faults become one fault. The breakthrough faults are unlikely to cross the longer bounding faults, but relict fault tips within the overlap zone are likely to be seen (Ferrill et al., 1999).

Spacing or the distance between faults is important in determining whether fault linkage has occurred or will occur. If the faults are spaced too far apart, local stress fields will not interact. Hence, fault linkage will not occur. Fault spacing at the surface and at depth may differ because of the dips of the faults. For example, the steeper the fault dip, the closer in space they need to be in order to link at shallow depths. Faults with shallower dips can be spaced farther apart and still link at a shallow depth.

Displacement vs. Distance Diagrams

Displacement vs. distance diagrams are used to show the total amount of offset at various positions along strike of a fault. Here, displacement vs. distance diagrams are used to emphasize displacement variations within linkage zones (cf., Reber et al., 2001; Taylor et al., 2001). Focusing on the linkage zones is important, because displacement anomalies in these areas help diagram and indicate which type of linkage occurred. This use is different from other studies (e.g. Cowie and Scholz, 1992; Cartwright et al., 1995; Bohnenstiehl and Kleinrock, 2000) that use displacement vs. distance diagrams to model the entire fault.

In the vicinity of salients or geometric bends that are convex toward the hanging wall, on displacement vs. distance diagram can be used to evaluate whether linkage occurred and the type of linkage providing two assumptions are valid: (1) The total amount of slip on each individual fault before linkage was zero at the fault tip. (2) Since
the time of linkage, the slip rate was not markedly greater in the linkage zone than in the middle 1/3 of each original fault. Thus, in a linkage zone, the displacement should markedly decrease near the former fault tips. Variations in displacement vs. distance were modeled along idealized faults to show patterns associated with underlapping faults, overlapping faults, and fault capture types (Fig. 4) (Taylor et al., 2001). New models for breakthrough hard linkage and soft linkage were created for this study and are described below (Fig. 4). These models are used in this study to interpret fault linkage zones along the central Sevier fault.

Along linked underlapping faults, the slip magnitude decreases sharply in the center of the fault, which is where the slip or displacement would be expected to be the greatest on unlinked faults (Fig. 4A). This decrease occurs at the linkage zone. After the faults linked, additional slip may occur along the entire fault, along zones defined by the geometry or along distinct earthquake rupture segments (discussed in segment boundaries section).

On a displacement vs. distance diagram, a basic overlapping type linkage zone shows less displacement across a broad bench at the site of linkage (Fig. 4B). The bench forms because two faults propagated past each other, so the total amount of displacement, added across both faults along strike in the linkage zone, is similar or the same. The bench length is the same as the length of the overlap zone (Taylor et al., 2001). However, during the soft linkage of overlapping faults, instead of a bench developing in the zone of linkage, the displacement tapers to zero (Fig. 4E).

Fault capture subtype linkage zones produce a series of plateaus with decreasing slip on a displacement vs. distance diagram (Fig. 4C). This decreasing series of plateaus
occur because the fault with the greatest amount or rate of slip intercepts the fault with the lesser amount of slip at a site with significant displacement. However, displacement at that site may be less than the maximum displacement on the intercepting fault. The fault with the lesser amount of slip is cut off and becomes a relict fault.

The breakthrough subtype linkage zone produces a pattern similar to the overlapping fault linkage zone on a displacement vs. distance diagram but with small amplitude perturbations within the plateau (Fig. 4D). If the displacement data are sampled with a small spacing, then "steps" occur where the cross faults are located. No cross faults exist at the tips of the bounding faults hence the total displacement abruptly increases in slip outside the linkage zone, following the displacement gradient.

Where a relay ramp forms in the linkage zone, the faults that bound the relay ramp have tapering slip as they enter the overlap zone (Crider and Pollard, 1998). These geometries can be related to the displacement gradients at the fault tips (Peacock and Sanderson, 1991).

Relay Ramps

Linkage of overlapping faults typically exhibit an interaction phase during which a relay ramp forms. A relay ramp is an inclined panel of rocks between two overlapping faults with smoothly curving tiplines (Fig. 5) (Larsen, 1988; Peacock and Sanderson, 1991; Crider and Pollard, 1998). In the relay ramp, the strike of bedding changes from parallel to the bounding faults outside the ramp to nearly perpendicular to the bounding faults within the ramp (Fig. 5) (e.g., Trudgill and Cartwright, 1994; Faulds and Varga, 1998; Ferrill et al., 1999; Moore and Schultz, 1999; Peacock et al., 2000; Ferrill and

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Relay ramps can range in area from square meters to 10's of square kilometers.

Relay ramps and the structures formed within the ramps are important to aid in the understanding of (1) how segmented long normal faults link, (2) how faults grow, and (3) how strain is transferred from one fault strand to another fault strand. Relay ramps also are important because they allow fluid (hydrocarbons or water) migration from the footwall to the hanging wall, which may form a fluid trap (Morley et al., 1990; Crider and Pollard, 1998; Dawers and Underhill, 2000).

Relay ramps initiate and begin to form in soft linkage zones between two fault tips. Relay ramps typically form along overlapping faults; including the subtypes of breakthrough faults and fault capture (Fig. 5). The relay ramp models below will be used to describe and interpret linkage zone structures exposed along the central Sevier fault.

Relay ramps connect the hanging wall of one fault strand to the footwall of another fault strand, effectively transfer strain between the two strands, and ultimately link two normal faults (Larsen, 1988; Morley et al., 1990; Peacock and Sanderson, 1991; Peacock and Sanderson, 1994; Trudgill and Cartwright, 1994; Crider and Pollard, 1998; Faulds and Varga, 1998; Ferrill et al., 1999; Moore and Schultz, 1999; Walsh et al., 1999; Zampieri, 2000; Peacock et al., 2000; Ferrill and Morris, 2001; Reber et al., 2001). The model or ideal relay ramp transfers strain from the hanging wall of one fault to the footwall of the other fault by (1) tilting of the bedding within the ramp, (2) vertical axis rotation, and (3) cutoff-parallel elongation without additional deformation to the relay ramp or the surrounding rocks (Ferrill and Morris, 2001).
A relay ramp accommodates displacement gradients along the bounding faults. These bounding faults typically have opposite displacement gradients (Ferrill and Morris, 2001). Peacock and Sanderson (1991) suggest that a relationship exists between the geometry of the relay ramp and the displacement variations of the bounding faults; a more complex displacement gradient leads to a more geometrically complex relay ramp. In addition, greater displacement gradients on the bounding faults form larger (vertical vs. horizontal dimension) ramps (Peacock and Sanderson, 1991; Peacock et al., 2000).

As slip continues after the initial formation, relay ramps commonly expand or propagate parallel to strike of the bounding faults (Fig. 5). Hence, the relay ramp must continue to deform to keep the hanging wall and footwall connected (Ferrill and Morris, 2001).

Breached relay ramps are completely bound by two hard linked faults and may contain cross faults or fractures (Peacock and Sanderson, 1994; Ferrill and Morris, 2001). These ramps can be further subdivided into breached top and base ramps (Crider, 2001). Breached top and base ramps occur when a bounding fault cuts across the ramp (hard linkage site) at the structurally higher or lower parts of the ramp, respectively (Fig. 5) (Crider, 2001). Cross faults in breached relay ramps may form because of tip interaction prior to fault overlap (Ferrill and Morris, 2001). This may explain why the breakthrough fault orientation is at an oblique angle to the relay ramp (Ferrill and Morris, 2001).

Relay ramps may contain a variety of structures. By definition, a relay ramp contains a fold and is essentially a monocline and trends approximately normal to the bounding faults (Fig. 5) (Larsen, 1988; Peacock and Sanderson, 1991; Peacock and Sanderson, 1994; Faulds and Varga, 1998). In addition, other contractile structures may develop within the relay ramp, including anticlines and synclines depending on the
geometry of the bounding faults. These fold axes are approximately parallel to the bounding faults and form in addition to the already existing ramp monocline. Structures such as these have been rarely studied in the past.

Segment Boundaries

Fault segments and the boundaries between them can be subdivided into three types: (1) structural, (2) geometric, and (3) earthquake (dePolo et al., 1991). It is possible, therefore, to define segment boundaries based on surface observations of fault geometry, scarps, footwall structures, kinematic indicators, and/or earthquake epicenters (McCalpin, 1996; Stewart and Taylor, 1996). However, most segment boundaries are not a single point, but rather a broad complexly faulted zone (Janecke, 1993).

Geometric segments are recognized by changes in fault zone morphology, fault trace orientations (bends, step-overs or en echelon faults, separations), and a change in fault separation or a gap in a fault zone (Fig. 6A) (dePolo et al., 1991; Keller and Pinter, 1996). Geometric segment boundaries typically exhibit a dramatic change in strike that shape a salient. These changes in strike usually occur in zones of linkage. Geometric segments may be consistently and objectively identified on aerial photographs or by detailed geologic mapping.

Structural segment boundaries end at a structural discontinuity (Fig. 5B) (dePolo et al., 1991). Structural discontinuities can be older faults or folds that strike at a high angle to the segmented fault. A change in the geologic material (e.g., changing from coherent rock to fault gouge back to coherent rock) crossed by the fault may be a
characteristic of a structural segment boundary (Fig. 6B) (Janecke, 1993; Keller and Pinter, 1996).

Earthquake segments are portions of a fault zone that rupture as a unit during an earthquake (Fig. 6) (dePolo et al., 1991; McCalpin, 1996). McCalpin (1996) further defines earthquake segments as "discrete portions of faults that have demonstrably ruptured to the surface two or more times". However, in large earthquakes more than one segment may rupture. Earthquake segments are separated by earthquake rupture terminations that are a zone that typically contains several fault splays and high amounts of fractured, crushed, and faulted rocks (Janecke, 1993). An earthquake segment boundary or earthquake discontinuity, is therefore defined as "a portion of a fault where at least two rupture zones have ends" and can potentially arrest earthquake ruptures (Wheeler, 1989; dePolo and Slemmons, 1990). The most reliable method of documenting earthquake segments is paleoseismological evaluation and fault behavioral data from historic earthquakes (Zhang et al., 1991). Determining earthquake segments is the most important concept for evaluating earthquakes and their associated hazards. However, earthquake segment boundaries do not always stop all propagating ruptures (Crone and Haller, 1991). For example, a large (M 7+) earthquake can rupture more than one earthquake segment boundary. Hence, earthquake hazard evaluation needs to be done beyond a determined earthquake segment boundary.

A segment boundary can be any one type, or a combination of geometric, structural, and earthquake boundaries (Fig. 6). For example, a structural boundary where an older fault strikes at a high angle to the segmented fault can also serve as an earthquake rupture boundary. An example would be the 1914 Pleasant Valley, central
Nevada earthquake. This earthquake was terminated by a structural discontinuity, and thus, is also an earthquake segment boundary (Zhang et al., 1999). Another example is a dramatic change in strike, a geometric segment boundary, that may also serve as an earthquake rupture boundary. An example of this type is the Lost River and Lemhi faults in east central Idaho. These faults have geometric bends that are also earthquake segment boundaries (Janecke, 1993). Hence, segment boundaries may have the physical characteristics of one or more type of boundary.

Some studies in seismology and fracture mechanics indicate that fault geometry can be important in the generation of earthquakes and rupture patterns (Bruhn et al., 1987; Menges, 1990). Indeed, studies along the Hurricane fault document that some recent earthquake rupture breaks are limited to geometric segments (Stenner et al., 1999a, 1999b). In contrast, dePolo et al. (1991) suggest that geometric segments in map view may not have a significant effect on earthquake ruptures with a normal sense of displacement during large (7.0+) magnitude earthquakes. However, smaller (e.g., M 3.0) earthquakes typically only rupture a single segment and the segment boundary will arrest the propagating earthquake. The size of the segment boundary that arrests an earthquake appears to scale with the length of the ruptured fault and the amount of displacement during the rupture (Zhang et al., 1999).
CHAPTER 3

REGIONAL TECTONIC BACKGROUND

Fault linkage models are motivated by and tested using natural examples (for this study, the central Sevier fault in southwestern Utah). To understand fault linkage models and the development of fault segments, the regional tectonics must be understood. Also, the regional deformation represents the regional stress field within which the faults and local stress field at the fault tips formed.

Introduction

Throughout the history of the western United States plate interactions along the western plate margin have influenced tectonism. Through the Paleozoic and into the Tertiary, subduction dominated. From the Jurassic to at least the late Cretaceous, the slab dip was steep (60°) (Atwater, 1970; Sveringhaus and Atwater, 1990; Atwater and Stock, 1998). However, from late Cretaceous through the Cenozoic, the slab dip changed to flat or shallow (<30°). As a result, two orogenies occurred near the western edge of the Colorado Plateau between latest Jurassic and Eocene: the Sevier and Laramide orogenies. These orogenies occurred because of shallow slab subduction. Folds and thrust faults of these orogenies can occur throughout the Utah Transition Zone to the High Plateaus subprovince of the Colorado Plateau. At ~23 Ma, a transform boundary began to form along the western edge of North America (Sveringhaus and Atwater, 1990). This event
is recognized by the replacement of the time-transgressive sequence of arc magmatism by the San Andreas transform fault (Atwater, 1970; Sveringhaus and Atwater, 1990). The length of the transform boundary has increased to nearly 1,125 km (700 mi) since its inception (Sveringhaus and Atwater, 1990).

Evolution of the Transform Boundary

At ~23 Ma the San Andreas transform boundary was initiated when the East Pacific Rise made contact with the North America Plate (Atwater, 1970). This change from subduction along the plate margin to a transform boundary had a great effect on the tectonic evolution of western North America. Dickinson and Snyder (1979) suggested that the formation of a transform boundary created a slab-window beneath part of western North America. However, Sveringhaus and Atwater (1990) and Atwater and Stock (1998) suggest that this slab-window is more of a slab-gap, meaning a completely slabless area exists underneath North America. The slabless area is a sub-rectangular shape rather than a "triangle" under North America. The formation of the slab-free zone relates to several geologic events including regional uplift of the Colorado Plateau, central Basin and Range extension, formation of the San Andreas fault system, and the end of arc magmatism.

Today most of the central Basin and Range, Utah Transition Zone, and Colorado Plateau (Fig. 1) overlie this slab-free zone. Basin and Range style normal faults have cut into the western margin of the Colorado Plateau in southwestern Utah. These faults probably initiated in the Miocene.
Regional Tectonics of Southwestern Utah

During the Phanerozoic, southwestern Utah was a site of (1) deposition of a thick cratonal Mesozoic and Cenozoic sedimentary sequence; (2) the Sevier Orogeny, mainly during the Mesozoic; (3) the Laramide orogeny mainly during the early Tertiary, (4) Cenozoic volcanism and sedimentation; and (5) Cenozoic extension. The following section provides a simplified tectonic overview of southwestern Utah including the southeastern Basin and Range Province, Utah Transition Zone, High Plateaus subprovince of the Colorado Plateau, and the western edge of the Colorado Plateau.

Mesozoic Sevier Orogeny

During the Jurassic into the Eocene, the Sevier Orogeny formed a contractile belt, the frontal part of which extends from southeastern California, through Utah, and into northern Canada (Armstrong, 1968). The onset of the Sevier Orogeny was probably caused by the subduction of the Farallon plate with accelerated plate convergence (Armstrong and Ward, 1991). During the last decade, most workers have agreed that the majority of deformation associated with the Sevier orogeny in southwestern Utah is bracketed between late Albian time and late Campanian (DeCelles, 1995; Lawton et al., 1997). Sevier thrusting resulted in tectonic thickening, development of an extensive foreland basin east of the thrust front, and the development of broad folds and uplifts (Armstrong, 1968; Axen et al., 1990; Burchfiel et al., 1992; Wannamaker et al., 2001). The foreland basin lies within the vicinity of and extends to the east of the present location of the Sevier fault. Surface breaking thrusts are thought to have only extended as far east as Cedar City (Fig. 1) (Hintze, 1988; Axen et al., 1990).
Laramide Orogeny

Shortly after the Sevier orogeny, the Laramide orogeny occurred between 75 and 35 Ma (Dickinson et al., 1988; Bird, 1998). During the early portion of the Laramide orogeny (75-65 Ma), the Kula Plate subducted under North America (Bird, 1998). After 65 Ma, the Farallon Plate began to subduct (Bird, 1998). At ~50 Ma, the subducted Kula/Farallon Plate transform boundary passed under the present western edge of the Colorado Plateau (Bird, 1998). Because of the plate configurations, this orogeny had driving mechanisms different from the Sevier orogeny. The Laramide orogeny was driven by basal traction of flat slab subduction, not by motions at the plate margin (Bird, 1998). Evidence of this orogeny (gentle folds) is visible to the east and south of the Paunsaugunt fault (Fig. 1) (Davis, 1999; Wannamaker et al., 2001). The Laramide orogeny formed gentle folds such as the monoclines in the eastern High Plateaus east of the study area (i.e., the Kaiparowits and Waterpocket folds). These folds are thought to overlie high-angle Precambrian normal faults, which were reactivated as reverse faults (Davis, 1978; Dumitru et al., 1994).

Cenozoic Volcanism

Volcanism in southern Utah began at ~30 Ma (Rowley, 1975; Best et al., 1980) and continued into the Holocene. Most of the basalt flows in southwestern Utah range from 10.8 to 0.3 Ma in age (Best et al., 1980). The basalt flows are generally younger to the east (Best et al., 1980; Nelson and Tingey, 1997). Basalt flows along the Sevier fault are ~0.5 Ma (Best et al., 1980; this study).
Along the latitude of the southern boundary of Utah (37°N), the effects of subduction of the Farallon Plate ended at ~10 Ma indicating that the post 10 Ma volcanic rocks in southwestern Utah are not related to active plate subduction (Best et al., 1980; Severinghaus and Atwater, 1990; Atwater and Stock, 1998). However, the volcanism in southern Utah may be related to Basin and Range style extension (Best et al., 1980; Nelson and Tingey, 1997). Cenozoic volcanic units crop out (1) near the Hurricane fault, (2) near Navajo Lake, (3) in the Marysvale volcanic field, and (4) along and near the central Sevier fault (Figs. 6 and 7) (Rowley, 1975; Best et al., 1980; Smith et al., 1999).

Late Cenozoic Extension in Southern Utah

Near St. George, the Hurricane fault defines the structural boundary between the Transition Zone and the High Plateaus. The Hurricane fault is an active, segmented long normal fault zone (Stewart and Taylor, 1996; Stewart et al., 1997; Taylor et al., 2001). Movement along the Hurricane fault probably initiated during the Miocene or Pliocene and continues today (Stenner et al., 1999; Davis, 1999; Taylor et al., 2001). Several earthquakes and Holocene fault scarps have been located along the Hurricane fault (Arabasz and Julander, 1986; Christenson and Nava, 1992; Stewart et al., 1997; Lund et al., 2002). A M 5.8 earthquake is thought to have occurred along the Hurricane fault in 1992 (Christenson and Nava, 1992).

The Sevier-Toroweap fault, a segmented long normal fault, lies ~65 km (~40 mi) to the east of the Hurricane fault. I will use the name Sevier fault when referring to the Utah portion, Toroweap fault when referring to the Arizona portion, and Sevier-Toroweap fault when referring to the entire fault. The Sevier-Toroweap fault can be

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
traced ~195 km (~120 mi) from the Grand Canyon in Arizona north into the Miocene Marysvale volcanic field in Utah (Davis, 1999). The Sevier fault probably initiated during the Miocene and may be active today (Smith and Arabasz, 1991; Hecker, 1993; Davis, 1999). The central Sevier fault has not been observed cutting Holocene sediments. However, Jackson (1990) and Hecker (1993) suggest that evidence for recent activity may be lacking or obscured because of active colluvial slopes and thick vegetation. The Sevier fault cuts Quaternary basalt and sediments suggesting at least Quaternary activity (Christenson and Nava, 1992; this study). A few earthquakes have been recorded in the vicinity (<5 km) of the Sevier fault (Arabasz and Julander, 1986) suggesting that this fault may have been active in the Holocene.

The Paunsaugunt fault is the easternmost long normal fault in the High Plateaus. The fault trace extends ~65 km (~40 mi) (Davis, 1999). The Paunsaugunt fault is thought to be the oldest of the three faults because the hanging wall is topographically higher than the footwall. This topographic reversal may be caused by a more resistant lithologic unit capping the hanging wall than the footwall, thus allowing the footwall to erode faster than the hanging wall. Such topographic reversal takes a significant time to form, supporting the suggestion that the Paunsaugunt fault has not ruptured recently (Schiefelbein and Taylor, 2000). The balanced rocks (hoodoos) of the Tertiary Claron Formation in Bryce Canyon National Park (Fig. 1) also may suggest a lack of large recent seismic events (Bruhn and Wu, 1993; Brune, 1996, Davis, 1999).
Definitions of Provinces in Southern Utah

In southern Utah, the Transition Zone is generally further defined by three different criteria: (1) structural geology, (2) physiography, and (3) geophysics. The structural definition is based on the structural geology of the area. The physiographic definition includes geographically defined boundaries. The geophysical definition is based on crustal thicknesses of the region.

Basin and Range Province

The Basin and Range province is characterized by a thin crust, high heat flow, magmatism, and north-south trending valleys and mountain ranges (Parsons, 1995; Wannamaker et al., 2001). These valleys and ranges are bounded by north-south striking long normal faults. The region is seismically active. Prior to Cenozoic extension, rocks in the Basin and Range province underwent several episodes of deformation (contraction and extension).

The region also had significant volcanism since its first initiation ~35 Ma (initiation time varies with latitude) and is seismically active. At the latitude of the Utah/Arizona border (37°N), the eastern boundary is defined as the Hurricane fault (Stewart et al., 1997).

Colorado Plateau

In southern Utah, the Colorado Plateau is defined as a physiographic and tectonic province that lies to the east of the Paunsaugunt fault. The Colorado Plateau is topographically high and contains generally gently dipping strata, broad regional folds, and lacks major thrust and normal faults. This province is underlain by as much as 50 km (31 mi) of crust and is considered relatively tectonically stable (e.g., Beghoul and
Barazangi, 1989; Nelson and Harris, 2001; Wannamaker et al., 2001). It has undergone little deformation since the Proterozoic (Wannamaker et al., 2001). However, contraction, volcanism, and extension have been repeated through geologic time along the flanks.

Utah Transition Zone

The Utah Transition Zone lies between the Basin and Range province and the Colorado Plateau. The Transition Zone changes in width from north to south. This transitional region is suggested to be an uplifted rift shoulder in the north along the Wasatch Front near Salt Lake City, Utah and its southern extension (Wannamaker et al., 2001). In southwestern Utah, the transition occurs across an ~62 mi (~100 km) wide zone (Wannamaker et al., 2001).

The initiation and boundaries of the Transition Zone are still not completely understood. The Transition Zone has characteristics of both the Basin and Range province and the Colorado Plateau. It contains a gradual change in geologic characteristics from Basin and Range style deformation to the less deformed tectonic style of the Colorado Plateau. It is thought that the Transition Zone is not related to Pacific and North American plate boundary interactions because the plate boundary stresses could not propagate this far into the continental interior (Wannamaker et al., 2001). Wannamaker et al. (2001) suggest that the Transition Zone has been an evolving structure since 25-30 Ma. This timing is based on the onset of extensional events, which create the present day Transition Zone (Wannamaker et al., 2001).

The physiographic and structural distinctions place the western boundary of the Transition Zone at the mouth of the Virgin River Gorge in Arizona and the eastern
boundary at the Hurricane fault. Structurally, the Transition Zone has Basin and Range-
type normal faults. Geophysically, the transition zone is defined by crustal thickness and
generally lies between the Hurricane and Paunsaugunt faults. The Transition Zone crust
is generally between 19-22 mi (30-35 km) thick (Wannamaker et al., 2001).

High Plateaus Subprovince of the Colorado Plateau

The High Plateaus subprovince of the Colorado Plateau is located between the
Transition Zone and the Colorado Plateau. This subprovince generally lies between the
Hurricane and the Paunsaugunt faults (Fig. 1) and incorporates the Grand Staircase. The
High Plateaus are divided by generally north-south oriented normal faults: the Hurricane,
Sevier-Toroweap, and Paunsaugunt faults, from west to east (Fig. 1). This region has
characteristics of the Colorado Plateau as well as the Transition Zone. The crustal
thickness in the High Plateaus is generally 22-25 mi (35-40 km), which is between the
thickness of the Transition Zone and the Colorado Plateau (Wannamaker et al., 2001).
The high-angle normal faults resemble those in the Transition Zone. Hence, the High
Plateaus are variously grouped with either the Transition Zone or the Colorado Plateau.
CHAPTER 4

STRATIGRAPHY

Stratigraphic units with many well-defined thin members are exposed in the High Plateaus subprovince and along the Sevier fault (Gregory, 1951; Hintze, 1973; Sargent and Philpott, 1987; Hintze, 1988; Stokes, 1988; Doelling, 1989). These thin members are ideal for documenting small stratigraphic separations and allow relatively small uncertainties in the calculations of stratigraphic separation along the Sevier fault and related strands and splays.

The stratigraphy exposed along the central Sevier fault consists of a thick succession of late Triassic to Cretaceous carbonate and siliciclastic rocks, which are unconformably overlain by Cenozoic volcanic and sedimentary units (Fig. 8). No metamorphic or intrusive units crop out in the study area. A detailed description of the lithologic units is presented on Plate 3. Units and thicknesses that are Triassic and older on the cross sections, but not exposed in the map area are from Hintze (1988) and Doelling et al. (1989) (Fig. 8). The units are dominantly limestone, dolostone, and sandstone (Fig. 8).

Mesozoic Stratigraphy

The exposed Mesozoic section is approximately 2,300 m (7,546 ft) thick, gently folded, and generally dips to the northwest and northeast (Fig. 9) (Gregory, 1951; Hintze,
1973, 1988; Sargent and Philpott, 1987; Stokes, 1988; Doelling et al., 1989; Nelson and Tinge, 1997). The Late Triassic through Cretaceous units in the study area dominantly consist of sandstone and shale with a minor amount of limestone of the Jurassic Carmel Formation (Fig. 9). Three unconformities exist in the Mesozoic section: the J-1, J-2, and K-1 (Hintze, 1973; Hintze, 1988; Marzolf, 1988; Stokes, 1988; Doelling et al., 1989) (Fig. 9).

Cenozoic Stratigraphy

Tertiary and Quaternary volcanic and sedimentary units unconformably overlie the Mesozoic succession (Fig. 9). The Cenozoic section is approximately 400 m (1,312 ft) thick (Fig. 9) (Gregory, 1951; Hintze, 1973, 1988; Sargent and Philpott, 1987; Stokes, 1988; Doelling et al., 1989; Nelson and Tinge, 1997). The Tertiary succession consists of a fresh water unit with mostly fluvial and lacustrine conglomerate and sandstone (Rowley et al., 1975; Stokes, 1988; Doelling et al., 1989; Taylor, 1993: Goldstrand, 1994). The Tertiary rocks generally dip to the northeast.

Late Cenozoic basalt is common in the region (Nelson and Tingy, 1997; Smith et al., 1999, Downing et al., 2001) and a flow crops out in the mapped area. This basalt is olivine rich with olivine phenocrysts up to 3 mm (0.11 in) in diameter. The ground mass is fine, crystalline and dark gray. Basalt flows near Spencer Bench have been dated by K-Ar techniques at 0.56 Ma +/- 0.07 Ma (Fig. 10 and Plate 1) (Best et al., 1980). Best et al. (1980) interpreted this flow to be a hawaiite. Using \(^{40}Ar^{39}Ar\) dating techniques (Appendices A and B), two samples (BRC-1 and BRM-2) from the northern portion of Spencer Bench and Black Mountain were dated (Figs. 10 and 11). One sample was
collected from the hanging wall at Black Rock Canyon, and the other sample was collected from the footwall of the Sevier fault at Black Mountain (Fig. 11 and Plate 1). The sample from Black Rock Canyon yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ isochron age of 0.564 +/- 0.02 Ma (Fig. 11). The sample from Black Mountain yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ isochron age of 0.58 +/- 0.05 Ma (Figs. 10 and 11). These ages are similar to the ages determined by Best et al. (1980) for volcanic rocks in Black Rock Canyon (Fig. 10).

Late Cenozoic sedimentary units include spring deposits, stream terraces, slope failures, colluvium, sinter-type spring deposits, and alluvium. The older part of the Quaternary succession contains (now consolidated) fluvial terrace deposits that are overlain by basalt. The most recent deposits are unconsolidated fluvial alluvial and surficial debris (Hintze, 1973; Hintze, 1988; Doelling et al., 1989). These late Cenozoic units unconformably overlie units ranging from Jurassic through the early Tertiary.
CHAPTER 5

STRUCTURE DESCRIPTIONS

Introduction

The Sevier fault brittlely deforms the nearly flat-lying to gently folded strata of the High Plateaus. Fault splays, strands, and separate normal faults were identified by fault breccia, gouge, and offset units. The sense of separation on each fault was determined by ages (inferred by lithology and fossils ages) of juxtaposed strata. The fault with greatest stratigraphic separation is referred to as the main strand. Because of the lack of kinematic indicators, the exact net-slip direction was not determined for the faults. New data from this study show that four relay ramps and a geometric bend, or salient, occur along the central Sevier fault. This section describes the newly collected data and the geometries of structures exposed in the study area are described below.

Sevier Fault

The Sevier/Toroweap fault generally strikes ~N30°E and dips 70–85°W along a trace length of ~350 km (220 mi) between the northern tip line (northern most point) in Miocene volcanic rocks near Richfield and the southern tip south of the Grand Canyon in Paleozoic rocks (Fig. 7) (Gregory, 1951; Doelling et al., 1989; Davis, 1999). The Sevier fault from the Arizona/Utah border to the northern termination is 260 km (158 mi) in length.
For the purpose of this study, the central Sevier fault will be subdivided into three, separate domains: the southern domain, central domain, and Spencer Bench domain (Fig 12A). Each of these domains contains different fault strands and splays. The strike of these strands varies between north-south and east-west, a 90° variation about the general ~N30°E strike. The "main strand" of the Sevier fault is defined here as the fault with the greatest stratigraphic separation. The fault that is the main strand changes along strike. The strikes vary from N5°E to N80°E.

Southern Domain - Orderville Relay Ramp

The southern domain extends from the southern boundary of the map area to ~1 km (~0.6 mi) north of the community of Orderville (37°15'50"N to 37°16'54"N) (Fig. 12A). This domain contains the Orderville relay ramp on which Davis (1999) made preliminary structural and stratigraphic observations. The rocks exposed in this domain range from late Triassic to Quaternary in age (Plate 2). Rocks as young as Cretaceous in age are faulted, but no Quaternary units are offset in this domain.

Two strands of the Sevier fault bound the Orderville relay ramp: A on the west and B on the east (Figs. 12A and 12B). Fault A, the main strand of the Sevier fault has a curved fault trace, but generally strikes N10°E and dips 76°W. The fault strike changes from approximately north to south in the south to northeast in the north (Figs. 12A and 12B). Fault A juxtaposes the Cretaceous Tropic Shale against Jurassic Navajo Sandstone for ~760 m (~2,500 ft) of stratigraphic separation. Fault B generally strikes N40°E and dips 79°W (Plate 4). From south to north, the strike of fault B curves from northeast to north, back to northeast and finally to north-south. This fault juxtaposes the Jurassic
Navajo Sandstone and the Jurassic Co-op Creek Member of the Carmel Formation for ~140 m (~450 ft) of stratigraphic separation (Plate 4).

Between faults A and B within the Orderville relay ramp (Fig. 13), map patterns, cross sections, and stereo plots show that the stratigraphic units form a plunging syncline oriented 17°, N7°W (Fig. 14A and Plate 4). The fold within the Orderville relay ramp is a gentle, subhorizontal, upright fold (cf., Ramsey, 1967). However, to the west of fault A and to the east of fault B, the strata are generally flat lying to gently west dipping.

Faults A and B connect at the surface at the southern end of the relay ramp (Figs. 12A and 12B and Plate 2). Cross section construction and retrodeformation indicate the interpretation that these faults also connect in the subsurface (Fig. 13 and Plate 4).

In the subsurface, the faults in this region are interpreted to have different geometries. Fault A has a relatively simple and planar geometry (Plate 4). Fault B is planar at the surface and becomes curved by a depth of ~1,220 m (~4,000 ft). This fault is required to be curved in order to restore cross sections (Fig. 13 and Plate 4).

The depth to the base of the relay ramp is interpreted to increase from south to north. Retrodeformation cross sections suggest that these faults connect in the southern portion of this region at a depth of 670 m (2,200 ft). However, in the northern portion of the relay ramp, the ramp probably initiates at a depth of ~2,135 m (7,000 ft) (Fig. 13 and Plate 4).

Central Domain - Stewart Canyon Overlap Zone

The central domain extends from ~10 km (6 mi) northeast of the community of Orderville to ~2 km (~1.2 mi) south of the community of Glendale (37°16'54"N to
37°19'29"N) (Figs. 12A and 12B). The southern part of this domain is here named the Stewart Canyon overlap zone (Figs. 12A and 12B). The Stewart Canyon overlap zone exposes rocks that range in age from Jurassic to Quaternary (Plate 1). The total stratigraphic separation in this domain ranges from 770 to 1,045 m (2,525 to 3,425 ft). Rocks as young as Cretaceous are faulted. However, no Quaternary offset is documented in this section.

The main strand of the Sevier fault within the Stewart Canyon overlap zone (Figs. 12A and 12B), has strikes that vary from N35°E to N65°E, and dips from 76-84°W. In this region a portion of the main strand of the Sevier fault is buried by Quaternary alluvium (Figs. 12A and 12B and Plate 1). Retrodeformable cross section construction geometrically requires the main strand of the fault to be under the alluvium, near the modern East Fork of the Virgin River (cross sections F-F' and E-E' on Plate 4) (Fig. 15). To the south, near cross section F-F', the main strand of the Sevier fault has 435 m (1,425 ft) of offset and places the Jurassic Windsor Member of the Carmel Formation next to Jurassic Navajo Sandstone (Fig. 16 and Plate 4). However, to the north near cross section E-E' the main strand of the Sevier fault has 390 m (1,275 ft) of stratigraphic separation (Fig. 16 and Plate 4), where it places Jurassic Navajo Sandstone against the Jurassic Windsor.

The Stewart Canyon overlap zone contains eleven fault strands with three different fault set orientations; striking northwest, northeast, northeast-east and dips of 69°-84° to the north and west (Figs. 12A and 12B). Two of these faults (faults D) strike ~N55°E but bend northward to strike nearly east-west (Figs. 12A and 12B). These strands are interpreted to connect at depth (cross section F-F' on Plate 4). At the surface,
the entire group of faults cuts the Jurassic Navajo Sandstone through the Cretaceous Dakota Sandstone in exposures. At cross section F - F', the Sevier fault zone has 770 m (2,525 ft) of stratigraphic separation (Fig. 16 and Plate 4). In cross section F-F' the westerly splay is interpreted to connect to the main strand at a depth of 1,280 m (4,200 ft) (Fig. 16 and Plate 4). The center fault (fault C) is interpreted to connect at depth with the western strand (fault B) at a depth of 960 m (3,150 ft) (Figs. 12A, 12B, and 16 and cross section F-F' on Plate 4).

Three relay ramps occur within the Stewart Canyon overlap zone: the Glendale, Stewart Canyon, and Elkheart Cliffs relay ramps (Figs. 12A, 12B, and 16). The ramps have steeply dipping bounding faults that either connect or appear to connect at depth. The differences among these three relay ramps are described below.

The Glendale relay ramp (Figs. 12A, 12B, and 16) is bounded by two faults that and interpreted to connect at a depth of 2,135 m (7,000 ft) to the north and a depth of ~2,745 m (9,000 ft) to the south (Figs. 12A, 12B, and 16 and Plate 4). The bounding faults are steeply dipping and planar. These bounding faults connect at the surface at the structurally lowest point of the ramp suggesting the ramp is base breached. A cross fault cuts the relay ramp and is bounded by the ramp bounding faults (Fig. 16 and Plate 4). This straight and planar cross fault is interpreted to connect with the easterly bounding fault at the surface as well as at depth. The connection is interpreted to occur at a depth of 930 m (3,050 ft) along cross section L-L' (Fig. 16 and Plate 4).

Within the Glendale relay ramp, map patterns and cross sections show a north plunging anticline oriented 3°, N59°E (Figs. 14B and 16 and Plate 4). This fold is classified as a gentle, subhorizontal, upright fold. However, to the east and west of the
Stewart Canyon overlap zone, the stratigraphic units are gently west dipping (3-7°) suggesting that the anticline is restricted to the ramp. Ramp-restricted folds, such as this one, have rarely been described because detailed studies of multipartite linkage zones with relay ramps has not be done.

The Stewart Canyon relay ramp is a breached ramp with both a base and a top breach. A top breach means that the bounding faults of the relay ramp connect at the structurally high part of the relay ramp. The two bounding faults appear to connect at the surface on both the north and south (Figs. 12A and 12B). However, the western bounding fault is buried by Quaternary alluvium. The faults are interpreted to be planar and appear to connect at depth (Fig. 16 and Plate 4). Two cross faults also cut the ramp (Figs. 12A and 12B). These faults terminate at the bounding faults. No fold in addition to the ramp monocline was observed within this relay ramp, but the entire relay ramp is not exposed.

The easternmost portion of the Stewart Canyon overlap zone contains three faults (Figs. 12A and 12B). The two eastern and subparallel faults have attitudes of approximately N40°E, ~85°NW (faults U' and T' on Figs. 12A and 12B). These faults juxtapose Jurassic Navajo Sandstone and the Jurassic Co-op Creek Member of the Carmel Formation at the surface for a total of ~100 m (~330 ft) of stratigraphic separation (Plate 2). The easternmost faults connect in map view and are interpreted to connect in cross section Y-Y' at a depth of 762 m (2,500 ft) (Fig. 16 and Plate 4). The third fault is orientated at a high angle to the main strand of the Sevier fault; it strikes ~N30°W and dips ~75°NE. This fault places the Jurassic Crystal Creek Member of the Carmel Formation next to the Jurassic Winsor Member with 183 m (600 ft) of stratigraphic
separation (cross section E-E' on Plate 4). This fault is interpreted to connect with the Sevier main strand at a depth of 335 m (1,100 ft) on cross section E-E' (Fig. 16 and Plate 4). The total amount of stratigraphic separation across the Sevier fault zone near cross section E to E' is 1,044 m (3,425 ft) (Plate 4).

Faults U' and T' overlap in map view with the western fault (V') of the Glendale relay ramp (Figs. 12A and 12B). Between these faults is a relay ramp here named the Elkheart Cliffs relay ramp. The bounding faults do not link in map view, however, they may link at depth (Figs. 12A, 12B, and 16). No fold besides the ramp monocline was observed within this ramp.

Map patterns indicate that the faults in the central domain connect at the surface (Plate 2 and Figs. 12A and 12B). Cross section construction and restoration suggests that faults within the Stewart Canyon overlap zone are interpreted to connect in the subsurface (Fig. 16 and Plate 4). However, the eastern two faults do not connect in map view with the western faults. Cross section analysis reveals that these faults are interpreted to appear to connect at depth (Fig. 16 and Plate 4).

Spencer Bench Domain

The Spencer Bench domain is located between the community of Glendale and the northern boundary of the mapped area (37°19'36"N to 37°23'29"N) (Fig. 12A). This domain exposes rocks that range in age from Cretaceous to Quaternary (Plate 1). An offset Quaternary (~570 ka) basalt flow is exposed on and near Black Mountain (Plate 1 and Fig. 12A). However, no Quaternary sediments or sedimentary rocks are offset (Plate 1).
In contrast to the other domains, in the Spencer Bench domain the Sevier fault is generally a single strand fault with hanging wall faults, not a complex splay zone. The main strand of the Sevier fault, labeled fault E on Figure 12A, strikes N40°E and dips 76-81°W. The total amount of stratigraphic offset across the four cross sections varies between 472 and 869 m (1,550 and 2,850 ft) within the Spencer Bench domain (cross sections A-A' through D-D' on Plate 4). The greatest amount of total stratigraphic separation across the Sevier fault zone is within the splay zone near cross section C-C' (Fig. 12A and Plate 4). Here the central Sevier fault zone has 518 to 640 m (1,700 to 2,100 ft) of stratigraphic separation. The stratigraphic separation decreases to the north and south from C-C'.

Eight faults, fault group C, are exposed to the northeast of Glendale (Fig. 12A). The faults within group C can be divided into a north-northwest striking fault set and a north-northeast fault set with one cross fault. The dips are generally 58-81°W. The total amount of stratigraphic offset across these faults is 543 m (1,780 ft) near cross section D-D' (Plate 4). The western splay connects with the main strand of the Sevier fault at the surface (cross section D-D' on Plate 4). However, the westernmost fault in the group, called fault C', dips east. Fault C' strikes N12°W and dips 73°E. It is interpreted to connect at depth with a west-dipping fault (cross section D-D' on Plate 4). All the faults are generally planar. Cross cutting fault relationships can be seen on the fault trace map (Fig. 12A). Fault E, the main strand, is cut by fault R' (Fig. 12A).

Fault set D lies just to the west of a bend in the main strand of the Sevier fault and comprises five hanging wall faults: three west-dipping, one east to southeast dipping, and one non-planar fault (inferred to restore cross sections) with northwest and north-dipping
sections (D') (Fig. 12A). The east-dipping fault and north-dipping fault section are buried by Quaternary alluvium (Fig. 12A and Plate 1), but are geometrically required to explain outcrop patterns. The west-dipping faults generally strike N25°E and dip between 79° and 85°W. The total stratigraphic separation along these faults is 175 m (575 ft) (cross section C-C' on Plate 4). The three western faults are interpreted to connect at depth (cross section C-C' on Plate 4). The western faults also appear to connect with fault D' at the surface (Fig. 12A and cross section C-C' on Plate 4). In map view, the generally north-south striking faults appear to terminate at the generally east-west striking fault (Fig. 12A). Thus, this east-west striking fault may be a transfer fault. The fourth fault from the west, O', is an east-dipping fault that is buried, but has an inferred attitude of N25°W, 80°E. It has a stratigraphic separation of 130 m (425 ft). This fault is interpreted to connect at a depth with the west-dipping strand to the east (cross section C-C' on Plate 4). Set D faults offset units as young as the Cretaceous Kaiparowits/Wahweap at the surface (cross section C-C' on Plate 4). The total stratigraphic separation for fault group D is 503 m (1,650 ft).

The main strand of the Sevier fault is the easternmost fault near fault set D, fault E (Fig. 12A and cross section C-C' on Plate 4). Between cross section D-D' and C-C', the Sevier fault forms a large bend with strikes, which vary from south to north: N70°E, N20°E, and N5°E. The stratigraphic separation is 549 m (1,800 ft). The main strand of the Sevier fault is interpreted to connect at depth with both the west-dipping and east-dipping faults of fault set D at (cross section C-C' on Plate 4). The total stratigraphic separation of fault set D and the main strand is 869 m (2,850 ft). North of fault set D, the Sevier fault strikes ~N35°E and dips 76°W and continues this pattern north to fault set F.
In this domain, the Sevier fault cuts Quaternary (~570 ka) basalt. Four fault strands, including the main strand, cut the Black Mountain basalt flow (Plate 1 and Fig. 12A). Three of these faults, called fault set F, strike N44°E. One dips 82°SE and the other two dip ~80° NW. The fourth fault is a cross fault with an attitude of N82°E, 80°N and ~1 meter (~3 feet) of stratigraphic separation. The total amount of post basalt stratigraphic offset across set F faults is ~3 m (~10 feet).

Folding within the Study Area

Along the central Sevier fault, the pre-Claron Formation units have a general north-northwest dip (1-19°) except in fault blocks or close to faults. Cross section construction and restoration requires that both the hanging wall and footwall to have undergone some normal fault drag. The cross sections (A-A', B-B', and C-C') show an anticline in the hanging wall of the main strand of the Sevier fault. In addition to this anticline, several regional folds exist near the study area (Fig. 7). In map view, the Claron Formation generally dips between 3 and 8° NE. However, this unit also has undergone some fault drag (cross section A-A'). The Quaternary conglomerate units all have dips of <10°E to NE.

The other folds are located within relay ramps, which are interpreted to be fault controlled. The following interpretations are based on combining the structure contour and map data from Doelling et al. (1989) and Davis (1999) and field data collected for this study.
CHAPTER 6

VIRGIN RIVER DEPOSITS

Introduction

The objective of this section is to provide data and interpretations of the fluvial deposits and how they relate to the central Sevier fault. These fluvial deposits provide information to help (1) understand the evolution of the East Fork of the Virgin River, and most importantly, (2) place age controls on faulting or tectonic deformation in the area. From here on, I will refer to the East Fork of the Virgin River as the Virgin River.

Three Quaternary fluvial deposits of different ages crop out along the central Sevier fault (Plates 1 and 2). The relative ages were based on the stratigraphic position of the deposits in the landscape. Assuming the stream has downcut through time, older deposits are exposed at higher elevations 1,939 - 1,963 m (6,360 - 6,440 ft). The oldest deposits are conglomerates that crop out 8 km (5 mi) north of Glendale (Qcgl). This conglomerate is older than the ~570 ka basalt, which unconformably overlies the conglomerate. The intermediate-aged Quaternary fluvial unit (Qcg) is conglomerate that crops out only south of the Hidden Lake spring system (Plates 1 and 2). This unit is located topographically lower, 1,707 - 1,865 m (5,600 - 6,120 ft), than the Qcgl, but higher than the modern alluvium and stream channel (Fig. 15). The Qcg is also unconformably overlain by a basalt flow southwest of Glendale (Fig. 15 and Plates 1 and 2). The modern channel is subparallel to the Sevier fault and lies along the fault trace.
south of Glendale and ~0.5 km (~1,500 ft) west of the fault, north of Glendale. The Quaternary alluvium and modern channel are younger than the basalt because of the lack of basalt flows on top of any of the deposits. The deposits contain basalt clasts and grains.

Modern Fluvial Deposits

The mapped modern Virgin River channel deposits have clasts smaller than four centimeters in diameter and are dominantly sand and gravel with few sandbars. The channel deposits become finer grained to the south. However, some large (>1 meter) clasts occur locally in the south. These clasts are probably evidence of flooding. The Sevier fault zone does not visibly offset the modern fluvial deposits.

The flood plain of the Virgin River is ~610 m (~2,000 ft) across in the south near 37°15'50"N to 37°20'30"N and <152 m (<500 ft) in the north near 37°20'30"N to 37°23'36"N (Fig. 15). This difference in flood plain width may be caused by the change in the gradient of the stream, a change in bedrock lithology, or an increase in discharge from the north to the south. The gradient of the Virgin River is steeper in the north than in the south (Fig. 15). North of Dry Wash, the gradient of the Virgin River is 0.026, and to the south of Dry Wash the gradient is 0.011. The bedrock lithology changes from the more resistant Cretaceous Kaiparowits/Wahweap Sandstone to the north to the less resistant mudstones and shales of the Tropic Shale, Dakota Sandstone, and Carmel Formation to the south. The amount of discharge is greater in the south than the north particularly because the Dry Wash channel contributes to the Virgin River north of Glendale (approximately 37°20'30"N) (Fig. 15 and Plates 1 and 2). Therefore, changes in
gradient, bedrock, and discharge may all impact the width of the Virgin River flood plain. Knowing and being able to predict the width of the flood plain is important because several people live along the Virgin River.

**Young Fluvial Conglomerate**

The young fluvial conglomerate (Qcg) has a lithologic make-up, which differs from the modern stream deposits (Fig. 17A). The conglomerate clasts comprise limestone, dolostone, chert, sandstone, basalt, and petrified wood. Generally, the clasts are well rounded and range from one centimeter to greater than a meter in diameter and graded bedding is present locally. However, the petrified wood is generally angular to subangular. The petrified wood is dark brown to black and appears to be agatized. The matrix consists of an indurated lithic sand. Discontinuous layers of lithic sandstone also occur throughout the conglomerate unit (Fig. 18A). The discontinuous layers of sandstone contain cross beds of the type (simple trough cross-stratification) seen in sandbars or migrating ripples (Prothero and Schwab, 1996). The cross beds, graded bedding, and channels (Fig. 18B) suggest that the Quaternary conglomerate has a fluvial origin.

From north to south, the gently dipping surfaces of the outcrops become topographically lower. These surfaces could have formed by (1) erosion, (2) as part of a floodplain, or (3) as stream terraces. (1) These surfaces may or may not have formed by erosion. If the surfaces were formed by erosion, the surrounding bedrock would have the same erosional characteristics. The bedrock contains no evidence of this type of erosion. (2) The surfaces did not form during flooding because floodplains typically are composed
of fine-grained sediments such as muds and silts. The deposits under these surfaces are sand to boulder sized. (3) Stream terraces form when the base level of an active stream drops. As the base level drops the steam begins to down cut leaving the old streambed at a higher elevation than the present stream elevation. The older terraces become inactive benches (Keller and Pinter, 1996; Prothero and Schwab, 1996). I interpret these conglomerate units to be old stream terraces, which may have been eroded. The paleo-Virgin River must have flowed from the north to the south primarily because the terraces become topographically lower toward the south (Fig. 15).

Older Fluvial Deposits

The older conglomerate (Qcgl) crops out in one location east of U.S. 89 and in three locations west of U.S. 89 (Fig. 15 and Plate 1). This may be because the older channel is farther west of the U.S. 89 or other outcrops have been eroded or not preserved.

Limestone, dolostone, chert, sandstone, and basalt are the dominant clasts in the conglomerate. Generally, the clasts are well rounded and range from one centimeter to greater than a meter in diameter and graded bedding is present locally. The matrix consists of a sandy siltstone.

The main lithologic difference between the older fluvial deposits and the younger fluvial deposits is the absence of petrified wood clasts in the older conglomerate. The absence of the petrified wood may be due to the fact that this unit unconformably overlies the Kaiparowits/Wahweap undivided Formation (Kkw) (Fig. 9). Therefore, the Virgin
River at the time of the deposition of the older conglomerate did not erode layers containing petrified wood within the Kkw.

Three additional differences between the older conglomerate and the other conglomerates help to distinguish the units. First, the older conglomerate is generally 73 m (240 ft) above the modern stream channel (Fig. 15), whereas the younger conglomerate (Qcg) is typically found between 12 - 37 m (40 - 120 ft) above the present Virgin River channel (Fig. 15). Another difference is that Qcg1 is not on the same grade as the Qcg indicating that they are separate deposits. Lastly, the older conglomerate has a finer grained matrix with 0.6 m (2 ft) clasts generally of basalt (Fig. 17B).

Both the older and the younger conglomerates are capped by basalt flows (Fig. 15 and Plates 1 and 2). The older conglomerate is capped by the ~570 ka basalt flow indicating that the conglomerate is older than 570 ka. In addition, both conglomerates contain clasts of basalt from other flows.

Interpretations

The bedding within the conglomerate and the original slope was used to determine if this unit was tectonically tilted. Beds formed by a south flowing stream generally dip gently to the south. The top surfaces of the exposures dip gently to the northeast and east (<10°NE and <10°E) indicating that they may be tectonically tilted.

Two possible sources of the petrified wood clasts in the Qcg are the Cretaceous Kaiparowits/Wahweap formations undivided or the Triassic Chinle Formation. Petrified wood was found within the Kaiparowits/Wahweap formations in the mapped area. The flow of the paleo-Virgin River was most likely from north to the south. Exposures of the Triassic Chinle Formation occur only to the south of the outcrops of Qcg and
Kaiparowits/Wahweap Formation is exposed near the outcrops and to the north. Also the petrified wood found in the conglomerate is darker in color and highly agatized. The petrified wood found in the Chinle Formation is generally a lighter color and not as agatized. However, petrified wood crops out in the Chinle Formation near Zion National Park, but is darker in color and highly agatized. I suggest that the petrified wood in the Qcg is derived from the Kaiparowits/Wahweap formation.

Discussion of the Virgin River Deposits

Modern Virgin River deposits have an overall smaller grain size than Qcg. This suggests that the present day flow is slower than the flow in the past. However, the grain size of the Qcg1 and the modern fluvial deposits are relatively similar indicating that the flow of the river that deposited Qcg1 and the modern flow rates are similar. Both are faster flow rates than the flow that deposited Qcg. Additionally, the original surface of the conglomerates was slightly to the south.

Faulting within the Quaternary Fluvial Deposits

None of the Quaternary conglomerate units within the mapped area are cut by a fault at the surface. This observation suggests that either surface ruptures are older than the conglomerate units along this section of the fault, or these deposits are not located on the faults. The later scenario is more probable because none of the fault strands in the area of interest project under the conglomerate. However, the 570 ka basalt is cut by faults and several of the conglomerate outcrops are tilted. The tilting was probably caused by faulting.
The active channel and floodplain of the Virgin River are located in the hanging wall just west of the main strand of the Sevier fault in the southern part of the area (Plate 2). This geometry fits the Leeder and Gawthorpe (1987) model of a continental half-graben with axial trough drainage. Both the model and the Sevier fault have footwall uplands with incised drainages. In both the model and the study area these drainages seem to flow nearly perpendicular to the main channel and the fault trace. Both have meandering streams or rivers that flow approximately parallel to the fault trace. The model suggests that as the faults continue to slip, sediments progressively onlap hanging wall units during extension as the stream migrates closer to the fault trace (Leeder and Gawthorpe, 1987). The southern portion of the Virgin River and Sevier fault fit this model. No abandoned meander belts occur in the modern alluvium to suggest progressive onlap and tilting during fault movement. However, all of the Qcg surfaces dip approximately 10° NE to 10°E. Because the fault dips west, when it moves, the sediments in the hanging wall are tilted toward the fault or to the east. These data suggest possible tilting during fault movement because the Sevier fault zone is generally to the east of the Virgin River.

In the northern portion of the area, the Virgin River and the Sevier fault lie farther apart. Near Glendale, the main strand of the Sevier fault bends to the northeast and the Virgin River continues to flow south and does not follow the trace of the fault. However, north of Glendale, a large tributary, Dry Wash Canyon (Plates 1 and 2,) to the Virgin River follows the Sevier fault as far north as Black Mountain (Fig. 1). The Quaternary alluvium within Dry Wash Canyon covers a possible transfer fault of set D (Fig. 12). Several of the Qcg outcrops are exposed in Dry Wash Canyon suggesting that this canyon
was a tributary to the Virgin River during the time of Qcg deposition (Plates 1 and 2 and Fig. 15). This implies that the Virgin River followed the trace of the Sevier fault in Dry Wash Canyon in the past, but a new drainage has formed to the west.
CHAPTER 7

STRUCTURAL INTERPRETATIONS

Two different types of linkage formed near the Orderville relay ramp and within the Stewart Canyon overlap zone. Within these linkage sites, relay ramps with fault parallel folds formed. Together these linkage sites form the Orderville geometric boundary, or salient. The following sections will discuss (1) the linkage zones and the structures formed within them, (2) stages of linkage, and (3) slip rates along the central Sevier fault.

Linkage

Examples of Fault Linkage

Originally isolated faults are interpreted to have linked between Orderville and the Stewart Canyon overlap zone to form the central Sevier fault (Figs. 12A and 12B). Total displacement vs. distance diagrams were created from where the central Sevier fault is generally a single strand in the north to the southern boundary of the mapped area (Fig. 19). The total displacement decreases within the linkage zones (Fig. 4). Within these linkage zones, two different styles of linkage were identified. Near Orderville, fault capture is suggested. In the Stewart Canyon overlap zone, linkage of overlapping faults is suggested. However, several fault tips overlap, and thus this fault zone is multipartite.
more complex than typically described (i.e., Ferrill et al., 1999). The two different styles are discussed below.

Fault Capture in the Orderville Area

Near Orderville, the central Sevier fault linked by fault capture. On displacement vs. distance diagrams the total displacement decreases near the Orderville relay ramp (Fig. 20A). Displacement decreases are expected to occur near linkage sites because linkage zones are typically located near original fault tips where the displacement is less. The pattern on the displacement vs. distance diagram for the Orderville area closely resembles the pattern for the model of fault capture (Fig. 4C). Both diagrams have a plateau in the area where the faults overlap. In this type of linkage, one fault has more or more rapid slip than the other fault. The fault with more or more rapid slip is the fault with the most displacement (Fig. 4C). In addition, the map fault trace pattern (Figs. 12A and 12B) closely resembles the fault trace pattern for the model of fault capture (Fig. 4C). Faults A and B (Figs. 12A and 12B), have nearly the same surface fault trace pattern as the model surface fault trace pattern (Fig. 4C).

Different stages of linkage were identified by the mapped fault trace pattern. For example, stage one, the least advanced stage of linkage, is indicated by two faults that are separate and isolate. Stage two is indicated by the linkage of two faults at one linkage site. Stage three, or the most advanced stage of linkage, occurs where two faults link at two linkage sites. One linkage site is buried under the Quaternary alluvium to the north of Orderville (Figs. 12A and 12B). The other linkage site is located where faults A' and B' connect at the surface to the south (Figs. 12A and 12B). The Orderville area is in an advanced stage of linkage via fault capture because the faults have two linkage sites.
I suggest that the faults in the Orderville area linked by fault capture because their initial fault spacing and orientations did not allow the fault tip stress fields to interact until the fault with the greater amount of slip, the western fault, propagated to approximately the center 1/3 of the eastern fault (Figs. 12A and 12B).

In the fault capture linkage area near Orderville, the Orderville relay ramp formed (Figs. 12A and 12B) (Davis, 1999; this study). The Orderville relay formed in a fault capture linkage situation, which is a type of hard linkage. The attitudes within the Orderville relay ramp reveal the typical ramp monocline (Fig. 5) as well as an additional fold (discussed later). This ramp is also breached at both the top and bottom at the two linkage sites (base and top breaches) (Figs. 12A and 12B).

Overlapping Faults in the Stewart Canyon Area

The Stewart Canyon overlap zone may be a strain transfer zone, as indicated by four major linked overlapping faults. The Stewart Canyon overlap zone is more complex than simple overlapping fault tip linkage. It is a strain transfer zone that involves at least twelve faults, four sites of linkage, and three relay ramps. The zone is subdivided into three domains: eastern, central, and western (Figs. 12A and 12B).

Eastern Stewart Canyon Overlap Zone

The eastern most fault (T') is interpreted to be a splay of the next fault to the west (U') (Figs. 12A and 12B). To the north near cross section E-E', the northeast dipping fault (Q') is also interpreted to be a splay of fault U' (Figs. 12A and 12B).

Farther to the north, faults U' and S', which connect in map view (Figs. 12A and 12B), form a fault slice. Fault S' was once the main strand, however, the stress fields changed and a new fault (U'') propagated, which became the main strand.
I suggest that the eastern portion of the Stewart Canyon overlap zone is a relay ramp and herein name it the Elkheart Cliffs relay ramp (Figs. 12A and 12B). This relay ramp formed between overlapping fault tips. On displacement vs. distance diagrams, the plotted data (Fig. 20D) closely resemble the shape predicted by the model for soft linkage via overlapping faults (Fig. 4E). Additionally, the bounding faults do not link at the surface suggesting soft linkage. However they may link at depth suggesting a hard linkage situation (Plate 4). Thus, both hard and soft linkage occur along these two faults.

Central Stewart Canyon Overlap Zone

In the central portion of the Stewart Canyon overlap zone, the faults that form the Glendale relay ramp are linked overlapping faults for several reasons (Figs. 12A and 12B). First, the displacement vs. distance profile (Fig. 20B), generally resembles the overlapping fault tips model (Fig. 4B). However, an anomaly exists within the linkage zone along the northern part of the linkage site (Fig. 20B). The location of the anomaly corresponds to the location of fault D, a breakthrough or cross fault. Therefore, the anomaly is most likely a direct result of that cross fault. Second, the mapped patterns for the central Stewart Canyon overlap zone closely resemble the model fault trace map patterns for overlapping faults (Figs. 4B and 20B). Both have overlapping faults that connect at the surface. The faults in the central Stewart Canyon overlap zone and in the models in map pattern overlap and connect (Figs. 4B, 12A, 12B, and 12B). In this case, hard linkage occurred because the ramp is breached on the basal end. However, this area also contains cross faults, which, require a combination of the overlapping and cross fault models (Figs. 4B and 20B). The central Stewart Canyon overlap zone mapped fault trace
patterns are interpreted to have formed by a combination of the overlapping faults (Taylor et al., 2001) and breakthrough fault linkage models (Fig. 4).

The Glendale relay ramp (Figs. 12A and 12B) formed between overlapping faults (V' and W') within the central portion of the Stewart Canyon overlap zone, with hard linkage and a base breach (physical connection of the faults at the structurally lowest point of the relay ramp). The attitudes of bedding within the ramp reveal the typical ramp monocline as well as an additional fold (discussed later). The Glendale relay ramp also contains a cross fault that may ultimately break down the relay ramp by continued slip along the faults.

Western Stewart Canyon Overlap Zone

The western faults linked overlapping faults with hard linkage at two sites, one to the north and one to the south (Figs. 12A and 12B). The pattern for the western portion of the Stewart Canyon overlap zone has a lens shape, like in the overlapping fault tips model. The displacement vs. distance diagram for the pattern of the Stewart Canyon relay ramp area (Figs. 12A and 12B) most closely matches the model of overlapping fault tips (Fig. 20B). However, the fault trace map shows cross faults. In addition, an anomaly or step is present on the displacement vs. distance diagram (Fig. 20B). I suggest that these faults formed after linkage because of the cross cutting relationships of the faults (Figs. 12A and 12B). The cross faults terminate sharply at the bounding faults with a high angle of intersection rather than the 30° typical of cross faults. Therefore, in this area late cross faults and overlapping faults, combined, formed the linkage site.

I suggest that these faults linked across overlapping fault tips because of fault spacing and fault tip stress field interaction (Chapter 2). The fault spacing was small
enough to allow both stress fields to interact with each other at the same time. Linkage by overlapping faults may also be an issue of propagation rates. For example, both faults have similar propagation rates and displacement, so when the stress fields interact, the faults link via overlapping type of linkage rather than fault capture.

Folds Within Relay Ramps

The Orderville relay ramp contains a fault-parallel syncline and the Glendale relay ramp contains a fault-parallel anticline (Figs. 13 and 14). The rocks outside of the bounding faults are generally flat lying or gently west dipping. If these folds formed by drag along the fault, the beds would "roll-over" and dip more steeply towards the fault or exhibit normal drag and dip steeply away from the fault. If the folds are fault propagation folds, the beds in the footwall would be deformed. However, neither geometry is the case. I suggest that the folds formed as a result of a downward decrease in space between the bounding faults (Figs. 13 and 16).

A downward decrease in space between two relay ramp bounding faults occurs because the faults merge at depth in the linkage zone (Fig. 21). At the moment when the ramp-bounding faults link, the rocks within the relay ramp fill the space between the faults (Fig. 21). However, if fault B or both fault A and B move (Fig. 21), the rocks within the fault-bounded wedge-shaped block are dropped down into a smaller space. This decrease requires the rocks to shorten normal to the bounding faults, which can be accomplished through a fault-parallel fold (Fig. 21). The more the faults slip, the tighter the fold becomes within the fault block. Therefore, fault-parallel folds within relay ramps suggest that faults bounding the relay ramp approach each other and/or merge with depth and the bounding faults have had significant slip after formation of the relay ramp.
The Glendale relay ramp contains a generally fault-parallel anticline. On Figs. 12A and 12B, notice that the axial trace of the fold bends and changes strike. This change suggests that the east-bounding fault is not planar at depth, but changes strike and/or dip with depth causing the axial surface of the fold to bend.

Because most of the Stewart Canyon relay ramp is buried under Quaternary alluvium, it is not know whether or not it contains a fold. Where the relay ramp is exposed, attitudes were difficult to collect because the Cretaceous Dakota Sandstone is a poorly exposed dominantly muddy shale. The attitudes that were collected are on coal seams. Based on mapping and cross section construction analyses, I suggest that the Stewart Canyon relay ramp is a zone of fault linkage.

Summary

The Orderville, Glendale, Stewart Canyon, and Elkheart Cliffs relay ramps have formed between overlapping faults. However, the fault capture subtype of overlapping linkage occurred near the Orderville relay ramp (Fig. 20). Breakthrough cross faults are important in the Glendale and Stewart Canyon relay ramps. These relay ramps were all identified by fault patterns and/or the attitudes of bedding between the bounding faults. The unique pattern of faults and relay ramps in the Stewart Canyon overlap zone may represent a triple ramp linkage situation where one ramp forms and with continued slip, another ramp forms while the first formed relay ramp becomes both base and top breached. Later another ramp forms, while the second ramp becomes base breached.

Stages of Relay Ramp Development in the Stewart Canyon Overlap Zone

The Stewart Canyon relay ramp is interpreted to have formed first, next the Glendale relay ramp, and finally the Elkheart Cliffs relay ramp. These stages of
development are based on (1) cross cutting fault trace patterns, (2) whether the relay ramp is breached or not (if the ramp is breached at how many sites), and (3) the number of cross faults, which ultimately lead to the break down the ramp. Breaching of the relay ramp suggests that the ramp is in its final stage of development and will begin to breakdown (Ferrill et al., 1999).

The Stewart Canyon relay ramp probably formed first because it has both a head and top breach. No anticline or syncline was found within the ramp suggesting that the ramp formed prior to the other ramps (i.e., the ramp couldn’t have formed through a pre-existing ramp with a fault parallel fold). However, there may be a fold, but most of the ramp is covered by Quaternary alluvium. The Glendale relay ramp probably formed next. This ramp has a base breach and a fault-parallel anticline. With additional slip along the bounding faults, the ramp will probably form a top breach and the fault-parallel anticline will become tighter. I suggest that the Elkheart Cliffs relay ramp formed last. This is interpreted because (1) the ramp is not breached, (2) there is no evidence of a fault-parallel fold, and (3) the bounding faults may connect at depth but not at the surface.

Stages of Linkage along the Central Sevier fault

The new data and analyses provided here allow recognition of five stages of linkage along the central Sevier fault.

During stage 1, the central Sevier fault initiated as six isolated faults: Spencer Bench segment (U'), X', V', W', Y', and Mt. Carmel segment (Z') (Fig. 22A). A possible relay ramp developed between faults X', V', and +/- W' (Figs. 22A and 23A).
This relay ramp is a combination of the Glendale and Stewart Canyon relay ramps. This stage of development is soft linkage.

During stage 2, near the community of Orderville, fault Y' continued to propagate south and fault Z' (Mt. Carmel segment) continued to propagate north (Fig. 22B). As these faults overlapped, they formed the Orderville relay ramp. After this ramp formed, hard linkage occurred. The relay ramp is double breached with a top and base breach. The syncline formed just before or after hard linkage. To the north, faults X' and V' continue to propagate ultimately linking by hard linkage to form a breached relay ramp (Figs. 22B and 23B). This breached ramp is the combined Glendale and Stewart Canyon relay ramps. While faults X' and V' link, fault W' propagated and divided the area between faults X' and V' into the Glendale and Stewart Canyon relay ramps (Figs. 22B and 23B). An anticline also formed within the Glendale relay ramp. Soft linkage occurred between faults X' and W' as well as W' and V' (Figs. 22B and 23B). To the northeast, fault U' (Spencer Bench segment) continued to propagate south. Between faults U' and V', the Elkheart Cliffs relay ramp developed soft linkage (Figs. 22B and 23B).

During stage 3, fault W' propagated to the north and linked by hard linkage with fault V' (Figs. 22C and 23C). This hard linkage site is a base breach of the Glendale relay ramp and isolates the Stewart Canyon relay ramp. In this stage the Stewart Canyon relay ramp is bound by three faults X', V' and W' (Figs. 22C and 23C). Cross faults continued to develop in the Stewart Canyon relay ramp (Figs. 22C and 23C). To the east, fault U' continued to propagate to the south and the Elkheart Cliffs relay ramp developed further by soft linkage (Figs. 22C and 23C).
During stage 4, a cross fault developed and cut the Glendale relay ramp and anticline (Figs. 22D and 23D). Fault W' propagated and linked with fault Z' to form a top breach on the Stewart Canyon relay ramp (Figs. 22D and 23D). In addition, a cross fault cutting the Stewart Canyon relay ramp formed. These cross faults have an atypical orientation of \(-90^\circ\) to faults X' and V' and subparallel (20') to V' (Figs. 22D and 23D). This non-standard orientation probably formed because the Stewart Canyon relay ramp has three bounding faults rather than the typical two bounding faults. To the east, fault U' continues to propagate farther south (Figs. 22D and 23D). Fault U' may possibly link at depth with fault V' to form a hard linkage site (Figs. 22D and 23D). Farther to the east, fault T' begins to splay from fault U' and propagates north (Figs. 22D and 23D).

During the final stage (stage 5), cross and breakthrough faults continued to develop and fault T' propagated farther northward (Figs. 22E and 23E). Stage 5 is also the modern fault trace map. Several of the faults have been buried by Quaternary alluvium.

Segments and Segment Boundaries

Typically geometric salients and segment boundaries form at linkage sites or along linkage zones between reentrants. The salient along the central Sevier fault between Orderville and Glendale is a large geometric bend containing linkage zones called the Orderville salient (Fig. 22E). This salient contains four linkage sites and the Orderville, Glendale, Stewart Canyon, and Elkheart Cliffs relay ramps. A salient or geometric segment boundary is a zone rather than a particular point (Fig. 22E). The Orderville salient lies between the Mt. Carmel segment to the south and the Spencer
Bench segment to the north. Both the Mt. Carmel and the Spencer Bench segments are reentrants to the Orderville salient (Fig. 22E).

Age Constraints and Slip Rates on the Sevier Fault

Different portions of the Sevier fault have different ages of last known surface rupture. The northern portion is geographically defined from Panguitch south to Black Mountain and is called the Spencer Bench geometric segment. The central portion is defined from Black Mountain south to Orderville and is called the Orderville salient. The southern portion is defined from Orderville south to Yellow Jacket Spring called the Mt. Carmel geometric segment (Fig. 1).

Slip Rates

Preliminary slip rate studies have been done for the northern portion of the Spencer Bench geometric segment (Hecker, 1993). Hecker (1993) states that the slip rate is 0.360 mm/year (0.014 in/year) near Red Canyon (Fig. 1). This slip rate was calculated for the last 560 ka using the post Red Canyon andesite slip and the age of the andesite (Best et al., 1980).

No slip calculations have been published for the central and southern portions of the Sevier fault. This study introduces new data and calculations of slip rates along the central portion of the Sevier fault.

Pre- and post-basalt slip rates for the central Sevier fault are useful to estimate (1) the age of initiation, (2) whether the slip rate has been constant through time, (3) possibly whether the region is at seismic risk in the future. To determine the age of initiation and pre-basalt slip rate, the post-basalt slip rate must be determined.
Post-basalt slip rates were calculated in the Spencer Bench domain near Black Mountain. Here, the Sevier fault displaced 570 ka basalt 10 meters (33 ft) (Best et al., 1980; this study) (Figs. 12A and 12B). Assuming the slip rate was constant since 570 ka, an average yearly slip rate for the Spencer Bench segment can be calculated from the equation: total offset of the basalt divided by the age of the basalt. Using this formula the slip rate for the last 570 ka is 0.0180 mm/year (0.0007 in/year).

After calculating the post-basalt offset the initiation of the Sevier fault can be determined by using the formula $r = \frac{d}{t}$ where $t =$ time, $d =$ distance or stratigraphic separation, and $r =$ post-basalt offset slip rate. The $d$ used was the greatest amount of stratigraphic separation along the Spencer Bench segment of the main strand of the central Sevier fault. This calculation assumes that the fault has had a constant slip rate throughout its entire history. By using this formula, central Sevier fault initiated 44 Ma. However, the 44 Ma age is older than expected because entire Tertiary Claron Formation is cut by the Sevier fault. Furthermore, the Claron Formation does not contain any evidence of syn-faulting deposition. Therefore, it is required that the initiation of the central Sevier fault is post-Claron. The top of the Claron Formation is ~30 Ma based on a date for a tuffaceous sandstone within the upper Claron (Lundin, 1989).

The pre-basalt slip rate was calculated based on cross section construction and using the formula $r = \frac{d}{t}$. Where $d =$ stratigraphic separation and $t =$ age of the top of the Claron Formation (30 Ma). The total offset was calculated on the top of the Jurassic Navajo Sandstone. This method of determining the total offset assumes that the slip rate has been constant through pre-basalt time and that slip initiated immediately after the cessation of deposition of the Tertiary Claron Formation. Thus, the minimum slip rate
for the pre-basalt offset is 0.0229 mm/year (0.0009 in/year). If slip initiated significantly later than when deposition of Claron Formation ceased, the rate would be faster.

So, based on the above calculations, two interpretations can be made. (1) The southern section of the central portion (Spencer Bench segment) of the Sevier fault has become less active through time. (2) The Red Canyon area is a separate geometric segment from the Spencer Bench segment with a different slip rate. Either interpretation agrees with calculations of decreasing slip rates along the Hurricane fault with time (Lund et al., 2002).

The post-basalt slip rate along the Spencer Bench segment is significantly less than the Quaternary slip rates for the northern portion of the Sevier fault. This suggests that the northern portion of the fault has been more active in the last 570 ka. These slip rates only suggest that the central Sevier fault has been active recently and may produce seismicity in the future.

Fault Scarps

Several fault scarps occur along the Sevier fault. In the northern portion, near Red Canyon, Hecker (1993) documented scarps, which based on scarp morphology may be as young as Holocene in age (Fig. 1). However, at the western entrance to Red Canyon, the Sevier fault has a total of ~900 m (~2,950 ft) of offset (Lundin, 1989). Here a 560 ka andesite is juxtaposed against the Tertiary Claron Formation with ~200 m (~660 ft) of offset (Best et al., 1980; Hecker, 1993). Christenson and Nava (1992) reported fault scarps in Quaternary alluvial fans to the east of Panguitch (Fig. 1). Along the central Sevier fault, no faults cut the Quaternary sediments. However, the 570 ka basalt on Black Mountain is offset (Figs. 12 and 1). Stream terraces of late Tertiary/Quaternary
age are tectonically tilted. Along the southern portion of the Sevier fault, south of Mt. Carmel Junction, Doelling et al. (1989) mapped alluvial gravels, eolian sands, and mixed eolian sands and alluvium cut by strands of the Sevier fault. The above fault scarp data suggest that seismic activity along the Sevier fault is youngest to the north and oldest in the central portion.

Both the slip rate and the ages of scarps suggest that the most recently active portion of the Sevier fault is the northern portion followed by the southern portion then the central portion. However, further studies and additional mapping will help constrain these relationships.

Folding along the Central Sevier Fault

By using the collected field data, I suggest that the folds in question do affect the Tertiary Claron Formation and therefore are a result of early Laramide with additional Cenozoic normal fault folding. The trace of the axial surface of the western syncline (Fig. 7) (Doelling et al., 1989) would be approximately along U.S. 89 (Fig. 7). The field area lies in the east limb of this fold, thus dips in the area should be north to northwest. The trace of the Harris Mountain anticlinal axial surface to the south (Doelling et al., 1989) crosses the trace of the Sevier fault near Orderville and continue north in the footwall (Fig. 7). The structure contours and attitudes of bedding suggest that these fold patterns are possible.

The Tertiary Claron Formation has an ~10°NE dip and the Quaternary conglomerate units have <10°E dips. This strata rotation was probably formed by tectonic tilting or fault drag along the Sevier fault. This warping deformed the already
existing Laramide folds and the Tertiary Claron Formation. This interpretation helps explain the north to northwest dipping pre- Tertiary Claron units and the east dips of the Tertiary Claron and post- Tertiary Claron units.

Cross section restoration suggests that the units near the faults are folded into the fault. This fold is parallel to the fault and is interpreted to be caused by Cenozoic normal fault drag along the Sevier fault.
NOTE TO USERS

Page(s) not included in the original manuscript are unavailable from the author or university. The manuscript was microfilmed as received.

62

This reproduction is the best copy available.
CHAPTER 8

EARTHQUAKE AND LANDSLIDE HAZARDS

Earthquakes

The central Sevier fault is located in the southern part of the Intermountain Seismic Belt (ISB), a tectonically active region with large (M 7.0+) earthquakes (Fig. 1). This belt extends from northwestern Montana to southern Nevada and northern Arizona and is characterized by shallow (<15 km focal depths) earthquakes (Smith and Sbar 1974; Christenson and Nava, 1992; Mason, 1996). Large prehistoric earthquakes of M 7.0 – 7.5 occurred in southwestern Utah, and thus, may possibly occur in the future (Christenson and Nava, 1992). Earthquakes that occurred prior to July 1962 are based on felt reports (shaking felt and reported by humans) whereas earthquakes occurring after July 1962 are based on instrumental data (Christenson and Nava, 1992). Historical earthquakes in southwestern Utah have reached magnitudes of 6.0 - 6.5 (Christenson and Nava, 1992). Some examples are the 1902 M 6.5 Richfield, 1902 M 6.3 Pine Valley, and 1921 M 6.3 Elsinore earthquakes (Christenson and Nava, 1992). Approximately 2,300 earthquakes >M 2.0 occurred in southwestern Utah since 1850 (Christenson and Nava, 1992), and approximately 20 earthquakes greater than M 4.0 occurred during this century in southwestern Utah and northwestern Arizona (Christenson and Nava, 1992). A M 5.5 - 5.7 earthquake was recorded in 1959 southeast of Kanab (Doelling et al., 1989; Christenson and Nava, 1992). Christenson and Nava (1992) document an earthquake of
Mercalli Intensity VII (Richter magnitude of ~5.7) near Kanab in 1887 and several M 2.0 – 4.0 earthquakes near the trace of the Sevier fault. However, it is difficult to determine whether these earthquakes occurred along the Sevier fault zone because earthquake locations and focal depth resolutions are poor. On January 1, 1924, a Mercalli Intensity III earthquake was felt in the town of Orderville (Fig. 1) (Doelling et al., 1989). From January 1, 1924, through November 27, 1927, fourteen aftershocks (Mercalli Intensity of II to III) were also felt in Orderville (Doelling et al., 1989). Doelling et al. (1989) suggest the January 1, 1924 earthquake and aftershocks were caused by movement along the Sevier fault zone. However, no Holocene fault scarps or ground ruptures are documented along the Sevier fault zone near Orderville, however deep earthquakes may not cause surface rupture. The proximity of these reported earthquakes to the Sevier fault, suggests that this fault may have Holocene activity.

The Sevier fault lacks evidence for Holocene surface rupture, but evidence for late Quaternary surface rupture does exist (Jackson, 1990; Christenson and Nava, 1992; Hecker, 1993). The Sevier fault offsets ~570 ka basalt near Black Mountain (Plate 1) (Best et al., 1980; this study), indicating surface rupture during the Quaternary. The lack of documented Holocene surface ruptures suggests recurrence intervals are greater than 10 to 30 ka (Christenson and Nava, 1992). However, Jackson (1990) and Hecker (1993) state that evidence for recent activity may be lacking or obscured because of active colluvial slopes and thick vegetation. Also, erosion by the Virgin River may have removed scarps. Christenson and Nava (1992) suggest relatively high late Quaternary slip rates of 0.30 - 0.47 mm/year (0.012 – 0.019 in/year) that seem to contradict the lack
of evidence for Holocene surface rupture. Little information is known about the average earthquake recurrence intervals along the Sevier fault in southwestern Utah.

Earthquakes of M 4.0 and higher generally cause a variety of earthquake and associated hazards. Some of the hazards in the region include ground shaking, surface rupture, liquefaction, flooding, and slope failures (rock falls, landslides, debris flows, avalanches, etc.) (Christenson and Nava, 1992; Harty, 1992; Hecker, 1993; Lund, 1997; Stewart et al., 1997a, 1997b; Reber et al., 2001). This study will focus on slope failures.

Landslides

A landslide is the downward movement of earth material along a distinct failure surface. Active landslides can range in velocity from one meter per day to as fast as 300 km/hour (186 mi/hour) (Rahn, 1996). Landslides that no longer move are considered inactive or stable (Rahn, 1996). This study provides new information on 14 landslides.

Identifying and Categorizing Landslides

Most of the landslides documented in southern Utah are at elevations greater than 1,829 m (6,000 ft) above sea level (Schroder, 1971) and are derived from the Cretaceous Tropic Shale, Dakota Sandstone, and Jurassic Carmel, Triassic Chinle, and Moenkopi Formations (Schroder, 1971; Doelling et al., 1989; Christenson and Nava, 1992; Harty, 1992; Lund, 1997; Stewart et al., 1997; Reber et al., 2001). These formations contain expandable clays such as montmorillonite (Mulvey, 1992). When wet, these clays can expand up to 2,000 times their original dry volume causing
landsides to occur within these high clay content collapsible soils and rock units (Mulvey, 1992).

One natural trigger for many landslides is earthquakes. Earthquake induced landslides typically occur on steep slopes (>25°) that have a relief greater than 152 m (500 ft) (Keefer, 1984; Rahn, 1996). Typically, such slopes can be found along streams, washes, or young faults. Failure occurs when the material is dislodged by earthquake shaking. After failure, the slopes are then typically undercut by streams or active washes (Keefer, 1984; Rahn, 1996). The amount of undercutting is dependent on how much and what type of material fell. Also, the amount of undercutting is dependent on whether or not the debris fell into the stream.

Naturally occurring landslides can also form by gravitational failure along bedding planes of weak units (i.e., shales and mudstones) or clay rich soils. The weakness and potential for failure can be increased by prolonged rain and freeze-thaw cycles (Harty, 1992; Rahn, 1996).

Human induced landslides are also common. Two ways in which humans induce landslides are (1) clear-cutting vegetation and (2) adding weight (i.e., building a structure) on or above a potential or existing stable slide. Clear-cutting vegetation causes a loss of roots, which lowers the shear strength of the soil or rock unit allowing it to potentially fail (Rahn, 1996). Adding weight to the potential slide or a stable pre-existing slide can accelerate or trigger movement of the slide because the angle of repose has been changed. Humans also cause landslides by providing a triggering mechanism for slope failure (Rahn, 1996). An example is cutting the toe of an existing landslide to build a
roadway or structure. Cutting the toe causes the slide to become unstable and begin to move.

Landslides are categorized into three types based on the lithology in which the landslide occurred: (1) bedrock, (2) soils, and (3) unconsolidated materials (Rahn, 1996). This study focuses on the landslides that occur in bedrock. Bedrock landslides are further categorized into four types: (1) rockfall, (2) rotational slump, (3) planar block slide, and (4) rockslide (Rahn, 1996) (Fig. 24). Rockfalls generally occur along steep cliffs and may occur in M 4.0 and greater earthquakes (Keefer, 1984; Harty, 1992). Along the central Sevier fault, fourteen rockfalls and/or rotational slumps were documented (Plates 1 and 2). The rockfalls are located near the high cliffs of the Navajo Sandstone and the Co-op Creek Member of the Carmel Formation. The rotational slumps are derived from the weak shale and mudstone units (Tropic Shale, Dakota Formation, Carmel Formation) near Glendale (Plates 2 and 3).

Regional Slope Failures

Landslides are common in southwestern Utah because the region experiences relatively high precipitation and has high elevation, steep slopes, earthquakes, and unstable geologic formations (Doelling et al., 1989; Harty, 1992). Many of these landslides have damaged infrastructure, homes, and businesses. However, these slides are relatively unstudied. Below are possible triggering mechanisms and classification of the fourteen landslides along the central Sevier fault.
Triggering Mechanisms for Long Valley Landslides

Landslides are common within the vicinity of the Sevier fault (Schroder, 1971; Doelling et al., 1989; Harty, 1992). Characteristic features of landslides include: (1) steep topography, (2) arcuate to linear scarps, (3) benched or hummocky topography, (4) bulging toes, (5) ponded or re-routed drainages, and (6) immature vegetation (compared the vegetation around the landslide) on the landslide (McCalpin, 1996). All of the fourteen landslides in the study area may have been natural slope failures in weak units triggered by high rainfall and/or the freeze-thaw cycle. Three landslides, labeled A, B, and C, were identified along the Glendale Bench Road (Plate 2 and Fig. 25) (Harty, 1992; this study). One of these landslides, slide A, has either been triggered or reactivated by humans (Fig. 25). The center of the landslide has been cut for road construction (Fig. 26A). Several failure precaution techniques have been applied to this landslide to prevent future failure. The first technique is to cut back the slope (above the road) of the existing landslide to a lower angle to prevent the landslide from sliding over the road (Fig. 26A). The second technique is to reinforce the landslide topographically below the road to prevent a new landslide from forming within the old slide (Fig. 26A). The other landslides, slides B and C, along the Glendale Bench Road may or may not have been human induced. No stabilization techniques have been performed on these slides.

In contrast, the landslide in the eastern portion of Dry Wash, called the Dry Wash Landslide, may have been triggered by ground shaking from a historical earthquake (Plate 1, Figs. 25 and 26B). To state that a landslide is seismically induced the landslide must be dated and associated with earthquake shaking (Keefer, 1994; McCalpin, 1996; Barnhardt and Kayen, 1999; Papadopoulos and Plessa, 2000).
To demonstrate whether an earthquake triggered a landslide is difficult because only a few studies have been done on seismically induced landslides. Therefore, the interpretations vary widely. Rahn (1996), McCalpin (1996), and Barnhardt and Kayen (1999) summarize several basic criteria to determine whether a landslide has a seismic origin. These techniques are used in this study. First, is the regional analysis of landslides. Commonly, in a seismically active zone, a group of landslides will occur simultaneously (Nikonov, 1988). However, single large landslides can also be triggered by earthquakes (Nikonov, 1988). Second, the landslide morphology must be analyzed. The hillslope from which the slide was derived must be at a steep angle with some topographic relief. In regions where the topographic relief is due to streams downcutting, the landslide is typically undercut by a stream. These landslides also may contain characteristics such as liquefaction features. Seismically induced landslides typically have a more blocky shape whereas slides that form because of intense rainfall typically have a more spread out and less blocky shape (Perrin and Hancox, 1992; Barnhardt and Kayen, 1999). Lastly, the historical records of reported earthquakes and landslides must match, keeping in mind that earthquake-triggered landslides may have a three to five day delay in movement (Rojstaczer and Wolf, 1992). This delay in movement may be caused by increased groundwater flow locally or time-dependent manifestations of increased pore water pressure due to ground shaking during an earthquake (Rojstaczer and Wolf, 1992). Papadopoulos and Plessa (2000) and Keefer (1984) suggest that earthquake triggered landslides usually occur in weak materials such as soils, weathered, sheared, heavily fractured, jointed, or saturated rocks.
Classification of the Dry Wash Landslide

By using the above stated techniques, the Dry Wash Landslide can be classified and its triggering mechanism can be evaluated. I suggest that the Dry Wash Landslide is a rotational slump (Fig. 24) and may have been triggered by the 1924 Orderville earthquake and/or associated aftershocks.

Evidence to support the Dry Wash Landslide as a rotation slump include steep topography, an arcuate to linear scarp, and hummocky topography (Fig. 26A). The Dry Wash Landslide also contains blocks that were tilted or rotated during failure. Several of the trees incorporated in the landslide are also rotated (Fig. 27A). A vegetation difference is notable between the landslide and the surrounding topography. Little to no new vegetation exists on the deposit and what new growth exists is sparse (Fig. 27A). The new growth consists of ~0.9 m (~3 ft) tall pine trees and immature manzanita, sage brush, yucca, and tall grass (Fig. 27B). This vegetation is less mature than the same types of vegetation on surfaces surrounding the landslide (Fig. 28A). However, the dead vegetation within the deposit is similar in maturity to the live vegetation surrounding the feature. Most of the vegetation incorporated within the landslide is highly decayed and lacks foliage (Figs 28B and 29A). This vegetation is rotated and incorporated within the landslide. However, some of incorporated vegetation survived the landslide and is growing at an oblique angle to its original growth direction giving the trunks of the trees a bent or hook shape (Fig. 27A). The original surface as well as vegetation before the failure is preserved both above and below (in the scarp graben) the head scarp of the slide (Figs. 24 and 29B). The toe is bulging and has ponded and rerouted drainages (Fig. 30A).
The age of the Dry Wash Landslide was determined by using historical methods, vegetation analysis, and geomorphic analysis. Historical methods include reports of events from local inhabitants. Local inhabitants of the region state that the slide occurred approximately 75 years ago. However, no written documentation of when the landslide occurred is available. Geomorphic analyses suggest that the landslide occurred relatively recently perhaps in the last century. The scarp of the Dry Wash Landslide is very steep (nearly vertical) with little degradation (Fig. 26B). The slip surface is on a steep (nearly vertical) slope with 37 - 46 m (120 - 150 ft) of relief. The surface of the landslide has a blocky to angular and hummocky shape with relatively few (1-2) stream channels cutting the landslide indicating little erosion has occurred on the slide. However, a stream undercuts the toe (Fig. 30A). Vegetation analysis also suggests that the landslide occurred recently, perhaps within the past century because the maturity of the vegetation incorporated within and living within the landslide is ~<100 years old. By the above analyses, I suggest that the Dry Wash Landslide is young (<100 years old).

Even though the Dry Wash Landslide fits the above stated criteria to be categorized as a seismically induced earthquake (cf., Rahn, 1996; McCalpin, 1996), I suggest that the evidence is lacking to be certain whether the Dry Wash Landslide was seismically induced. First, only an approximate date of when the landslide occurred was documented. No written historical records were found. Therefore, it is difficult to say whether the landslide occurred approximately at the same time as the 1924 Orderville earthquake swarm. Secondly, the vegetation and geomorphic descriptions of the Dry Wash Landslide also fit the descriptions of landslides that were not triggered by
earthquakes. Therefore, by using the above criteria and data the Dry Wash Landslide may or may not be seismically induced.

Ethical Assessment of Hazards

Natural disasters such as earthquakes and landslides are unavoidable and can threaten life and property. Investigations of landslides and potentially active faults involve good science as well as ethical scientific practices (Cronin and Sverdrup, 1998). Thus, great care should be taken when locating new sites for structures. Areas above, below, as well as on the weak shale and mudstones should be avoided. Potential earthquake and landslide hazards should be analyzed before new structures are built. Land and building owners should be made aware of any potential earthquake and associated hazards. A geoscientist must follow a code of ethics to ensure the reduction of life and property loss during a natural disaster (Cronin and Sverdrup, 1998). Therefore, with better earthquake building codes, understanding of landslides and their locations, ethical scientific practice, and increased public awareness, the possible life and property loss from such natural hazards can be minimized.
CHAPTER 9

TECTONIC INTERPRETATIONS

Introduction

Additional data and analysis may help resolve some of the controversial topics about the evolution of the western edge of the Colorado Plateau. Discussed below are the northern termination of the Sevier fault, relationships of the Basin and Range style faults in southwestern Utah, and the age of folding within and near the study area.

Northern Termination of the Sevier Fault

Controversy about where the Sevier fault terminates to the north is found throughout the literature. Most workers agree that the Sevier fault ends near or within the Marysvale Volcanic field (Fig. 7). Determining the northern termination is important to determine the seismic potential of the Sevier fault as well as to determine if the Sevier fault connects to the Wasatch fault zone to the north.

Previous workers (i.e., Eardley and Beutner, 1934) mapped the Sevier fault as a single strand cutting the Marysvale Volcanic Field and place the northern termination near Central, Utah (Fig. 7). However, the Utah state geological map shows the Sevier fault ending in the middle of the Marysvale Volcanic Field. Later mapping (Rowley et al., 1981) suggested that the Sevier fault has several splays and strands cutting the Marysvale Volcanic Field up to 5 km (3.1 mi) north of Piute Reservoir and possibly
farther north. Hecker (1993) showed Quaternary faulting along trend of the Sevier fault to Richfield. However, Hecker (1993) showed no Quaternary scarps between Panguitch and the southern portion of the Piute Reservoir (Fig. 7). This suggests that either the Sevier fault does not exist in this region or its last movement is pre-Quaternary. However D. Simon (personal communication 2002) documented Holocene events near the Piute Reservoir. Davis (1999) suggested that the Sevier fault lost its characteristics within the Marysvale Volcanic Field. However, Rowley (personal communication 2002) observed scarps indicating that the Sevier fault does cut the Marysvale Volcanic Field and terminates near Richfield. These observations suggest that the Sevier fault does not connect with the Wasatch fault, and terminates near Central or Richfield (Fig. 7).

Other Long Normal Fault Relationships

The Hurricane, Sevier, and Paunsaugunt faults have the same general structural characteristics (i.e., down-to-the-west, steeply dipping, segmented, etc.). However, their relationships to each other may provide an insight to the evolution of the western margin of the Colorado Plateau.

First, the greatest amount of seismicity is along the Hurricane fault with the largest recorded earthquake in the last decade (M 5.8) (Arabasz et al., 1992; Pechmann et al., 1992). Some seismicity occurs near the Sevier fault, but less than along the Hurricane fault (Davis, 1999). Two earthquakes have been recorded along the trace of the Sevier fault in the last century (Doelling et al., 1989; Davis 1999). The Paunsaugunt fault has had no recorded seismic events within the last 100 years (Doelling et al., 1989; Engdahl and Rinehart, 1991; Davis, 1999).
Second, offset units become younger to the west. For example, the Hurricane fault offsets Holocene units and several Quaternary sedimentary deposits (Stewart et al., 1997). Quaternary basalt is also offset (Stewart and Taylor, 1996; Stewart et al., 1997). The Sevier fault offsets Quaternary basalts (Best et al., 1980) and Quaternary sediments (Doelling et al., 1989; Hecker, 1993). The Sevier fault also tectonically tilts stream terrace deposits near Orderville and Glendale (Fig. 1). However, along the northern portion, near the Piute Reservoir, as many as four events have occurred in the Holocene (Fig. 7) (D. Simon personal communication, 2002). Mapping by Bowers (1991) along the Paunsaugunt faults shows only one location, south of Bryce Canyon National Park, with fault scarps that cut Quaternary units. The two scarps are <1 meter (<~3 ft) high and are located in Pliocene to possibly Holocene pediment surfaces (Fig. 7).

Third, the Paunsaugunt fault has reversed topography (the hanging wall is topographically higher than the footwall) (Doelling et al., 1989; Bowers, 1991). This indicates either the units in the hanging wall are more susceptible to erosion than the footwall units or the fault has not had recent movement. Along the Paunsaugunt fault, erosion, little to no movement along the fault, or both options are probable. Using the above previously published data and new data from this study, I agree with the previous suggestion that the faults are more active or younger to the west (i.e., Doelling et al., 1989; Davis 1999; Schiefelbein and Taylor, 2000).

Sevier, Laramide, or Cenozoic Regional Folding within the Study Area

Broad regional folds can be found from the vicinity of Zion National Park east through the Colorado Plateau (Doelling et al., 1989; Davis, 1999). From structure
contour maps Doelling et al. (1989) suggested that the Mt. Harris anticline lies in the hanging wall of the Sevier fault south of Mt. Carmel Junction (Fig. 7). They also suggested that the synclines lie in the hanging wall north of Black Mountain and in the footwall east of Black Mountain (Figs. 7 and 1).

These folds may have been formed during the Sevier orogeny, Laramide orogeny, or by Cenozoic normal faulting. Davis (1978) and Wannamaker et al. (2001) suggested a Laramide age for these folds. However, Davis (1999) suggested that several folds located near the normal fault traces formed by fault drag. Data from this study suggest that these folds were formed during the Laramide orogeny, Cenozoic normal faulting, and/or both.
CHAPTER 10

PETROLEUM POTENTIAL

Normal Fault Linkage and Hydrocarbon Production

The hanging walls and footwalls linked by relay ramps as well as structures within the relay ramp can form migration pathways and/or traps for hydrocarbons (Morley et al., 1990; Peacock and Sanderson, 1994; Dawers and Underhill, 2000; this study). Relay ramps can be important for finding hydrocarbon traps because fault-parallel folds within the ramps, in addition to the ramp monoclines may be traps (Morley et al., 1990; Peacock and Sanderson, 1994). The bounding faults of and/or breakthrough faults within relay ramps can (1) form barriers to hydrocarbon migration, (2) act as hydrocarbon flow pathways, or (3) be permeable such that the hydrocarbons can pass through the fault. Below, relay ramps will be discussed as potential traps and/or migration pathways for hydrocarbons.

Relay ramps with different internal structures trap hydrocarbons in different locations. Relay ramps that do not have associated fault parallel folds, but have impermeable faults typically trap hydrocarbons on the up-dip side of the ramp (Fig. 31A). Relay ramps that contain fault parallel anticlines, such as those recognized in this study, trap hydrocarbons within the structurally highest portion of the anticline (Fig. 31B). Relay ramps with fault parallel synclines should trap hydrocarbons along the limbs of the fold near the bounding faults, if the faults are impermeable (Fig. 31C). With
breakthrough faults, hydrocarbons may accumulate within fault bounded blocks depending on whether the faults are permeable (Fig. 31D). These hydrocarbons can either migrate from the source rock up along a non-permeable fault or through a permeable fault and into the topographically highest part of the ramp below the cap rock (Fig. 31). The amount of hydrocarbon accumulation depends upon the source rock.

In addition to relay ramps, physical fault linkage may be important for hydrocarbon exploration. For example, if two faults with overlapping fault tips link at one site and a fault-parallel anticline develops within the relay ramp, then four-way-closure can form. The four closures are: (1) the linkage site, (2) the ramp monocline, and (3 and 4) the two limbs of the anticline. However, if the faults link via overlapping fault tips along breakthrough faults, then a relay ramp may or may not form. However, a structure to trap the hydrocarbons can still form (Ferrill and Morris, 2001).

**Hydrocarbon Production Near Study Area**

Hydrocarbon producing fields located near the central Sevier fault include the Virgin oil field, Upper Valley field, and Anderson Junction field (Fig. 32). The source rocks for these fields include the Pennsylvanian Hermosa Formation, Permian Hermit and Kaibab Formations as well as the Virgin Limestone and Timpoweap Members of the Triassic Moenkopi Formation (Fig. 8) (Peterson, 1974; Hintze, 1988; Van Kooten, 1988; Doelling et al., 1989; Harris, 1994; S.J. Reber, personal communication 2001). The structures that have been explored include folds associated with the Laramide and Sevier orogenies and Cenozoic normal faults. For the Anderson Junction and Virgin oil fields the Hurricane fault was considered to be a migration pathway (Peterson, 1974; Harris,
In the Anderson Junction field, the oil was trapped either on an anticlinal closure of the Kanarra anticline, a fault wedge of the Hurricane fault, or the Virgin anticlinorium (Peterson, 1974; Harris, 1994). In the Upper Valley field, hydrocarbons were trapped and pumped out of the Upper Valley anticline. The total number of barrels produced in southwestern Utah between the first oil production in the state in 1907 (Virgin field) and 1988 is approximately 26 million barrels (26 MMBO) (Peterson, 1974; Van Kooten, 1988; Doelling et al., 1989). However, the total amount of oil produced in the entire state of Utah is ~900 million barrels (900 MMBO).

The High Plateaus subprovince near the Sevier fault may be a region for future hydrocarbon exploration. Today, the number of oil producing fields are minimal in the area. However, four exploration holes with shows of oil and/or gas have been drilled in the footwall near Mt. Carmel, and one hole with no shows of oil or gas was drilled in the footwall near Orderville (Fig. 32) (Doelling et al., 1989). Four relay ramps have been identified along the Sevier fault (Davis, 1999; this study). These relay ramps and associated faults fit the above models for hydrocarbon traps and/or migration pathways. By understanding relay ramps and the types of linkage zones along the Sevier fault, these structures may be used as analogs for potential traps and/or migration pathways in other oil producing extensional regimes (e.g., North Sea, Gulf of Suez, and the East African Rift).
CHAPTER II

CONCLUSIONS

Recognition of large convex geometric bends, or salients, along faults coincides with concepts that long faults form by linkage of two or more shorter faults. Linkage typically creates salients along the trace of the fault that geometrically segment the faults. Segmented long faults can form by a number of different types of linkage. However, models of segment linkage generally do not address multipartite linkage zones. Such studies of active linked or linking faults have several applied significances. Fault linkage zones are important to the petroleum industry to understand migration pathways and where potential traps exist, and important to the public to understand the potential earthquake and landslide hazards for the region. This study focuses on multipartite linkage zones and the structures formed within these zones using the central Sevier fault as a case study.

Two main types of fault linkage and several subtypes are currently recognized: overlapping tips, simple underlapping tips, fault capture, and breakthrough faults. Within overlapping fault linkage zones, relay ramps typically form. Understanding the relay ramps and the structures within is necessary to fully describe linkage zones. However, fault-parallel folds within relay ramps have not been discussed at length.

80

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
The Sevier fault is a segmented long normal fault that probably initiated in the Miocene (15 - 12 Ma) (Davis, 1999). The Sevier fault is generally a N30°E striking, steeply (>75°) west dipping, multi-strand normal fault.

Two subtypes of fault linkage were documented along the central Sevier fault. The first is a fault capture situation in the Orderville relay ramp area (Fig. 12). The second is a series of overlapping faults with cross faults in the Stewart Canyon overlap zone (Fig. 12). This overlap zone contains three relay ramps (Glendale, Stewart Canyon, and Elkheart Cliffs) (Fig. 12). Relay ramps are a structure that allows strain transfer between two faults (Fig. 5). The Stewart Canyon relay ramp is different from the simple relay ramp model; it is bound by three faults.

Along the central Sevier fault, two structures were identified within the relay ramps. In the Orderville relay ramp and the Glendale relay ramp, fault parallel folds are exposed within the relay ramp. In addition, in the Glendale relay ramp cross or breakthrough faults were identified. These faults cut the fault parallel fold. The multipartite nature of the region between Orderville and Glendale has a series of linkage sites that form a large salient across which the Mt. Carmel segment and Spencer Bench segment linked.

The Sevier fault is possibly an active, at least active in the Quaternary, fault. It offsets ~570 ka basalt and tilts young (Pleistocene?) river deposits. Earthquakes have also been felt and recorded near the Sevier fault. The area of interest also has landslide hazards. Several landslides which maybe seismically induced have been identified in the area.
In conclusion, this study provided (1) new natural examples of multipartite normal fault linkage zones, (2) an evaluation of the earthquake and landslide hazards along the central Sevier fault, and (3) new data and interpretations for the regional tectonics of southern Utah.
APPENDIX A

METHODS

The techniques of data collection and analyses include field mapping, cross-section construction, stereographic analyses, and $^{40}$Ar/$^{39}$Ar isotopic dating. An overview of each technique is presented below.

Field Mapping Techniques

Geologic mapping was the primary technique used for data collection. Approximately 30 km$^2$ (19 mi$^2$) were mapped in Kane County, southwestern Utah during the summer of 2000. Mapping was done using standard geologic techniques at a scale of 1:12,000. The topographic base was enlarged from the Orderville, Glendale, and Long Valley 7.5' U.S.G.S. quadrangles printed from the MapTech topographic map computer program. Color aerial photographs were used to aid in locating geologic features, structures, and formations. However, all mapping was based on direct field observation.

Cross Section Construction Techniques

Retrodeformable cross sections were constructed from structural and stratigraphic data and relationships observed and mapped in the field. All cross sections were drawn approximately perpendicular to the strike of the faults in order to analyze along strike variations in splay zones and along single strands of the fault. All fault attitudes were
calculated by three point problems and/or structure contours (Marshak and Mitra, 1988; Rowland and Duebendorfer, 1994) because no faults in the study area yielded a measurable surface. Apparent dips were calculated by using the alignment diagram for solving apparent dip problems (Rowland and Duebendorfer, 1994). The cross sections were constructed under the assumptions that plane strain occurred, the volume of rock remained constant, and the bedding thickness remained constant. The bed lengths balance and no loss of area occurred. Bed lengths in both restored and deformed cross sections can be and are within the standard uncertainty of 5-10% (Rowland and Duebendorfer, 1994). Constant unit thickness is based on (1) the calculated thickness from the map pattern of exposed units in the study area and (2) the published thickness of subsurface units (Figs. 8 and 9) (Hintze, 1988; Stokes, 1988; Doelling et al., 1989).

The geometries of the faults are based on the surface data and the ability to be retrodeformed along each cross section. Standard cross section retrodeformation techniques were used for the faults (e.g., Gibbs, 1983; Davison, 1986; Williams and Vann, 1987; Vendeville, 1991; White and Yielding, 1991; White, 1992; Kerr and White, 1994; Song and Cawood, 2001).

Stereographic Analyses

Several stereographic analyses were done on structures within the study area. Stereonets were created to show the attitudes of folds within the relay ramps. All stereographic analyses were done using the computer program GeOrient.
Two Quaternary basalt samples from the same flow were collected for $^{40}$Ar/$^{39}$Ar isotopic dating as part of this study. BRC-1 was collected from the hanging wall and BRM-2 was collected from the footwall of the Sevier fault. Approximately 2.25 kg (5 lbs) of each sample was collected and trimmed of weathered surfaces in the field. Thin sections were made and analyzed from each sample to ensure that the samples could be isotopically dated. The samples were crushed and sieved to uniform sizes. The sieve size chosen was the size that yielded the largest possible individual crystals that lacked an adhering matrix. Olivine and volcanic glass were removed from the samples by mineral separation methods including heavy liquids and hand picking. All mineral separations were completed by the author at the UNLV Mineral Separation Lab.

Approximately 0.1 oz (250 mg) of basaltic groundmass from each sample were sent to the TRIGA Reactor at the University of Michigan for irradiation. Both samples were then dated using the $^{40}$Ar/$^{39}$Ar dating techniques at the Nevada Isotope Geochronology Lab under the direction of Dr. Terry Spell. Methods of $^{40}$Ar/$^{39}$Ar dating are described in McDougall and Harrison (1988).
<table>
<thead>
<tr>
<th>Step</th>
<th>36Ar</th>
<th>37Ar</th>
<th>38Ar</th>
<th>39Ar</th>
<th>40Ar</th>
<th>%40Ar*</th>
<th>% 39Ar rslrd</th>
<th>Ca/K</th>
<th>40Ar*/39ArK</th>
<th>Age (ka)</th>
<th>1s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.168</td>
<td>21.043</td>
<td>7.099</td>
<td>46.681</td>
<td>347.471</td>
<td>4.5</td>
<td>3.2</td>
<td>3.02204972</td>
<td>385.3463</td>
<td>581</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>0.373</td>
<td>21.399</td>
<td>4.397</td>
<td>65.996</td>
<td>127.538</td>
<td>21.7</td>
<td>4.5</td>
<td>2.17319728</td>
<td>474.9860</td>
<td>693</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>0.399</td>
<td>34.899</td>
<td>4.783</td>
<td>137.595</td>
<td>157.175</td>
<td>33.7</td>
<td>9.5</td>
<td>1.69969812</td>
<td>437.4950</td>
<td>647</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>0.483</td>
<td>50.267</td>
<td>4.95</td>
<td>228.484</td>
<td>201.768</td>
<td>40.6</td>
<td>15.7</td>
<td>1.47420945</td>
<td>408.8139</td>
<td>611</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>0.459</td>
<td>52.0</td>
<td>4.276</td>
<td>247.133</td>
<td>211.537</td>
<td>43.1</td>
<td>17.0</td>
<td>1.40992569</td>
<td>415.1381</td>
<td>619</td>
<td>14</td>
</tr>
<tr>
<td>6</td>
<td>0.425</td>
<td>44.595</td>
<td>3.282</td>
<td>199.718</td>
<td>192.101</td>
<td>37.5</td>
<td>13.7</td>
<td>1.49624894</td>
<td>400.9480</td>
<td>601</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>0.631</td>
<td>62.979</td>
<td>3.666</td>
<td>210.743</td>
<td>243.816</td>
<td>30.9</td>
<td>14.5</td>
<td>2.00282796</td>
<td>403.3032</td>
<td>604</td>
<td>18</td>
</tr>
<tr>
<td>8</td>
<td>0.523</td>
<td>48.595</td>
<td>2.555</td>
<td>183.313</td>
<td>216.163</td>
<td>25.0</td>
<td>7.3</td>
<td>3.06702336</td>
<td>493.2572</td>
<td>715</td>
<td>21</td>
</tr>
<tr>
<td>9</td>
<td>0.648</td>
<td>59.985</td>
<td>2.684</td>
<td>86.579</td>
<td>206.163</td>
<td>16.7</td>
<td>6.0</td>
<td>4.64703833</td>
<td>450.4271</td>
<td>663</td>
<td>26</td>
</tr>
<tr>
<td>10</td>
<td>2.409</td>
<td>561.781</td>
<td>6.719</td>
<td>107.924</td>
<td>612.525</td>
<td>7.7</td>
<td>4.5</td>
<td>35.234524</td>
<td>533.9035</td>
<td>763</td>
<td>142</td>
</tr>
<tr>
<td>11</td>
<td>0.962</td>
<td>53.545</td>
<td>0.949</td>
<td>12.408</td>
<td>274.831</td>
<td>3.4</td>
<td>0.9</td>
<td>29.157435</td>
<td>974.6847</td>
<td>1215</td>
<td>159</td>
</tr>
<tr>
<td>12</td>
<td>0.998</td>
<td>12.953</td>
<td>0.371</td>
<td>3.255</td>
<td>288.36</td>
<td>0.7</td>
<td>0.2</td>
<td>26.869229</td>
<td>790.8199</td>
<td>1040</td>
<td>545</td>
</tr>
</tbody>
</table>

**BRM-2, Footwall basalt**

<table>
<thead>
<tr>
<th>Step</th>
<th>36Ar</th>
<th>37Ar</th>
<th>38Ar</th>
<th>39Ar</th>
<th>40Ar</th>
<th>%40Ar*</th>
<th>% 39Ar rslrd</th>
<th>Ca/K</th>
<th>40Ar*/39ArK</th>
<th>Age (ka)</th>
<th>1s.d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.561</td>
<td>35.768</td>
<td>9.069</td>
<td>73.269</td>
<td>1334.228</td>
<td>1.6</td>
<td>5.5</td>
<td>3.3034434</td>
<td>338.2579</td>
<td>522</td>
<td>123</td>
</tr>
<tr>
<td>2</td>
<td>1.152</td>
<td>44.009</td>
<td>8.491</td>
<td>102.421</td>
<td>363.437</td>
<td>11.5</td>
<td>7.6</td>
<td>2.9309522</td>
<td>448.6136</td>
<td>713</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>1.15</td>
<td>52.307</td>
<td>10.25</td>
<td>187.277</td>
<td>366.931</td>
<td>17.2</td>
<td>14.0</td>
<td>1.9046093</td>
<td>414.9916</td>
<td>622</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>0.648</td>
<td>49.131</td>
<td>9.547</td>
<td>241.597</td>
<td>409.738</td>
<td>21.5</td>
<td>18.0</td>
<td>1.3865164</td>
<td>429.2611</td>
<td>640</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>1.133</td>
<td>41.9</td>
<td>6.166</td>
<td>203.626</td>
<td>388.245</td>
<td>17.4</td>
<td>15.2</td>
<td>1.4020511</td>
<td>379.1655</td>
<td>576</td>
<td>21</td>
</tr>
<tr>
<td>6</td>
<td>1.01</td>
<td>35.703</td>
<td>3.478</td>
<td>142.427</td>
<td>338.564</td>
<td>15.6</td>
<td>10.6</td>
<td>1.7092890</td>
<td>429.2611</td>
<td>640</td>
<td>29</td>
</tr>
<tr>
<td>7</td>
<td>1.223</td>
<td>47.142</td>
<td>3.528</td>
<td>143.132</td>
<td>404.517</td>
<td>14.7</td>
<td>10.7</td>
<td>2.2461796</td>
<td>498.6021</td>
<td>725</td>
<td>26</td>
</tr>
<tr>
<td>8</td>
<td>1.038</td>
<td>38.102</td>
<td>2.812</td>
<td>75.708</td>
<td>322.777</td>
<td>9.9</td>
<td>5.6</td>
<td>3.4334775</td>
<td>502.7836</td>
<td>730</td>
<td>52</td>
</tr>
<tr>
<td>9</td>
<td>1.437</td>
<td>59.372</td>
<td>3.47</td>
<td>75.865</td>
<td>426.994</td>
<td>5.9</td>
<td>5.7</td>
<td>3.5421669</td>
<td>381.4743</td>
<td>579</td>
<td>49</td>
</tr>
<tr>
<td>10</td>
<td>3.555</td>
<td>488.233</td>
<td>6.421</td>
<td>82.936</td>
<td>952.688</td>
<td>4.1</td>
<td>6.2</td>
<td>40.610412</td>
<td>597.7710</td>
<td>840</td>
<td>181</td>
</tr>
<tr>
<td>11</td>
<td>1.022</td>
<td>68.762</td>
<td>1.164</td>
<td>13.183</td>
<td>307.063</td>
<td>9.9</td>
<td>1.0</td>
<td>35.9321625</td>
<td>7036.4809</td>
<td>3747</td>
<td>283</td>
</tr>
</tbody>
</table>

**Appended B.** 

$^{40}Ar^{39}Ar$ step heating data for basalt with olivine and glass removed. Only nine steps are used in each isochron calculation (Fig. 11).
Figure 1. This location map shows the Hurricane fault, the Sevier-Toroweap fault, the Paunsaugunt fault and their locations relative to the Basin and Range province, Transition Zone, and the Colorado Plateau. The ISB (Intermountain Seismic Belt) is located north of the labeled dashed line. The study area is indicated by the dark gray polygon.
Figure 2. Stages of fault propagation and linkage, with stages 1-3 in chronological order. Diagram A is the three general steps for linkage of underlapping type faults. Diagram B (overlapping type fault tips), C (fault capture subtype), and D (breakthrough fault linkage subtype) show the three types of linkage that occur in overlapping fault tips. Boxes labeled 1 show the first stage of linkage. The faults and stress fields have interacted with each other but have not linked. Boxes labeled 2 show the second stage of linkage. The faults and stress fields have interacted with each other but the total fault displacement is not yet complete. Boxes labeled 3 show the final phase of linkage. The shaded areas and arrows represent the total fault displacement. The heavier lines represent the normal faults. This diagram is modified from Reber et al. (2001) and Taylor et al. (2001).
Figure 3. These diagrams show the local stress field location and interactions. The + signs represent the locations where the faults may be located after the next rupture. The - signs are areas that are not likely to fail during the next rupture. The contour lines represent the numerically modeled shear stress with darker gray fill for higher values. The enclosed shapes represent the local stress field for each fault. Diagram A is a representation of radial propagation. B is underlapping faults. C is continued slip along the faults in diagram B (underlapping faults). D is overlapping faults. In diagram D, a relay ramp (strain transfer zone) has formed between the overlapping fault tips. Ball and bar are on the hanging wall of each fault. Diagram A is modified from Cowie and Shipton (1998). Diagrams B - D are modified from Crider and Pollard (1998) and Crider (2001).
Figure 4. This diagram shows model displacement vs. distance diagrams for two types (A and B) and two subtypes (C and D) of fault linkage. The distance is measured along the strike of a piece of a fault across the linkage zone. The data density for diagram D was doubled within the linkage zone to show the "step" pattern. The ball and bar are on the hanging wall. The shaded area and arrows represent the amount of displacement along the fault. The axes are unitless because the models are independent of scale. Diagrams A through C are modified from Taylor et al. (2001).
Figure 4 cont. This diagram (E) shows model displacement vs. distance diagrams for soft linkage in an overlapping fault linkage situation.
Figure 5. The diagramed faults overlap in A, link by fault capture in B, and link by breakthrough faults in C. A relay ramp formed between the overlapping faults in each diagram. Diagram B is an example of a top breached ramp. Notice the changes in the strikes of the beds in the ramp. The different shades of gray represent different strata. The arrows represent the amount of displacement along the fault. The heavy lines represent the normal faults.
Figure 6. This figure shows three types of segment boundaries: (A) a geometric segment boundary, (B) a combined structural and geometric segment boundary, and (C) a combined earthquake and geometric segment boundary at which the earthquake rupture terminated. Earthquakes may also initiate at boundaries. The dark gray shaded regions and thin arrows represent the total amount of offset along the fault. The heavier weight lines represent normal faults, and the thicker arrows represent motion along the fault.
Figure 7. This location map shows the Sevier fault, axial surfaces, and the approximate northern termination. Axial surface data are from Doelling et al. (1989) and Bowers (1991). Fault trace data are from Hecker (1993). The northern termination of the Sevier fault was determined using literature. The approximate location for the Marysvale Volcanic Field is represented by the light gray shaded area.

Legend

- Normal Fault
- Syncline
- Anticline
- Roadways
- Towns

<table>
<thead>
<tr>
<th>Miles</th>
<th>0</th>
<th>15</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kilometers</td>
<td>0</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 8. This stratigraphic column represents units in the subsurface of the study area. Standard symbols are used for rock types; wavy bands are used for volcanic flows, black ovals are used for coal, triangles are used for gypsum, open angles with lines represent cross beds, filled circles are used for chert, asterisks represent Precambrian basement rocks. The triangles with the crosses outside the stratigraphic column represent hydrocarbon producing units. Data from Gregory (1951), Hintze (1973, 1988), Stokes (1988), and Doelling et al. (1989).
<table>
<thead>
<tr>
<th>Age</th>
<th>Unit</th>
<th>Thickness Rock (ft)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Surficial deposits</td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Basalt flows</td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td>Tertiary</td>
<td>Claron Formation</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Kaiparowits and Wahweap Formations undivided</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Straight Cliffs SS</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tropic (Mancos) Shale</td>
<td>760</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dakota SS</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Jurassic</td>
<td>Carmel Fm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Winsor Mbr</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Paria River Mbr</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crystal Creek Mbr</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Co-op Creek Mbr</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Navajo Sandstone (main body)</td>
<td>2000</td>
<td></td>
</tr>
</tbody>
</table>

Fresh water unit. Consists of mostly fluvial and lacustrine conglomerate, sandstone and limestone.

Largely terrigenous rocks derived from the Sevier Orogenic Belt. Deposited along a coastal plane where coal-bearing non-marine sandstone and conglomerate interfinger with marine shale of mid-continental seaway.

Represent two distinct paleoenvironments (1) sandy desert - Navajo Sandstone and (2) shallow marine invasion - Carmel Formation.

Figure 9. This stratigraphic column represents mapped units. Standard symbols are used for rock types; wavy bands are used for volcanic flows, black ovals are used for coal, triangles are used for gypsum, and open angles with lines represent cross beds. Data from Gregory (1951), Cashion (1967), Hintze (1973), Rowley et al. (1975), Geesaman and Voorhees (1980), Hintze (1988), Marzolf (1988), Stokes (1988), Doelling et al. (1989), and Goldstrand (1994).
Figure 10. The diagram is a simplified geologic map of the study area. Geographic locations and sample collection sites are indicated. The heavy weight lines are faults. The Virgin River is shown by a lighter weight line.
Figure 11. The above diagram shows the isochron plots for the Black Rock Canyon basalt and Black Mountain basalt. Nine steps for each sample (shown by ellipses indicating uncertainty) were used to determine the isochron age. The Black Rock Canyon basalt is shown in black and the Black Mountain basalt is shown in gray.
Figure 12A. This diagram represents the fault traces in the Sevier fault zone. The ball and bar symbols are on the hanging wall. The labeled cross sections, fault domains, sets, and strands are discussed in the text. The main strand is colored gray. The light gray dashed lines are where the displacement vs. distance diagrams were constructed.
Figure 12B. This diagram represents the fault traces in the Stewart Canyon and Orderville areas. The ball and bar symbols are on the hanging wall. The labeled cross sections, fault domains, sets, and strands are discussed in the text. The main strand is colored gray.
Figure 25. The geologic map of the central portion of the study area shows both the Dry Wash Landslide and the landslides along the Glendale Bench Road. Notice that the landslides occur in the Cretaceous Tropic (Kt) and Dakota (Kd) Formations.
Figure 13. The fence diagram shows the fault parallel syncline within the Orderville relay ramp. Notice that the strata outside the relay ramp are nearly flat lying. Also, notice to the south, the area along N-N' between the faults at the surface and at depth decreases as the space decreases. The heavy weight lines represent normal faults. The white represents bedding planes within the syncline with light weight lines representing structure contours. The stratigraphy and stratigraphic symbols are described on Plate 3. Cross sections on Plate 4 were used to constrain the shape of the syncline. The unlabeled vertical lines are tie lines. However, several cross sections were removed to show the syncline shape.
Figure 14. These beta plots show the attitudes of bedding within two relay ramps and fold axes orientations. A shows beds and the synclinal axis orientation within the Orderville relay ramp. B shows the attitude of beds and anticlinal axis within the Glendale relay ramp.
Figure 15. This diagram is a Quaternary geologic map of the central Sevier fault. The faults are in the heavy-weight solid, dashed, and dotted lines indicating a certain location, an approximate location, and a buried fault respectively. The Virgin River is shown with a heavy gray solid line.
Figure 16. The fence diagram shows the fault parallel anticline within the Glendale relay ramp. Notice that the strata outside the relay ramp is nearly flat lying. However, the strata within the ramp form a fault parallel anticline. The faults appear to connect at depth hence there is a decrease in space within the relay ramp. Notice within the ramp there are cross faults which cut through the relay ramp. The heavy weight lines represent normal faults. The white represents the bedding planes showing the anticline with the light lines representing structure contours. The stratigraphy and stratigraphic symbols are described on Plate 3. Cross sections on Plate 4 were used to constrain the shape of the anticline. The unnamed vertical lines represent tie lines. Several cross sections were removed to show the anticline shape.
Figure 17. Photo A shows the younger conglomerate (Qcg). Notice the variation in size and composition of the clasts. In the lower left corner is a sandbar. Photo taken facing north. Rockhammer for scale. The outcrop faces south. Photo B is the older conglomerate (Qcg1). This unit is overall finer grained. Notice the large basalt clasts. Person (Robert Kerscher) for scale is 1.75 meters (5'9") tall.
Figure 18. Photo A is a roadcut along U.S. 89 of the Cretaceous Dakota Sandstone unconformably overlain by the younger conglomerate. The black unit in the left of the photo is one of the coal seams in the Dakota Sandstone. The photo was taken facing west. Photo B is a sandbar within the young conglomerate. This photo was taken facing north.
Figure 19. This diagram shows the displacement vs. distance profiles (A - D) for each major fault. The vertical scale differs among the plots. A is the easternmost fault, is the westernmost fault, and (E) the central Sevier fault as a whole. Displacement was plotted along even increments of distance for each fault. Distance was measured along the fault.
Figure 20. The diagram shows the displacement vs. distance profiles along potential linkage zones in the Sevier fault. A is near the Orderville relay ramp. B is the Glendale relay ramp. C shows the Stewart Canyon relay ramp area. D is the Elkheart Cliffs relay ramp. The relay ramps are located in the center of the diagrams. The displacement is the total stratigraphic offset of the bounding faults.
Figure 21. These diagrams show the evolution of a fault bounded panel of rocks with the formation of a fault-parallel syncline within the relay ramp. The faults are the heavy weighted lines and the relay ramp is labeled.
Figure 22. This diagram shows the stages of linkage for the central Sevier fault. A is the oldest and E is the modern fault trace map. Boxes B - D could be in any order. There are no timing constraints of which linkage happened first, second, or third. The black lines represent faults. The gray lines in the last diagram represent the main strand. The fold symbols show the approximate timing of folding within the relay ramps.
Figure 23. The fault trace map of the Stewart Canyon overlap zone shows the stages of development. Diagrams A - E are in chronological order with A representing the youngest time and E representing the oldest time. The gray lines represent the faults with relatively unconstrained timing and the black lines indicate faults with moderate to well constrained timing.
Figure 24. This diagram shows the different types of landslides. The landslides found in the study are rockfall and rotational slump types. From Varnes (1958) and Rahn (1996).
Figure 25. The geologic map of the central portion of the study area shows both the Dry Wash Landslide and the landslides along the Glendale Bench Road. Notice that the landslides occur in the Cretaceous Tropic (Kt) and Dakota (Kd) Formations.
Figure 26. Photo A shows the Glendale Bench Road landslide. Notice remediation techniques used to stabilize the landslide. This photo is facing northeast. Photo B is a view of the Dry Wash Landslide. This landslide has a steep and arcuate shape scarp. The photo is facing northeast.
Figure 27. A = Young pine tree incorporated into the Dry Wash Landslide. The pine tree survived the landslide and is now growing at an oblique angle to its original growth path. Most of the landslide has little to no new growth. Photo is facing north-northeast. B = New growth on the Dry Wash Landslide. The dark green bushes are manzanita. The steep slope in the background is the head scarp of the landslide. The gray to black layers near the skyline are coal seams. The photo is facing southeast. The person (Robert Kerscher) is 1.75 m (5'9") tall.
Figure 28. A = Sparse and immature vegetation on the landslide (in the foreground). Along the skyline the vegetation is denser and more mature. Photo A is facing southeast. B = The dead vegetation incorporated within the landslide has no foliage and is highly decayed. Photo B is facing south-southeast. The person (Robert Kerscher) is 5'9" (1.75 m) tall.
Figure 29. A = Wood from a tree incorporated into the landslide. Rock hammer for scale. B = The scarp and scarp graben of the Dry Wash Landslide. The scarp graben is the topographically lower area with the large trees. These trees were once at the same elevation as the trees on the skyline. The photo faces southeast.
Figure 30. The Dry Wash Landslide is rerouting streams. Person (Robert Kerscher) is standing in one of the rerouted streams. Robert is 1.75 m (5'9") tall. The steep slope behind him is the toe of the landslide.
Figure 31. These cross sectional models show hydrocarbon accumulation within relay ramps in extensional linkage zones. A=classic relay ramp. B=fault parallel anticline within the ramp. C=fault parallel syncline within the ramp. D=breakthrough faults within the ramp. The large filled shapes are potential hydrocarbon accumulation positions within the relay ramp.
Figure 32. This map of southwestern Utah shows the oil fields in the region and the exploration holes along the Sevier fault. The solid circles represent communities. The open circles represent dry exploration holes. The half filled circles represent exploration holes that have shows of oil and/or gas. The gray filled shapes represent the oil fields in the region. Data are from Doelling et al. (1989).
REFERENCES


Faulds, J.E. and Varga, R.J., 1998, The role of accommodation zones and transfer zones
in the regional segmentation of extended terranes: Geological Society of America

implications for growth and seismicity of active normal faults: Journal of
Structural Geology, v. 21, p. 1,027-1,038.

Ferrill, D.A. and Morris, A.P., 2001, Displacement gradient and deformation in normal

Gibbs, A.D., 1983, Balanced cross-section construction from seismic sections in areas of

Goldstrand, P.M., 1994, Tectonic development of Upper Cretaceous to Eocene strata of

Gregory, H.E., 1951, The geology and geography of the Paunsaugunt region Utah:

Gupta, A. and Scholz, C.H., 2000, A model of normal fault interaction based on

Harris, J.E., 1994, Anderson Junction oil field, Washington County, Utah in Schalla, R.A.

Harty, K.M., 1992, Landslide distribution and hazards in southwestern Utah, in Harty,
K.M., ed., Engineering and Environmental Geology of Southwestern Utah: Utah

Hecker, S., 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard

Hintze, L.F., 1973, Geologic History of Utah: Brigham Young University Geology
Studies 20, 181 p.

Hintze, L.F., 1988, Geologic History of Utah: Brigham Young University Geology

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.


Marzolf, J.E., 1988, Reconstruction of Late Triassic and Early and Middle Jurassic sedimentary basis: Southwestern Colorado Plateau to the Eastern Mojave Desert, in Weide, D. and Faber, M.L. eds., This extended land: Geological Journeys in the Southern Basin and Range: Field Trip Guidebook: Geological Society of America Cordilleran Section Meeting, UNLV Department of Geoscience Special Publication 2, p. 177-200.


VITA

Graduate College
University of Nevada, Las Vegas

Ilisa M. Schiefelbein

Address:
UNLV Department of Geoscience
4505 Maryland Pkwy Box 454010
Las Vegas, Nevada 89154-4010

Degrees:
Bachelor of Science, Geology, 1998
University of Wisconsin - Milwaukee

Special Honors and Awards:
AAPG Research Grant, GSA Research Grant, Sigma Xi Research Grant, Arizona/Nevada Academy of Science Research Grant, UNLV Graduate Student Association Research Grant, UWM Travel Grant to the GSA Cordilleran Section Meeting, Two GSA Cordilleran Section Student Travel Grants, UWM Athletic Scholarship, Indiana University Field Camp Scholarship, UWM Field Camp Scholarship, ARCO Undergraduate Research and Travel Grant, Elk's Club Outstanding Student Scholarship, Jefferson School Parent/Teacher Outstanding Student Scholarship, UNLV Geoscience Dept. Scholarship, UNLV Graduate College Summer Session Scholarship, Two GSA Engineering Geology Division Shlemon Awards

Publications:


Thesis Title: Fault Segmentation, Linkage, and Earthquake Hazards Along the Sevier Fault, Southwestern Utah

Thesis Examination Committee:
Chairperson, Dr. Wanda J. Taylor, Ph.D.
Committee Member, Dr. Eugene I. Smith, Ph.D.
Committee Member, Dr. Terry Spell, Ph.D.
Graduate Faculty Representative, Dr. Barbara Luke, Ph.D.
NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

UMI
Plate 1 - Geologic I
Map of the Northern...
Section of Long Valle
a Schiefelbein
2002
ey, Southwestern Utah
Area of overlap
Kilometers
0 0.5 1

Miles
0 0.5 1

Scale = 1:12,000

Map with Plate 2 is below dashed black line.
NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

UMI
Plate 2 - Geologic M
Map of the Southern Section

Ilse Sch...
Section of Long Valley, Schiebelbein
2002
Area of overlap with Plate 1 is above diagram.
Stern Utah

Overlap with Plate 1 is above dashed black line.
Scale = 1:12,000
NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

UMI
Surficial Deposits

Quaternary Landfill
Kane County Landfill. Actively used.

Quaternary Alluvium
Weakly indurated to nonindurated deposits in active washes and floodplains. Deposit types vary from sandstone (yellow, pinkish orange, white), limestone (yellowish gray to gray, pink), and silt (brown) to sand, gravel, and developed soils. Clast (within the deposit) sizes range from silt to boulder and shapes vary from rounded to angular. Much of this unit is occupied by humans or actively cultivated. The contacts are sharp. Thickness of beds or unit is unknown.

Quaternary Alluvium Second
Weakly indurated to nonindurated deposits in active washes and floodplains. Deposit is a developed soil with active washes. The parent material is basalt. Clast (within the deposit) size range from silt to pebble and shape is well-rounded. The pebbles are derived from the basal Tertiary Claron Formations. Much of this unit is occupied by humans or actively cultivated. The contacts are sharp. Thickness of beds or unit is unknown.

Quaternary Landslide
Includes all slope failures. Size ranges from 228.6 - 243.8 m (750 - 800 ft) in diameter. Associated with steep slopes or weakly indurated units. Internal blocks range from silt size to greater than 1 m (3 ft). Clasts are generally rotated, and trees and bushes are uprooted creating hummocky topography. Classified as a rotational slump.

Quaternary Colluvium 1
Quartz sand. Color is pink to white. Grain size is medium to fine. Unconsolidated. Eroded from adjacent Navajo Sandstone cliffs.

Quaternary Colluvium 2
Unconsolidated clasts of platy limestone. Color is gray to pale yellow on both the fresh and weathered surfaces. Clasts are 5 - 10 cm (2 - 4 in) wide and ~ 2 cm (~0.75 in) thick. Angular to rounded.
Descriptions of Map Units

Cretaceous Kaiparowits/Wahweap Formations Undivided
The unit consists of alternating sandstone, mudstone, siltstone, and conglomerate. Color is pale yellow to white on both the fresh and weathered surface. Thickness varies from 1.27 cm (0.5 - 3 ft) thick. Also contains ripple marks. The siltstone to conglomerate layers are 0.2 - 0.9 m (0.5 - 3 ft) thick. Layers are discontinuous. Generally clast supported. Clasts are very well-rounded and dominantly a cliff forming unit. However, some of the mudstones are exposures. Total thickness = 457 m (1500 ft).

Cretaceous Straight Cliffs Formation
The upper rock type in the unit is a lithic sandstone. Colors are pale drab yellow on the weathered surface. Coarse to medium grained sandstone as shrimp burrows, cephalopods, pelecypods, oysters, and shark (and) iron concretions. Upper contact is sharp. Forms steep cliffs. Rock layers of the lower unit are siltstone interbedded with coal. The siltstone is drab weathered surfaces with dark gray to black coal beds. The coal bed is ~30.5 cm (1 ft) thick. The lower contact is gradational. Poorly lithified. Total thickness = 73.2 m (240 ft).

Cretaceous Tropic Shale
Mudstone, siltstone, and sandstone. The top unit is sandstone. Colors are pale weathered surfaces. Grain size is medium to fine. The lower part of mudstone and siltstone. Olive gray to drab green on both fresh and coarsens upward. The upper and lower contacts are gradational. Poorly exposed. A 0.5 m (1.5 ft) thick bed of septarian nodules in a yellow nodules range from 10.2 - 30.5 cm (4 - 12 in) in diameter and the other. Some of the nodules are fractured. The interior contains yellow calcite. Size. The formation is poorly lithified and weathers to form slopes. Total thickness = 305 m (760 ft).

Cretaceous Dakota Sandstone
Limestone, mudstone, and shale. The upper part of the unit is lime weathered surfaces. Abundant oysters. The upper bed is sharp. Generally forms float covered surfaces. The lower part of the formation is poorly exposed. A mudstone over both fresh and weathered surfaces. Contains two dikes.
Plate 3

Siltstone, and conglomerate. Sandstone and fresh and weathered surfaces. Calcite air, and clay. Cross beds are low angle and 5.1 siltstone to mudstone is pink to purple in varies from 0.9 - 3.7 m (3 - 12 ft) thick. Also are conglomerate layers and lenses. The lenses are discontinuous and commonly form rounded and 1.3 - 2.5 cm (0.5 - 1 in) in diameter and dolostone. Contacts are sharp. Mudstones and siltstones weather to a slope.

Lithology. Color is yellowish gray both fresh and m grained. Contains low angle cross-beds as, and shark teeth. Contains 2.5 - 5.1 cm (1 - 2 cm) of cliffs. Rock types of the poorly exposed one is drab gray on both fresh and the coal beds are splintery, thinly bedded, and poorly lithified and weathers to form a slope.

Unit is limestone. Yellowish green to gray on the upper and lower contacts of the oyster lower part is shale to mudstone. Color is two discontinuous coal beds. The coal is yellow calcite crystals up to 1.3 cm (0.5 in) in m slopes and valleys. Total thickness = 231.7 m.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Legend

--- --- --- --- --- --- ---
Lithologic contact. Dashed where approximate, where concealed.

--- --- --- --- --- ?
Fault contact. Dashed where approximately line concealed. ? where the fault existence is uncertain in the hangingwall.

70
Strike and dip of bedding.

A. 20  B. 35
A = Anticline showing trace of axial surface and p
Syncline showing trace of axial surface and p

Age Correlation of Map Units

Surficial Deposits

Qlf Qa Qls Qc1 Qc2 Qas Holocene

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
**Legend**

- - - - - Lithologic contact. Dashed where approximately located. Dotted where concealed.

- - - - ? Fault contact. Dashed where approximately located. Dotted where concealed. ? where the fault existence is uncertain. Ball and bar are on the hangingwall.

Strike and dip of bedding.

A = Anticline showing trace of axial surface and plunge of axis. B = Syncline showing trace of axial surface and plunge of axis.

---

**Age Correlation of Map Units**

Deposits

Qcl  Qc2  Qas  Holocene

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
**Quaternary Colluvium 2**
Unconsolidated clasts of platy limestone. Color is gray to pale yellow on both the fresh and weathered surfaces. Clasts are 5 - 10 cm (2 - 4 in) wide and ~2 cm (~0.75 in) thick. Angular to subangular. Transport direction is downslope movement. Source is the nearby Co-op Creek Member of the Carmel Formation.

**Long Valley Quaternary Spring Deposit**
Spring deposit, tan to brown on both fresh and weathered surfaces. Fine grained. Cemented with silica and locally small amounts of carbonate. Millimeter to centimeter nearly planar beds of silica possibly opaline. Weathers to a resistant high. Associated with springs. Based on field observations is classified as thin-bedded opaline sinter facies (Jarvis et al., 1998; Campbell et al., 2001; Braunstein and Lowe, 2001). Total thickness 12.2 m (0 - 40 ft).

**Young Quaternary Conglomerate**
Clast supported conglomerate. Framework is composed of poorly sorted consolidated conglomerate and sandstone. Clast lithologies include limestone (yellow, gray, pink), sandstone (yellow to gray), basalt (dark gray to brown), and petrified wood (light to dark brown and black). Clasts are rounded to angular. Size of clasts ranges from sand to greater than 1.5 m (5 ft). Contains 30.5 cm (1 ft) thick layers of medium to coarse-grained lithic sandstone. Color is tan on weathered surfaces and light tan to yellow on fresh surfaces. Sandstone locally contains low-angle crossbeds. Upper and lower contacts are sharp. Weathers to rubbly slope or cliff former. Total thickness 9 m (3 - 30 ft).

**Old Quaternary Conglomerate**
Clast supported conglomerate. Framework is composed of poorly sorted consolidated sand and gravel. Clast lithologies include limestone (yellow, gray, pink), sandstone (yellow to gray), and basalt (dark gray to brown). Clasts are rounded to angular. Size of clasts ranges from sand to ~0.5 m (~1.5 ft). Contains 30.5 cm (1 ft) thick layers of medium to coarse-grained lithic sandstone. Color is tan on weathered surfaces and light tan to yellow on fresh surfaces. Locally contains low-angle crossbeds. Upper and lower contacts are sharp. Weathers to rubbly slope or cliff former. Outcrops topographically higher than Qcg. Total thickness is ~12 m (~40 ft).

**Bedrock**

**Quaternary Basalt**
Basalt, brown to black on weathered surfaces and dark gray on fresh surfaces. Fine crystalline. Phenocrysts of olivine ~5 mm (0.125 in), plagioclase ~2.5 mm (0.0625 in), and pyroxene. Vesiculated in the bottom 0.9 - 1.8 m (3 - 6 ft), dense middle 4.6 - 13.7 m (15 - 45 ft), and vesicular top 0.9 - 1.8 m (3 - 6 ft). Weathers to a resistant cap unconformably overlying Quaternary, Tertiary, and Cretaceous rocks. Unit thickness is 6.1 - 18.3 m (20 - 60 ft).

**Tertiary Claron Formation**
Limestone, conglomerate, and sandstone to siltstone. Subdivided into two members - upper...
Cretaceous Dakota Sandstone
Limestone, mudstone, and shale. The upper part of the unit is limed both fresh and weathered surfaces. Abundant oysters. The upper \textit{bed} is sharp. Generally forms float covered surfaces. The lower part is olive gray on both fresh and weathered surfaces. Contains two dark gray to black on both fresh and weathered surfaces, splinters contain selenite gypsum. Gypsum crystals occur in 2.5 - 5.1 cm (1 - 2 in) length. The unit is generally poorly sorted, forms valleys. The lower contact is sharp and the upper contact is m (320 ft).

Jurassic Carmel Formation - Winsor Member
Conglomerate, silty fine-grained sandstone, and siltstone. The upper \textit{part} is pale yellow on both fresh and weathered surfaces. Generally massive sand. Clasts are well-rounded, gravel size, and composed of chert, fine-grained, yellow to white sandstone with well-rounded grains of alternating beds of silty fine-grained sandstone and siltstone. Brown. Beds are \textit{~0.9 m} (~3 ft) thick. Upper and lower unit contacts weathers to a slope or forms valleys. Total thickness = \textit{85.3 m} (280 ft).

Jurassic Carmel Formation - Paria River Member
Limestone, gypsum, shale, and siltstone. The upper unit is fine-grained surface and very light gray fresh surface. Abundant pelecypods. Poorly exposed. Lower unit has three alabaster gypsum layers sedimentation. The gypsum is dirty white on the weathered surface and fresh surface. Has a sugary texture. Weathers to blocky ledges. Es shale and siltstone are greenish gray and reddish brown on both surfaces. The bedding layers vary in thickness from 2.5 - 7.6 cm (1 - 3 in). Contacts between thick are sharp. Upper and lower contacts are gradational. Weathers to slope or forms valleys. Total thickness = \textit{73.2 m} (240 ft).

Jurassic Carmel Formation - Crystal Creek Member
Fine-grained siltstone, sandy shale to sandstone, and limestone. The upper unit is siltstone with sandy shale to sandstone interbeds. Colors range from gray both fresh and weathered surfaces. Weakly indurated. Abundant stringers. Forms valleys and slopes. Upper and lower contacts are gradational. Weathers to slope or forms valleys. Total thickness = \textit{51.8 m} (170 ft).

Jurassic Carmel Formation - Co-op Creek Member
Sandy siltstone to siltstone and limestone. The upper unit is lime and form small cliffs. The basal 1.8 m (6 ft) are a sandy siltstone to red on both fresh and weathered surfaces. The bedding layer is thick. Forms slopes. Under the upper limestone is a fine grained yellow on both fresh and weathered surfaces. The limestone is of reddish siltstone. Lower limestone layers are platy with calcite between. The bedding thickness is \textit{~2.5 cm} (~1 in). Upper contact is sharp. Pentacrinites, bryozoans, and oysters are common. Weather thickness = \textit{121.9 m} (400 ft).
unit is limestone. Yellowish green to gray on
the upper and lower contacts of the oyster
the lower part is shale to mudstone. Color is
contains two discontinuous coal beds. The coal is
r. splintery, thinly bedded, and typically
5 - 5.1 cm (1 - 2 in) beds. The crystals range in
eral poorly lithified, weathers to a slope, and
or contact is gradational. Total thickness = 97.5

unit is a conglomerate layer.
erarchy matrix supported. Matrix is clay to fine
ed of chert and quartzite. The middle unit is a
eded grains. The lower unit rock types consist
siltstone. Colors range from brick red to
unit contacts are gradational. Member
35.3 m (280 ft).

unit is fine-grained limestone. Gray weathered
eyecods. Forms a resistant ledge. Unit is
layers separated by layers of shale and
urface and white to locally motteled on the
ledges. Each layer is ~0.9 m (~3 ft) thick. The
on both fresh and weathered surfaces. Beds
the gypsum, shale and siltstone are
ers to slopes and rounded hills. Total

umber
estone. The upper unit is a alternating
ers range from red, brown, yellow, and greenish
ed. Abundant gypsum talus and light gray
cts are gradational. The bottom of unit is
ellow on weathered surfaces and pale yellow
= 51.8 m (170 ft).

umber
unit is limestone. Beds are 0.9 m (3 ft) thick
siltstone to siltstone. Colors are grayish green
ling layers vary from 2.5 - 91.4 cm (1 - 36 in)
grained limestone. Color is pale yellow to
stone is divided by a 10.2 cm (4 in) thick layer
ith calcite layers 1.3 cm (0.5 in) thick
pper contact is gradational and lower contact
athers to a platy talus slope. Total

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Bedrock

**Quaternary Basalt**
Basalt, brown to black on weathered surfaces and dark gray on fresh surfaces. Fine crystalline phenocrysts of olivine ~5 mm (0.125 in), plagioclase ~2.5 mm (0.0625 in), and pyroxene. Vesiculated bottom 0.9 - 1.8 m (3 - 6 ft), dense middle 4.6 - 13.7 m (15 - 45 ft), and vesicular top 0.9 - 1.8 m (3 - 6 ft). Weathers to a resistant cap unconformably overlying Quaternary, Tertiary, and Cretaceous rocks. Unit thickness is 6.1 - 18.3 m (20 - 60 ft).

**Tertiary Claron Formation**
Limestone, conglomerate, and sandstone to siltstone. Subdivided into two members - upper and lower pink. The white member is a thick to medium bedded fresh water limestone. Gray on weathered surfaces and chalky white on fresh surfaces. Contacts are sharp. Caverns (2.5 - 7.6 cm (1 - 3 in) in diameter) filled with calcite. Thickness is 91.4 m (300 ft). The upper pink unit is a sandy limestone. Pink to red on weathered surface and light pink on fresh surface. The lower part of the unit contains scattered pebbles of Precambrian to Paleozoic quartzite, chert, limestone, dolostone. Pebbles are very well-rounded. The lower member is fluvi-lacustrine in origin (Hintze, 1988; Doelling et al., 1989). Contacts are sharp. Thickness is 152.4 m (500 ft). Unit weathers to hoodoos, steep cliffs, or steep slopes. Total thickness = 243.8 m (800 ft).
Jurassic Carmel Formation - Co-op Creek Member
Sandy siltstone to siltstone and limestone. The upper unit is limy and forms small cliffs. The basal 13 m (40 ft) are a sandy siltstone and red on both fresh and weathered surfaces. The bedding is sharp. Pentacrinus, bryozoans, and oysters are common. Weathering forms small cliffs. Forms cliffs. Total thickness = 121.9 m (400 ft).

Jurassic Navajo Sandstone
Well-rounded, well-sorted, fine-grained, friable quartz sandstone, and/or calcite. Red, orange, tan, to white on both fresh and weathered surfaces. The bedding thickness ranges from 0.9 - 9.1 m (3 - 30 ft). Upper and lower units are sharp. Forms cliffs. Total thickness = 609.6 m (2000 ft).

Jurassic Purple Butte Formation
Light pink on both fresh and weathered surfaces. The limestone is sharp. Contains 1.3 - 2.5 cm (0.5 - 1 in) red to orange oxidation spots on fresh surfaces. Weathering forms small cliffs. Forms cliffs. Total thickness = 254.5 m (836 ft).

Jurassic Navajo Sandstone
Well-rounded, well-sorted, fine-grained, friable quartz sandstone, and/or calcite. Red, orange, tan, to white on both fresh and weathered surfaces. The bedding thickness ranges from 0.9 - 9.1 m (3 - 30 ft). Upper and lower units are sharp. Pentacrinus, bryozoans, and oysters are common. Weathering forms small cliffs. Forms cliffs. Total thickness = 609.6 m (2000 ft).

Jurassic Carmel Formation - Co-op Creek Member
Sandy siltstone to siltstone and limestone. The upper unit is limy and forms small cliffs. The basal 13 m (40 ft) are a sandy siltstone and red on both fresh and weathered surfaces. The bedding is sharp. Pentacrinus, bryozoans, and oysters are common. Weathering forms small cliffs. Forms cliffs. Total thickness = 121.9 m (400 ft).

Jurassic Navajo Sandstone
Well-rounded, well-sorted, fine-grained, friable quartz sandstone, and/or calcite. Red, orange, tan, to white on both fresh and weathered surfaces. The bedding thickness ranges from 0.9 - 9.1 m (3 - 30 ft). Upper and lower units are sharp. Pentacrinus, bryozoans, and oysters are common. Weathering forms small cliffs. Forms cliffs. Total thickness = 609.6 m (2000 ft).

Jurassic Purple Butte Formation
Light pink on both fresh and weathered surfaces. The limestone is sharp. Contains 1.3 - 2.5 cm (0.5 - 1 in) red to orange oxidation spots on fresh surfaces. Weathering forms small cliffs. Forms cliffs. Total thickness = 254.5 m (836 ft).
Kontacts are gradational. The bottom of unit is yellow on weathered surfaces and pale yellow. Is s = 51.8 m (170 ft).

r unit is limestone. Beds are 0.9 m (3 ft) thick y siltstone to siltstone. Colors are grayish green edding layers vary from 2.5 - 91.4 cm (1 - 36 in) ine grained limestone. Color is pale yellow to nestone is divided by a 10.2 cm (4 in) thick layer with calcite layers 1.3 cm (0.5 in) thick pper contact is gradational and lower contact mon. Weathers to a platy talus slope. Total

sandstone cemented with hematite, silica, h and weathered surfaces. Cross-bedded. Upper and lower unit contacts are sharp. on spots on both fresh and weathered surfaces.
Jurassic

Triassic - Jurassic
NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS
Plate 4a

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
a - Cross Sections
s for Mapped Area

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

UMI
Plate 4b - Cross
Mapped Area