NEOTECTONIC ASSESSMENT OF THE SOUTHERN WASSUK RANGE,
WESTERN NEVADA

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Master of Science

By
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presented by Julie Heins,
a candidate for the degree of Master of Science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ iii

TABLE OF CONTENTS ........................................................................................................ iv

LIST OF FIGURES ................................................................................................................ vi

ABSTRACT ........................................................................................................................... viii

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

CHAPTER 2: GEOLOGIC SETTING ....................................................................................... 8
  2.1 Regional Context .......................................................................................................... 8
  2.2 Tectonic Evolution ....................................................................................................... 9
  2.3 Stratigraphic History ................................................................................................... 12
  2.4 Neotectonic Activity .................................................................................................. 13

CHAPTER 3: NEOTECTONIC GEOMORPHOLOGY .............................................................. 22
  3.1 Overview and Basic Idea ............................................................................................ 22
  Initial and Modified Scarp Conditions ............................................................................. 23
  Degradation via the Diffusion Equation ......................................................................... 24
  3.2 Data Acquisition: sUAV Photogrammetry and LiDAR ............................................ 25
    sUAV Photogrammetry Data ........................................................................................ 25
    LiDAR Data .................................................................................................................. 26
  3.3 Scarp Profiling and Diffusivity Calibration ................................................................ 26
    Scarp Profiling .............................................................................................................. 26
    Diffusivity Calibration .................................................................................................. 27
  3.4 Results ......................................................................................................................... 28
    Single-Event Fault Scarp Profiles ................................................................................ 28
    Multi-Event Fault Scarp Profiles .................................................................................. 29

CHAPTER 4: SHALLOW GEOPHYSICS .............................................................................. 47
  4.1 Overview and Basic Idea ............................................................................................ 47
  4.2 Seismic Refraction ....................................................................................................... 48
    Data Processing ............................................................................................................ 49
  4.3 Fan-Shots: Fault-Zone Guided Waves ....................................................................... 50
    Data Processing ............................................................................................................ 51
  4.4 Results ......................................................................................................................... 51

CHAPTER 5: DISCUSSION AND CONCLUSIONS .............................................................. 59
  Conclusions ...................................................................................................................... 62
LIST OF FIGURES

Figure 1-1: Western U.S. tectonic map and elevation map of the Wassuk Range ........ 5
Figure 1-2: Fault scarp of the Wassuk Range-front .................................................. 6
Figure 1-3: Schematic diagram of proposed models ..................................................... 7
Figure 2-1: Structural map of the WRFZ .................................................................. 15
Figure 2-2: Velocity domains of the central Walker Lane ........................................... 16
Figure 2-3: Displacement field of the Wassuk Range fault zone ............................... 17
Figure 2-4: Geologic map with tilting domains of the southern Wassuk Range ........ 18
Figure 2-5: Late Mesozoic-Cenozoic geology of the Wassuk Range ....................... 19
Figure 2-6: Quaternary surficial deposits of Whiskey Flat ................................. 20
Figure 3-1: Fault-scarp anatomy ............................................................................... 31
Figure 3-2: Whiskey Flat study site ......................................................................... 32
Figure 3-3: sUAV photo frames over 3D surface example ......................................... 33
Figure 3-4: Schematic fault-scarp profile ................................................................. 34
Figure 3-5: Degradation and aggradation profiles .................................................... 35
Figure 3-6: Maximum displacement vs. moment magnitude ..................................... 36
Figure 3-6: Relationship of throw vs. $\kappa t$ .............................................................. 37
Figure 3-8: Whiskey Flat canyons with profile line locations .................................... 38
Figure 3-9: North Canyon profile with known age ................................................. 43
Figure 3-10: Radiocarbon determination vs. calibrated date ..................................... 44
Figure 3-11: Single-event fault-scarp profiles ......................................................... 45
Figure 3-12: Multi-event fault-scarp profiles ............................................................ 46
Figure 4-1: Geophysical survey location ................................................................. 53
Figure 4-2: Refraction survey design .................................................................. 54
Figure 4-3: P-wave refraction tomography model .................................................. 55
Figure 4-4: Fan-shot amplitude plots ................................................................. 56
Figure 4-5: Maximum amplitude plot ................................................................. 57
Figure 4-6: Schematic cross section interpretation .................................................. 58
Figure 5-1: Range-bounding normal faults west of WRFZ ........................................ 65

Figure 5-2: Geodetic shear map of the southern Wassuk Range ................................. 66
NEOTECTONIC ASSESSMENT OF THE SOUTHERN WASSUK RANGE, WESTERN NEVADA

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Abstract

Active deformation across western North America is distributed across a broad zone spanning from the San Andreas fault system to the Basin and Range Province. The Wassuk Range fault zone (WRFZ), located within the Walker Lane deformation belt of the western Basin and Range, is a N- to NNW-striking normal fault system. With its oblique orientation to the wide-scale, NW-trending shear between Pacific and North American plates, it demonstrates a transtensional regime. The Whiskey Flat study area (southern WRFZ) corresponds with east-dipping, late Quaternary fault scarps (~1-7 meters) along the range front. Seismic and photogrammetric methods were used to examine underlying geometry and fault scarp morphology. Through these imaging techniques, fault scarp degradation modeling assessed the kinematic evolution and long-term slip rate of ~0.10-0.36 mm/yr, accommodating 0.49-1.4 mm/yr of E-W extension. Significantly, this extension rate is slightly faster than northern and central segments of the Wassuk Range. Holocene earthquakes are estimated to have occurred between 687 and 3774 years ago with magnitudes that range from 6.9 to 7.1. In addition, seismic refraction imaging reveals a potential asymmetric half-graben formation, supporting the idea of a dominant normal fault system that aligns with the broad, NW-trending, right-lateral shear of the Walker Lane and associating plate boundaries. This study demonstrates how structural evolution, neotectonic activity, and future deformation can be gleaned from seismic imaging techniques and numerical models of landscape morphology.
Chapter 1: Introduction

Active deformation across western North America is distributed across a broad zone spanning from the San Andreas fault system to the Basin and Range Province. Neotectonic features, particularly in the western Basin and Range (e.g., the Walker Lane deformation zone), are key to estimate rates of deformation. The Walker Lane, a large (500-km-long by 100-km-wide), NW-striking dextral fault zone, is bounded by extending crust of the Basin and Range in the east and uplift of the Sierra Nevada mountains in the west (Figure 1-1A). Within this context, the Wassuk Range fault zone (WRFZ) lies in the center, bounded by a NNW-striking and east-dipping normal fault system that traces about 80 km near the California-Nevada border. Northern and central segments of the WRFZ have been previously studied within a neotectonic context (e.g., Wesnousky, 2005; Bormann et al., 2012; Surpless and Kroeger, 2014) that focus on slip rate constraints. This study, however, focuses on the southern segment (around Whiskey Flat area), a region in which transtensional strain may be accommodated. Using landscape elements (e.g., scarp morphology, fault geometry), the southern Wassuk Range is key to assessing kinematic models of the WRFZ as well as within the Walker Lane and western Basin and Range.

Geologically recent (e.g., Neogene-Quaternary) vertical and horizontal crustal movements have produced neotectonic features such as fault scarps, which can provide useful geomorphic markers for quantifying the recent deformation. The southern Wassuk Range contains fault scarps that cut through alluvium and demonstrate vertical offsets of approximately 1 to 7 meters (as seen at Canyon A in Figure 1-2). Furthermore, these scarps can be evidence for prehistoric surface-faulting earthquakes through
morphological analyses (Hanks et al., 1984). The intent of this project is to establish the geometry and kinematics of faults within the Whiskey Flat area (i.e., fault dip and deformation rates), the history and recurrence of fault displacements (i.e., earthquake magnitudes and recurrence intervals) along individual faults and in the province as a whole, and the patterns of migration of seismic and tectonic activity (i.e., progression or regression of earthquake activity and deformation rates). In addition, variations of deformation rates and earthquake activity are spatially and temporally correlated to surrounding fault segments for a comprehensive analysis.

Previously proposed hypotheses based on corresponding kinematic models can be tested for the southern Wassuk Range and its role within the WRFZ, Walker Lane, and western Basin and Range. These models and testable predictions for the Whiskey Flat area include:

(1) Distributed right-lateral shear (<1.5 mm/yr) is proposed throughout the central Walker Lane (Bormann et al., 2016). Thus, dextral deformation is likely accommodated along the WRFZ. This model predicts that a clockwise component of vertical-axis rotation of the footwall (southern Wassuk Range) is accommodating dextral deformation (*Figure 1-3A*).

(2) The NNW-striking WRFZ is not directly perpendicular to the E-W direction of maximum extension (Bormann et al., 2010; Surpless and Kroeger, 2014). Thus, this model predicts that a right-lateral component of strike-slip faulting is either accommodated along the fault plane (oblique normal fault) or partitioned between the normal range-bounding fault system and NW-striking dextral faults to the east (*Figure 1-3B*).
(3) NE-striking sinistral faults are inferred to act as transfer zones separating segments of the WRFZ (Wesnousky, 2005; Pierce et al., 2021; Surpless and Thorne, 2021). Varying strike directions (NW to NE) of the range-bounding fault segments also create a step-like or sinuous nature. This model predicts that a right-lateral component of strike-slip faulting is accommodated through NW-striking dextral faults east of the Wassuk Range, which are conjugate to the sinistral faults and define an angle of ~70° (Figure 1-3C).

Two main efforts address the nature of the southern WRFZ and provide a basis for comparing prior model predictions:

(1) Local, detailed micro-geomorphologic features are analyzed to assess recent rates of dip slip and possible strike slip fault movements. Geomorphic characteristics of young fault scarps can be useful to evaluate the probable ages of fault displacements (Wallace, 1977). Additionally, without radiometric dates, quantitative assessments require an alternative mode of estimating age. Thus, a fault-scarp analysis via degradation modeling permits the scarp’s age and uplift rate to be assessed. Constraints on the magnitudes of paleo-earthquakes can be inferred from scarp heights (Hanks et al., 1984; Wells and Coppersmith, 1994). These age estimates provide a means of ranking fault scarps according to relative geomorphic ages within a general framework between several hundred to several thousand years old.

(2) Subsurface geophysical imaging is applied to constrain fault geometry that ultimately correlate with surface kinematic results. The seismic line’s location was acquired across what was deemed a viable (i.e., evident in aerial imagery) fault scarp using
three imaging methods: refraction, and off-fault fan-shots. These data are combined
to attempt a comprehensive assessment of the fault’s location.

This project aims to quantify characteristics of scarp morphology through
photogrammetric methods and model the underlying structures through subsurface
geophysical surveys. To test previous models, drone-based data combined with the
seismic element provide a 3D model of the fault scarp to be created, correlated to other’s
slip rate and age data, and analyzed for seismic hazard potential.

Fault slip rates and temporal patterns of faulting can be correlated to previously
studied surfaces on the Wassuk Range front. This correlation allows the degree of
consistency to be determined between fault segments. Inconsistency may represent
temporal variability of the deformation rates in this part of the Basin and Range. Since
areas north of this study area (e.g., Penrod Canyon, Copper Canyon, Rose Creek, North
Canyon) have previously been studied (e.g., Wesnousky, 2005; Bormann et al., 2012), it
is significant to distinguish whether the earthquake-generating segment of the southern
WRFZ is consistent with the studied northern and central sections. In addition, these
tectonic parameters greatly influence landscape evolution and are of interest for seismic
hazard implications (McCalpin, 1996; Keller and Pinter, 1996). The earthquake hazard
component offers great societal significance through knowing the slip rates and pattern of
earthquake repetition. Overall, the techniques described provide a robust neotectonic
assessment of the fault scarp’s kinematic evolution and long-term slip rate.
Figure 1-1: A) Schematic tectonic map (denoted as 1A) showing the Wassuk Range within Walker Lane near the California-Nevada border, relative to the San Andreas fault system, Sierra Nevada mountains, and western Basin and Range. B) Localized elevation map (denoted as 1B) of the Wassuk Range showing the Whiskey Flat study site.
Figure 1-2: Perspective of the Wassuk Range facing west at Canyon A showing the spatial extent of the fault scarp (yellow arrow pointing to the tonal contrast of the scarp face). The scarp at this location is about 6 meters in vertical displacement.
Figure 1-3: Proposed models that predict dextral faulting accommodation of the southern WRFZ.  

A) Clockwise fault-block rotation from ~4 Ma to present-day; 

B) Oblique normal fault and out-board and/or buried dextral faults (arrows represent regional dextral shear); 

C) Conjugate fault system (arrows represent regional extension).

Denotations:
- BS Benton Springs fault
- PS Petrified Springs fault
- WF Whiskey Flat (southern WRFZ)
- AH Anchorite Hills fault
- MD Mina Deflection
- OV Owens Valley fault
- WM White Mountains fault
- EX Excelsior fault
- RS Rattlesnake fault
- HV Huntoon Valley
- RSM Rhodes Salt Marsh
- TM Teels Marsh
Chapter 2: Geologic Setting

2.1 Regional Context

The Wassuk Range is host to one of many discontinuous fault systems within the broad Walker Lane shear zone (Figure 1A). The Walker Lane is a significant tectonic region because it defines an overall NW-trending transtensional shear zone that accommodates 20-25% of the ~50 mm/yr of right-lateral motion between the Pacific and North American plates (Faulds and Henry, 2008). Scientific literature (e.g., Wesnousky, 2005; Pierce et al., 2021; Surpless et al., 2021) generally divides the zone into three main sections—northern, central, and southern, each containing different fault systems and strain accommodation rates and patterns.

The northern and southern zones mostly align with the overall NW-SE dextral shear orientation (Wesnousky, 2005), however, additional faults in the central Walker Lane exist east of the WRFZ that also demonstrate NW-striking, right-lateral faults that likely accommodate dextral shear (e.g., Benton Springs, Petrified Springs, Gumdrop Hills, and Indian Head) (Figure 2-1).

The complexity of deformation increases in between these sets of dextral strike-slip faults where the NNW-striking Wassuk Range normal fault and a series of NE-striking sinistral faults (e.g., Anchorite Hills, Rattlesnake, and Excelsior Mountains) make up the central Walker Lane (Figure 2-1). This region is significant because it displays a fault system that kinematically opposes the surrounding faults; the resemblance of a bend shape implies its tectonic evolution, stratigraphic history, and ongoing neotectonic activity.
2.2 Tectonic Evolution

Slemmons et al. (1979) documented a late Cenozoic record of the active faults and style of deformation between the Sierra Nevada and western Basin and Range including the Walker Lane region. They discussed how many Mesozoic faults in this area were reactivated in mid-Tertiary time and have continued to display slow normal slip rates. More recent studies (e.g., Surpless, 2012) have further constrained the timing of events through geologic mapping, geochemical analysis of igneous lithologies, geochronology, and structural data that generally agree with two episodes of Neogene extensional deformation. These events affected the Wassuk Range front, dividing the faults into roughly two generations.

The first generation of reactivated faults endured E-W directed back-arc extension around mid-Miocene time (15-12 Ma) (e.g., Dilles and Gans, 1995; Stockli et al., 2002; Surpless et al., 2002). Like many other places throughout the Basin and Range and Walker Lane, this large-magnitude extension was preceded by early Miocene volcanism (Dilles and Gans, 1995; Stockli et al., 2002; Surpless et al., 2002). Following the first episode of extension (12-9 Ma), paleomagnetic measurements (Hammond et al., 2011) suggest a decrease in rotation as a result from footwall cooling after the highest rates of extension subsided (Surpless, 2012). The currently active, east-dipping normal faults are considered the second generation of faults that evolved from the most recent (mid-Pliocene, ~4 Ma) episode of rapid extension (e.g., Stockli et al., 2002; Faulds and Henry, 2008; Surpless, 2012) and have continued to deform (westward tilt) to the present (Wesnousky, 2005; Bornmann et al., 2010; Surpless and Thorne, 2021).
The subsequent extension within the Wassuk Range throughout the Neogene period was primarily accommodated by tilting and footwall rotation along strike and large-offset normal faults (Carlson et al., 2003; Blewitt et al., 2009; Dilles and Gans, 1995; Stockli et al., 2002; Surpless et al., 2002). As extension, rotation, and displacement continued to the present, changes in tilt domains represent possible fault transfer zones and releasing bends beyond the transtensional environment of the central Walker Lane into the northern and southern Walker Lane. These general observations are supported by previous studies (e.g., Oldow et al., 2001; Gorysnki et al., 2013; Dong et al., 2014; Murphy et al., 2009) that recognize how the degree of tilting and extension decrease in both northern and southern directions of the central Walker Lane wherein right-lateral shear dominates. More specifically, these studies demonstrate geologic efforts to elucidate the complex nature of transtensional faulting within the central Walker Lane, including the inferred displacement transfer and clockwise component of vertical-axis rotation of the fault-bounded blocks. This transtensional environment was initiated by a change in plate motion between the Pacific and North American plates (Faulds and Henry, 2008; Hammond et al., 2009), where left-lateral shear zones north and south of the Wassuk Range developed and currently make up the northern and southern boundaries of the central Walker Lane.

Oldow et al. (2001) utilized GPS velocity measurements to elucidate displacement patterns on a broad scale throughout the Walker Lane and major adjacent feature including the Sierra Nevada mountains, western Basin and Range, and eastern California Shear Zone (ECSZ) (Figure 2-2). Their results indicate that the velocity field of the central Walker Lane, in particular, is a zone of displacement transfer between
distributed faults that link the ECSZ (also referred to as the southern Walker Lane) to the northern Walker Lane. On a smaller scale, the displacement field of Wassuk Range was mapped by Dong et al. (2014), who also used GPS velocity measurements (Figure 2-3). Through their intention to compare geodetic and geologic determined data, their results reveal the segmentation of strain between normal and dextral faults (colored arrows along the range front in Figure 2-3). Thus, despite the current E-W extension pattern of the Wassuk Range, right-lateral strike-slip components of displacement are considered a requirement to accommodate the ongoing shear of the Walker Lane’s oblique orientation (Oldow et al., 2001; Wesnousky, 2005; Dong et al., 2014).

Gorynski et al. (2013) used thermochronometric and $^{40}$Ar/$^{39}$Ar age data to constrain the evolution of extension and degree of westward tilting in the southern Wassuk Range. They divided this section of the fault zone into four main blocks (Figure 2-4; as well as Surpless and Thorne, 2021 in Figure 5-2)—Mt. Grant, Coryville, Lucky Boy, and Anchorite Hills blocks (oriented from north to south). Gorynski et al. (2013) and Surpless and Thorne (2021) refer to the Whiskey Flat region for this project as Lucky Boy and Anchorite Hills blocks. Nevertheless, the results from Gorynski et al. (2013) reveal that the Lucky Boy and Anchorite Hills blocks tilted less (15-35° and >10°, respectively) compared to higher degrees in the northernmost region of Mt. Grant block (60-70°) (Figure 2-4). This suggests a linear variability and a feasible explanation of a shallowing brittle-ductile transition zone in the southern direction.

In addition to fluctuating tilt domains, clockwise vertical-axis rotations are inferred based on the ~45°-difference in strike of the southern Lucky Boy block and Anchorite Hills block compared to the northern blocks (Gorynski et al., 2013), indicating
a structural relationship to the curvilinear fault trace of Whiskey Flat’s range-bounding fault system. A similar phenomenon is explained by Surpless and Thorne (2021), referring to this curvature as one of many relatively small- and large-scale right-steps along the extent of Wassuk Range. Left-lateral strike-slip faults throughout the fault system (e.g., Anchorite Hills) are common explanations for the step-like or sinuous nature (e.g., Bormann et al., 2016; Surpless and Thorne, 2021; Pierce et al., 2021) and may play a role in future deformation of the WRFZ. The southern increase of variation in normal faults along these blocks also demonstrates a $\geq 90^\circ$-difference in strike compared to the NW-striking dextral faults to the east (Figure 1-3C).

2.3 Stratigraphic History

The central Walker Lane’s stratigraphy ranges from Mesozoic to Miocene rocks that predate the initiation of the shear zone (Gorynski et al., 2013). Pre-Cenozoic basement rocks of this region consist of Triassic-Lower Jurassic metasedimentary and metavolcanic rocks that were intruded by mid-Jurassic-Cretaceous granitic plutons and silicic plutonic rocks (e.g., quartz monzonite) (Dilles and Gans, 1995; Surpless and Thorne; 2021) (Figure 2-5). These Jurassic-Cretaceous volcanic rocks formed from arc magmatism and were part of the Sierra Nevada batholith prior to Basin and Range extension (Surpless, 2012). The deposition of these volcanic rocks also preceded the first episode of extension within the Wassuk Range (15-12 Ma).

Late Cretaceous-Paleogene erosion resulted in the formation of a prominent, laterally continuous unconformity across pre-Cenozoic basement rocks throughout western Nevada and eastern California (Surpless, 2012). Continuous uplift is interpreted
throughout the Walker Lane after the unconformity’s formation until the late Paleogene period, at which an eruption is represented by silicic (rhyolite) ash-flow tuffs (Surpless and Thorne, 2021; Surpless et al. 2002). Overlying this nonconformity is a sequence of Oligocene tuffaceous and siliciclastic rocks and mid-Miocene andesites (e.g., Lincoln Flat) (Dilles and Gans, 1995).

The extrusion of the mid-Miocene Lincoln Flat andesite immediately precedes extension in the WRFZ, and its attitude reflects the cumulative Neogene tilting of the southern Wassuk Range footwall (Dilles and Gans, 1995; Stockli et al., 2002; Surpless et al., 2002). Also during this period, the offset rhyolite tuffs as well as older granites and volcaniclastic rocks are interpreted to indicate the onset of the Walker Lane deformation in which NW-striking strike-slip faults have taken up 48-60 km of right-lateral displacement (Dilles and Gans, 1995). Tilted late Miocene basaltic andesites overlie the sedimentary rocks of the Wassuk Group (Surpless and Thorne, 2021), creating a slight angular unconformity. Quaternary alluvial fan deposits observed today juxtapose Tertiary conglomerates and basaltic andesite (Lee et al., 2009) (Figure 2-6).

2.4 Neotectonic Activity

The right-stepping trace of the WRFZ displays triangular facets steeper than the angle of repose (Bormann et al., 2010) and young fault scarps that truncate older alluvial fans, implying ongoing deformation. Documented range-bounding fault scarps across active alluvial fans are expressed between ~2 and 8 meters in vertical displacement, compared to ~1-7 meters in the southern WRFZ). Examples of previously studied areas
along the range front include Penrod Canyon, Copper Canyon, Rose Creek, and North Canyon (oriented from north to south, respectively) (*Figure 2-I*).

A faceted fault spur analysis indicates that uplift rates of Penrod Canyon range from $0.69 \pm 0.20$ mm/yr in the north to $0.95 \pm 0.20$ mm/yr in the south near Mt. Grant (Surpless and Kroeger, 2014). Fault scarp degradation modeling of Copper Canyon reveals a 2.8-meter vertical offset that yields an age of $\sim 1455$ years (late Holocene) when mass diffusivity is assumed to be $1.1 \text{ m}^2/\text{kyr}$ (Wesnousky, 2005). Trenching observations coupled with age data from the Rose Creek alluvial fan reveal at least three significant seismic events have occurred in the last 9400 years with the two most recent surface-rupturing earthquakes estimating between 3650 and 4450 years ago (Bormann et al., 2010). These earthquakes infer a direct relationship to the total $\sim 7$-meter vertical offset, yielding a Holocene vertical displacement rate of $0.7 \pm 0.1$ mm/yr (Bormann et al., 2012). Based on radiocarbon data ($^{14}$C) sampled from the North Canyon’s footwall, the last earthquake event along the WRFZ is estimated to be $3960 \pm 35$ years ago (Wesnousky, 2005).

A compilation of neotectonic data assists in interpreting potential fault-block transformations (i.e., rotation and tilting) that may interfere with ongoing deformation and extension rates within the WRFZ. Based on geodetic data, an extension rate of 0.5-1.0 mm/yr for the WRFZ suggests E-W strain accommodation (Bormann et al., 2010). Paleoseismicity reveals the late Pleistocene-Holocene uplift rate along the WRFZ to be $\sim 0.3$-0.8 mm/yr (Bormann et al., 2012).
Figure 2-1: Structural map of the WRFZ and surrounding areas showing normal, right-lateral, and left-lateral components of faulting. Yellow boxes represent prior neotectonic studies. Red box represents the Whiskey Flat study site. (NMB: North Mono Basin; key for additional faults in Figure 1-3).
Figure 2-2: Velocity domains of central Walker Lane in between the Basin and Range and Sierra Nevada mountains (modified from Oldow et al., 2001). Yellow dots represent distributed GPS sites used for data acquisition. Note the geodetic expression of NW-directed strain appearing oblique to the dominant N- and NNW-striking WRFZ.
Figure 2-3: GPS-measured displacement field in the vicinity of the WRFZ (black line) (modified from Dong et al., 2014 and Wesnousky et al., 2012). Arrows are drawn from an assumed fixed Sierra Nevada block and shear is oriented oblique to the range front (revealed by longer arrows in the NE corner). In the white boxes, normal and strike-slip fault slip-rate values are geologic sourced (black text) and geodetic sourced (purple and blue text). Note the increased variability between datasets south of Walker Lake.
Figure 2-4: Geologic map of the southern Wassuk Range (modified from Gorynski et al., 2013) showing the range-bounding normal fault system on the east and distributed left-lateral strike-slip faults near the right-steps separating the four classified blocks. Variations in dip and west-directed tilting of basement rocks are shown for each block.
Figure 2-5: Bedrock geology map of the WRFZ (modified from Surpless and Thorne,
Figure 2-6: Quaternary geology map of the southern Wassuk Range. Map extents were cropped from the “Powell Mountain quadrangle, Mineral County, Nevada” and downloaded from the USGS/AASG National Geologic Map Database (modified from Stewart, J.H., Johannesen, D.C., and Dohrenwend, J.C., 1981); index on the following page.
### Surficial Deposits

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### Volcanic and Sedimentary Rocks

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<td>Tb</td>
<td>BASALT</td>
</tr>
<tr>
<td>Tbc</td>
<td>BASALTIC CINDER CONE</td>
</tr>
<tr>
<td>Tcv</td>
<td>COAL VALLEY FORMATION</td>
</tr>
<tr>
<td>Tsb</td>
<td>SEDIMENTARY ROCKS AND BRECCIA</td>
</tr>
<tr>
<td>Tr</td>
<td>RHYOLITE</td>
</tr>
<tr>
<td>Tt</td>
<td>TUFF</td>
</tr>
<tr>
<td>Ts</td>
<td>SEDIMENTARY ROCKS</td>
</tr>
</tbody>
</table>

### Plutonic and Metamorphic Rocks

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kac</td>
<td>GRANODIORITE OF ALUM CREEK</td>
</tr>
<tr>
<td>Khv</td>
<td>GRANODIORITE HUNTOON VALLEY</td>
</tr>
<tr>
<td>KJct</td>
<td>GRANODIORITE OF CAT CANYON</td>
</tr>
<tr>
<td>Kjb</td>
<td>GRANITIC ROCKS OF BABBITT</td>
</tr>
<tr>
<td>KJcc</td>
<td>GRANITE OF CORY CREEK</td>
</tr>
<tr>
<td>KJh</td>
<td>HORNBLende BIOTITE GRANODIORITE</td>
</tr>
<tr>
<td>KJgd</td>
<td>GRANPDIORITE AND RELATED ROCKS</td>
</tr>
<tr>
<td>KJd</td>
<td>DIORITE AND RELATED ROCKS</td>
</tr>
<tr>
<td>KJwf</td>
<td>GRANITE OF WHISKEY FLAT</td>
</tr>
<tr>
<td>KJpm</td>
<td>GRANITE OF POWELL MOUNTAIN</td>
</tr>
<tr>
<td>Kigu</td>
<td>GRANITIC ROCKS, UNDIVIDED</td>
</tr>
<tr>
<td>KPmv</td>
<td>METAVOLCANIC ROCKS</td>
</tr>
<tr>
<td>Kpmi</td>
<td>METAMORPHIC AND INTRUSIVE ROCKS, UNDIVIDED</td>
</tr>
</tbody>
</table>
Chapter 3: Neotectonic Geomorphology

3.1 Overview and Basic Idea

To address the neotectonic nature and kinematic evolution of the southern WRFZ, several steps were applied to measure, characterize, and analyze the fault scarp’s morphology. In any type of surface material (e.g., bedrock, unconsolidated sediment), fault-scarp morphology changes over time; the degree and rate in which it changes are pertinent for assessing local seismic hazard. Two main factors that contribute to rate of fault-scarp morphology include weathering and transport; the shape of the slope depends on which process is dominant (i.e., occurs faster). Slopes can either be classified as weathering-limited (weathering occurs more slowly) or transport-limited (transport occurs more slowly) in which the slower process limits erosion. Weathering-limited slopes are characterized by bare rock exposed at the surface and gradients that can be very steep, even vertical. Transport-limited slopes are characterized by a cover of sediment at the surface. Since the Wassuk Range front largely contains faulted alluvial fans covered with loose, unconsolidated material, the scarp slopes can be classified as transport-limited slopes (Mayer, 1984; Blair and McPherson, 2009).

Analyzing fault-scarp morphology can be achieved by measuring fault-scarp surfaces and modeling their profiles. Degraded fault scarps resemble the error function, and the degradation process of these slopes is assumed to mirror a sediment diffusive process; thus, evolution of slope morphology can be quantitatively evaluated via the diffusion equation (Hanks et al., 1984). To do this, numerous measured scarp profiles (curves) were fit to generated synthetic profiles. The relationship between scarp heights and slope angels can then be analyzed and used to estimate corresponding ages from the
morphology of scarps of known age. Long-term slip rates can also be estimated to infer horizontal extension and deformation.

*Initial and Modified Scarp Conditions*

Fault scarps generally represent any amount of planar surface displacement created by vertical or near-vertical motion along a fault. In this study, the fault displacements analyzed are assumed to have occurred as sudden offsets by earthquakes (one or multiple events) rather than slow tectonic creep. The fault scarp’s anatomical parts (*Figure 3-1*) are important to distinguish for understanding the initial scarp characteristics after an earthquake and corresponding modification process as the scarp degrades with time.

The Wassuk Range front is made up of scarps along a normal fault zone where the footwall forms the mountain and hanging wall forms the adjacent basin (sometimes referred to as Walker Lake basin). These normal fault scarps dip away from the upthrown block with initial rupture angles usually expected to range between 50 and 60 degrees for the associated deposited material (Wallace, 1977). Once formed, they immediately begin to change through erosional processes (degradation) such as weathering and sedimentation. The material on the scarp’s free face plays a large role in the rate of scarp degradation; in this study, the scarps are in poorly indurated alluvial fan deposits (Quaternary) (*Figure 2-6*). With these types of scarps formed, the loose sediment begins to fall from the free face and accumulates on the sloping surface (debris slope) below around the angle of repose (typically 30 to 35 degrees). A more gently sloping wedge at the base of the scarp (wash slope) is consequentially produced; and eventually, the free face disappears and rounding of the crest begins. Wallace (1977)
estimated that at least several hundred years is required to remove the free face from
scars in poorly indurated material. As a result, the scarp slope is decreased, and the
profile further modified.

**Degradation via the Diffusion Equation**

Fault-scarp diffusion modeling of eroded, modified profiles can produce a
quantitative assessment of the scarp’s evolution by determining long-term slip rate and
ultimately the age. Multiple faulted surfaces were observed on the Wassuk Range front
that inferred single- and multi-event (composite) scarps. Single-event scarps refer to one
surface-rupturing event that imply one age value. In contrast, composite scarps refer to
several surface-rupturing events that imply an average earthquake recurrence interval
(measured in thousands of years) (Mayer, 1984). Successful application of this
morphological dating method requires selection of an appropriate sediment transport
model and calibration of the associated parameters, i.e., determining if a scarp represents
one or more events (Mattson and Bruhn, 2001).

The methodology referenced the methodology for modeling both single- and
multi-event fault scarps came from Hanks et al. (1984) and Hanks (2000) using solutions
from Hirano’s equation

$$\frac{\partial u}{\partial t} - \kappa \frac{\partial^2 u}{\partial x^2} = 0$$

that either assume a single uplift event

$$u(x, t) = a \text{ erf}\left(\frac{x}{2\sqrt{\kappa t}}\right) + bx$$

or a steady-state uplift event
\[ u(x, t) = (a + At) \operatorname{erf} \left( \frac{x}{2\sqrt{kt}} \right) + \frac{Ax^2}{2\kappa} \left[ \operatorname{erf} \left( \frac{x}{2\sqrt{kt}} \right) - sgn(x) \right] + \left( \frac{Ax}{\kappa} \sqrt{\frac{kt}{\pi}} \right) e^{\left( \frac{-x^2}{4kt} \right)} + bx \]

and were used for the basis of generating the profiles in Python (https://github.com/seanpolun/pyScarpFit). Diffusion parameters are solved by a grid search, identifying the midpoint of the scarp (defined as \( x = 0 \)), the upper and lower far-field slope (\( \alpha \)), and the vertical offset of the scarp (\( d \)) (Figure 3-5A). The degrading part of the fault scarp is the convex curvature where \( x > 0 \) whereas the aggrading portion is the antisymmetric equivalent (i.e., concave curvature) where \( x < 0 \) (Hanks et al., 1984) (Figure 3-5B).

### 3.2 Data Acquisition: sUAV Photogrammetry and LiDAR

**sUAV Photogrammetry Data**

High-resolution topographic data (DEM) covering the fault scarp in five sites (chosen based on accessibility and visibility of the fault scarp) (Figure 3-2) was collected by low-altitude photogrammetry. Aerial photos were acquired using small unmanned systems (sUAV a.k.a. “drones”). The photogrammetric technique for obtaining these datasets utilized Structure-from-Motion (SfM) (Fonstad et al., 2013) to estimate 3D structures from 2D image sequences and were also coupled with local motion signals. In contrast to classical photogrammetry with stereoscopic image pairs, SfM solves the camera’s pose and scene geometry simultaneously and automatically, using a highly redundant bundle adjustment based on matching features in multiple overlapping, offset images (3 or more photos). Ground-control points (GCP) were also placed throughout the survey’s extent and measured through a terrestrial photogrammetric technique using
RTK equipment for post-processing elevation precision. Each survey captured 500 to 1200 photos (depending on the area) in which a 5-cm pixel DEM was later constructed.

**LiDAR Data**

Available LiDAR (light detection and ranging) data was downloaded via OpenTopography to complement the sUAV photogrammetry surveys. Data extracted were part of a larger dataset collected by NCALM (National Center for Airborne Laser Mapping) in 2015 that covers northern Walker Lane to the northern portion of the Whiskey Flat area. Although this data does not cover the remaining study area in Whiskey Flat (Figure 3-2), they permit testing the effects of data sources (and data resolution) on the fault scarp modeling (Table 3-1). Using the LiDAR point cloud data, a profile with a known radiocarbon age was extracted at the North Canyon study site (Wesnousky, 2005) to calibrate a new value of mass diffusivity.

### 3.3 Scarp Profiling and Diffusivity Calibration

**Scarp Profiling**

Seven scarp profiles along the fault zone were extracted from each surveyed location to elucidate geomorphic and tectonic evolution. These scarps are a culmination of inferred single- and multi-event faulted surfaces based on relative parameters (grouped together with similar vertical displacement components and amount of degradation). A one-dimensional, non-linear sediment transport (scarp degradation) model was applied to these profiles and calibrated with associated parameters of mass diffusivity (rate of degradation) and vertical displacement (throw) from the regional slope from the maximum displacement. To do this, the combined sUAV photogrammetry and LiDAR
data were converted to pointCloud data (georeferenced points) and aligned to the correct elevation and spatial orientation using the ground-control point locations (Figure 3-3). Through the Metashape software, 5-cm DEM models were produced. From these models, several pairs of points (X and Y values as UTM coordinates) on either side of the WRFZ were extracted to produce cross-sectional profiles (red lines in Figure 3-8A-E).

**Diffusivity Calibration**

A new value for mass diffusivity (Kappa) is calibrated using a known radiocarbon age of 3960 ± 35 \(^{14}\)C B.P. (Wesnousky, 2005) from the North Canyon study site north of Whiskey Flat (Figure 3-9). Using the OxCal program (Bronk-Ramsey, 2001), the radiocarbon correction from Stuiver and Reimer (1993) provides a calendrical date of 2340-2580 B.C. with 95% confidence (Figure 3-10). After considering the sample’s date (2005 A.D.), the actual age ranges from 4345-4585 years or an average of 4.465 ± 0.12 kyr. Kappa is equal to the quotient of this averaged age and the model-estimated \( \kappa t \) value (11.5 ± 1.0 m\(^2\)) (Figure 3-9). Using the equation from Tsoulfanidis (1938),

\[
\frac{\mu_1 \pm \sigma_1}{\mu_2 \pm \sigma_2} = \frac{\mu_1}{\mu_2} \pm \frac{\mu_1}{\mu_2} \sqrt{\frac{\sigma_1^2}{\mu_1^2} + \frac{\sigma_2^2}{\mu_2^2}}
\]

Kappa and its uncertainty are calculated where each variable and corresponding coefficients are listed in the table below:

<table>
<thead>
<tr>
<th>Equation variable</th>
<th>Variable meanings</th>
<th>Estimated coefficients</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_1 )</td>
<td>( \kappa t )</td>
<td>11.5</td>
<td>m(^2)</td>
</tr>
<tr>
<td>( \sigma_1 )</td>
<td>( \kappa t ) uncertainty</td>
<td>1.0</td>
<td>m(^2)</td>
</tr>
<tr>
<td>( \mu_2 )</td>
<td>( t )</td>
<td>4.465</td>
<td>kyr</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>( t ) uncertainty</td>
<td>0.12</td>
<td>kyr</td>
</tr>
</tbody>
</table>

Thus, Kappa is approximately 2.58 ± 0.23 m\(^2\)/kyr.
3.4 Results

The throw \((H)\) and degree of degradation \((\kappa t)\) are estimated for both single- and multi-event scarps from the degradation models. The new diffusivity constant is applied to calculate ages \((t)\) of the faulted surfaces. Composite scarp data are used to calculate earthquake recurrence intervals and uplift rates from each throw component. Additional deformation rates are calculated using basic trigonometry including dip slip and extension rates. Single-event scarp data, however, are used to calculate the timing of the last surface-rupturing event and corresponding earthquake magnitudes (Wells and Coppersmith, 1994).

The best-fit profiles for single- and multi-event scarps within Whiskey Flat also include uncertainties \([u(x_i)]\) on the fault scarp’s throw, \(\kappa t\), \(\kappa\), age, and deformation rates. Calculations for each single- and multi-event profile with corresponding uncertainties are displayed in the tables below.

**Single-Event Fault Scarp Profiles**

Fault-scarp profiles from Powell and Jim canyons are interpreted as single-event scarps *(Figure 3-11)*. Their estimated throws range from \(1.24 \pm 0.35\) (Powell) to \(1.20 \pm 0.20\) (Jim) meters, which are interpreted to result from the last surface-rupturing earthquake events (approx. 687-3774 years ago).

<table>
<thead>
<tr>
<th>Canyon</th>
<th>Powell</th>
<th>(u(x_i))</th>
<th>Jim</th>
<th>(u(x_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H) (m)</td>
<td>1.24 ± 0.35</td>
<td>1.20 ± 0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\kappa t) (m²)</td>
<td>4.2 ± 2.4</td>
<td>8.6 ± 0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\kappa) (m²/kyr)</td>
<td>2.58 ± 0.23</td>
<td>2.58 ± 0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t) (years)</td>
<td>1631 ± 944</td>
<td>3339 ± 435</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Based on empirical relationships between maximum surface displacement (MD) of normal faults and moment magnitude (M), the log-linear regression equation from Wells and Coppersmith (1994),

\[ M = 6.69 + 0.74 \times \log(\text{MD}) \]

is used to approximate the magnitudes on each scarp, where MD is interpreted as throw (Figure 3-6).

<table>
<thead>
<tr>
<th>Canyon</th>
<th>Powell $u(x_i)$</th>
<th>Jim $u(x_i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD (m): 55°</td>
<td>2.2 ± 0.62</td>
<td>2.1 ± 0.35</td>
</tr>
<tr>
<td>MD (m): 65°</td>
<td>2.9 ± 0.83</td>
<td>2.8 ± 0.47</td>
</tr>
<tr>
<td>M: 55°</td>
<td>6.9 ± 0.1</td>
<td>6.9 ± 0.1</td>
</tr>
<tr>
<td>M: 65°</td>
<td>7.0 ± 0.1</td>
<td>7.0 ± 0.1</td>
</tr>
</tbody>
</table>

Thus, earthquake magnitudes range from 6.8 to 7.1.

**Multi-Event Fault Scarp Profiles**

Composite fault scarp profiles from Johnston Canyon (Table 3-1), Canyon A (Table 3-2), and Canyon B (Table 3-3) were analyzed using a steady-state model (Hanks et al., 1984) (Figure 3-12). These scarp profiles range from 2.7 to 6.6 meters in vertical displacement. Dividing $\kappa t$ by the mass diffusivity yields the range in ages (t) of the fault surfaces between ~5838 (Canyon B – Profile 1) and ~26,384 (Canyon A – Profile 2) years. Long-term uplift rates range from 0.23 (Canyon A – Profile 2) to 0.54 (Johnston Canyon) mm/yr. To calculate corresponding dip slip and extension rates via trigonometry, an assumed range of slope angle is assumed to range from 55 to 65 (average for transport-limited slopes; Wallace, 1977). Thus, long-term dip slip rates are estimated from 0.09 (Canyon A – Profile 2) to 0.36 (Canyon B – Profile 1) mm/yr. Horizontal extension rates, however, range from 0.33 (Canyon A – Profile 2) to 1.4
(Canyon B – Profile 1) mm/yr. Thus, Canyon B demonstrates the largest extension rate for the local section of the fault zone.

**Table 3-1: Johnston Canyon (sUAV compared to LiDAR data acquisition)**

<table>
<thead>
<tr>
<th>Canyon</th>
<th>Johnston (sUAV)</th>
<th>Johnston (LiDAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (m)</td>
<td>5.08 ± 0.30</td>
<td>5.52 ± 0.25</td>
</tr>
<tr>
<td>κt (m²)</td>
<td>28.0 ± 3.2</td>
<td>26.6 ± 2.4</td>
</tr>
<tr>
<td>κ (m²/kyr)</td>
<td>2.58 ± 0.23</td>
<td>2.58 ± 0.23</td>
</tr>
<tr>
<td>t (years)</td>
<td>10,871 ± 1588</td>
<td>10,328 ± 1324</td>
</tr>
<tr>
<td>Uplift (mm/yr)</td>
<td>0.47 ± 0.07</td>
<td>0.53 ± 0.07</td>
</tr>
<tr>
<td>Ext. (mm/yr): 55°</td>
<td>0.67 ± 0.11</td>
<td>0.76 ± 0.10</td>
</tr>
<tr>
<td>Ext. (mm/yr): 65°</td>
<td>1.0 ± 0.16</td>
<td>1.146 ± 0.16</td>
</tr>
<tr>
<td>Dip Slip (mm/yr): 55°</td>
<td>0.27 ± 0.04</td>
<td>0.31 ± 0.04</td>
</tr>
<tr>
<td>Dip Slip (mm/yr): 65°</td>
<td>0.20 ± 0.03</td>
<td>0.23 ± 0.03</td>
</tr>
</tbody>
</table>

**Table 3-2: Canyon A – Profiles 1 & 2**

<table>
<thead>
<tr>
<th>Canyon</th>
<th>A – Profile 1</th>
<th>A – Profile 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (m)</td>
<td>3.8 ± 0.20</td>
<td>6.2 ± 0.35</td>
</tr>
<tr>
<td>κt (m²)</td>
<td>33.3 ± 4.5</td>
<td>59.2 ± 6.9</td>
</tr>
<tr>
<td>κ (m²/kyr)</td>
<td>2.58 ± 0.23</td>
<td>2.58 ± 0.23</td>
</tr>
<tr>
<td>t (years)</td>
<td>12,929 ± 2107</td>
<td>22,985 ± 3399</td>
</tr>
<tr>
<td>Uplift (mm/yr)</td>
<td>0.29 ± 0.05</td>
<td>0.27 ± 0.04</td>
</tr>
<tr>
<td>Ext. (mm/yr): 55°</td>
<td>0.42 ± 0.07</td>
<td>0.39 ± 0.06</td>
</tr>
<tr>
<td>Ext. (mm/yr): 65°</td>
<td>0.63 ± 0.11</td>
<td>0.58 ± 0.09</td>
</tr>
<tr>
<td>Dip Slip (mm/yr): 55°</td>
<td>0.17 ± 0.03</td>
<td>0.15 ± 0.02</td>
</tr>
<tr>
<td>Dip Slip (mm/yr): 65°</td>
<td>0.12 ± 0.02</td>
<td>0.11 ± 0.02</td>
</tr>
</tbody>
</table>

**Table 3-3: Canyon B – Profiles 1 & 2**

<table>
<thead>
<tr>
<th>Canyon</th>
<th>B – Profile 1</th>
<th>B – Profile 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (m)</td>
<td>3.74 ± 0.20</td>
<td>2.88 ± 0.15</td>
</tr>
<tr>
<td>κt (m²)</td>
<td>17.6 ± 2.0</td>
<td>26.7 ± 2.9</td>
</tr>
<tr>
<td>κ (m²/kyr)</td>
<td>2.58 ± 0.23</td>
<td>2.58 ± 0.23</td>
</tr>
<tr>
<td>t (years)</td>
<td>6833 ± 995</td>
<td>10,367 ± 1469</td>
</tr>
<tr>
<td>Uplift (mm/yr)</td>
<td>0.55 ± 0.09</td>
<td>0.28 ± 0.04</td>
</tr>
<tr>
<td>Ext. (mm/yr): 55°</td>
<td>0.78 ± 0.12</td>
<td>0.40 ± 0.06</td>
</tr>
<tr>
<td>Ext. (mm/yr): 65°</td>
<td>1.17 ± 0.18</td>
<td>0.60 ± 0.09</td>
</tr>
<tr>
<td>Dip Slip (mm/yr): 55°</td>
<td>0.31 ± 0.05</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>Dip Slip (mm/yr): 65°</td>
<td>0.23 ± 0.04</td>
<td>0.12 ± 0.02</td>
</tr>
</tbody>
</table>
Figure 3-1: Anatomical parts of a typical fault scarp in loose, unconfined sediment (modified from Wallace, *GSA Bull.*, 1988).
Figure 3-2: Whiskey Flat study area showing the five canyon locations (denoted as yellow boxes) where photogrammetric data was collected and scarp profiles were extracted, including Powell Canyon, which is where the geophysical survey was conducted. Red star represents North Canyon study site, the location where airborne LiDAR data was extracted to calibrate a new mass diffusivity constant.
Figure 3-3: Metashape AgiSoft demonstrating the distribution of photo frames (blue rectangles) relative to the 3D surface derived from the photogrammetric processing. This example is facing obliquely North at Jim Canyon.
Figure 3-4: Fault scarp profile showing the values used to calculate diffusivity parameters.
Figure 3-5: Degradation (convex) and aggradation (concave) profiles (modified from Hanks et al., 1984), where A) shows the relationship between diffusivity (κ) and time (t) over a vertical displacement (i.e., elevation) of 20 meters, and B) shows how the scarp slope evolves as a function of κt and t (kyrs).
Figure 3-6: Log-linear regression graph showing equation used for normal faults. This equation is based on empirical relationships between maximum surface displacement (MD) and moment magnitude (M). (modified from Wells and Coppersmith, 1994).
Figure 3-7: Relationship between $\kappa t$ (from steady-state scarp degradation modeling) and throw with corresponding errors.
Figure 3-8A: The northernmost canyon (Johnston Canyon) showing the composite scarp profile that was extracted for degradation modeling.
Figure 3-8B: Canyon A (unnamed canyon) showing composite scarp profiles (1 and 2) that were extracted for degradation modeling.
Figure 3-8C: Canyon B (unnamed canyon) showing composite scarp profiles (1 and 2) that were extracted for degradation modeling.
Figure 3-8D: Jim Canyon showing a single-event scarp (Profile 1) that was extracted for degradation modeling. Profile 2 was not used in final results due to close analysis that revealed its location to be invalid.
Figure 3-8E: Powell Canyon showing the location of the geophysical profile (similar to Figure 4-1). A single-event profile was extracted in this location (unmarked, but shown in Figure 3-11).
Figure 3-9: Scarp profile from the North Canyon study site with a known radiocarbon age of 3960 ± 35 $^{14}$C B.P. (Wesnousky, 2005).
Figure 3-10: Distribution of radiocarbon ages with calculated calendrical dates (from Oxcal program; Bronk-Ramsey, 2001). The correction curve applied from Stuiver & Reimer (1993) provides a calendrical date of 2340-2580 B.C. with 95% confidence.
Figure 3-11: Single-event fault scarp profiles of Jim and Powell Canyon were analyzed for the last surface-rupturing events in the southern Wassuk Range. $H$ represents the throw.
Figure 3.12: Multi-event (composite) scarps extracted for estimating deformation rates in the southern Wassuk Range.
Chapter 4: Shallow Geophysics

4.1 Overview and Basic Idea

Refraction seismology was utilized to acquire subsurface data (e.g., depth, geometry) for the southern Wassuk Range. Detailed images produced from these methods can help infer the underlying structural geometry and fault characteristics.

The concept involved in these methods is derived from the principle of elastic waves (waves that propagate through the earth as elastic waves are referred to as seismic waves). From the source at the surface, seismic waves are transmitted into the earth wherein most of the energy is refracted or reflected at each lithological interface (the remaining energy is absorbed). Because these waves travel with different velocities in different layer formations, we can distinguish both lateral and depth variations through a physical and relevant parameter: seismic velocity. And since our goal is to analyze the depth and geometry of any potential subsurface feature, we must estimate the velocity of the rocks.

The dataset derived from each survey consists of a series of travel times versus distance (two-way travel time). These datasets enable us to reconstruct the refracted/reflected wave paths since most of the sound from the source is returned back to the surface, i.e., measuring the time between the initial sound made and the returned echo. For both types of wave paths, this time travel difference depends upon the physical property (elastic parameters) of the material in which the waves are traveling through as well as the attitudes of the beds.

The geophysical assessment of the study area involved three seismic survey approaches—a 198-meter refraction survey and two fan-shots (refraction method) about
100 meters perpendicular to the main seismic line (*Figure 4-1*). For all three surveys, a seismic Betsy gun with 8-gauge shells was manually operated as the source and several vertical component, 40-Hz geophones (electro-magnetic devices) placed in the ground’s surface acted as the receivers.

4.2 Seismic Refraction

The seismic refraction survey was conducted in Powell Canyon, the southernmost location in this study (*Figure 3-2*), ran perpendicularly across the fault zone, and extending 198 meters in length. The approach involved a fixed spread (“common offset”) array in which the 56 geophones used were fixed to the ground with predetermined 3-meter spacing. This geophone array was overlaid with shot locations (where the Betsy gun was shot) with predetermined 6-meter spacing (survey design displayed in *Figure 4-2*).

Geophone and shot spacing along the seismic line was verified prior to data collection using flags and measuring tapes. Shot holes were then dug to about a foot in depth, either by hand or using an auger, depending on the quality of surface material. These holes helped to accommodate the blast of the seismic Betsy gun and retain as much energy into the ground. Each geophone was installed manually by pressing the geophone’s 3-inch spike into the ground to establish a firm contact with the surrounding earth material; this assured a good coupling to the ground for direct transfer of seismic energy from the ground to the geophone. Each geophone was connected via a multi-channel data cable to a digital data recorder (Geometrics Seismograph). Confirmation of the proper placement of the geophones and correct orientation of the communication
cable was made by performing tap tests on each geophone while observing the signal strength display on the display screen on the recording unit. Once the recording unit was calibrated, we began the survey downslope at the 324-meter source location and worked our way toward the range front, ending at the 522-meter source location. Data collected at each location were obtained from only one shot impact; if the data on the seismograph displayed too much noise, the shot was redone, replacing the previous shot impact data.

*Data Processing*

Travel times of refracted P- and S-waves change direction as they pass through each medium (e.g., $V_1$ and $V_2$ layers) which indicate a change in speed and wavelength. The principal portion of these wave paths are along the interface between each layer, thus, approximately horizontal. Travel times of refracted wave paths are therefore interpreted in terms of depths to subsurface interfaces and speeds at which the waves travel through the subsurface within each layer.

We used SeisImager/2D refraction software to integrate refraction modeling and interpretation. Raw field data records were first imported as individual files into the PickWin module, with each record demonstrating the impact along the seismic profile from one shot location. P-wave shot gathers were developed and the first-arrival travel times (first breaks) were picked; no filters were necessary in the picking. Based on the reciprocity between shot and receiver pairs, the majority of P-wave first arrivals were measured within 0.5 seconds. The P-wave’s first arrival was measured for every corresponding geophone (56) from each shot point (34) along the profile; this resulted in a total of 1,904 first arrivals we used to develop the P-wave velocity model.
These picks were combined into one file that was imported into the Plotrefa module. Here, inflection points along the cross over distances were selected to infer a change in slope, thus, a change in seismic wave speed (V₁ layer to V₂ layer). Vertical variations between interfaces (time inversion analysis) was applied from field-measured elevation points that were also imported for accurate topographic profiling. This time inversion model helped generate an initial velocity model to be used as the starting model for the tomographic inversion. The final P-wave seismic-refraction tomography model was generated to map the lateral variations in velocity (*Figure 4-3*).

### 4.3 Fan-Shots: Fault-Zone Guided Waves

The third element to the seismic investigation involved a refraction survey that ran 200 meters covering the width of the alluvial fan (perpendicular to the previous two surveys) (*Figure 4-1*). The purpose of collecting these north and south fan-shots was to see the fault guided S-waves trapped within the underlying fault plane, supported by the idea that individual fault traces can be identified based on discrete low-velocity zones and high-amplitude “guided waves” (Li et al., 2012). The importance of locating individual traces within overall fault zones is to assess relative slip rates and earthquake event timing (Catchings et al., 2020). Numerous studies (e.g., Ross and Ben-Zion, 2015; Gulley et al., 2017; Qiu et al., 2020) have documented the wave-guide effect and the seismic energy that can travel along and within fault zones; this seismic energy is referred to as fault-zone guided (or trapped) waves. These waves are characterized by getting trapped in the fault zone through internal reflections between low-velocity fault zones and higher velocity wall rocks (country-rock).
Numerical studies have shown that high-amplitude guided waves are generated and propagate within fault zones only when the source is located within the fault zone or when the source underlies a fault zone that extends only to shallow depths. Thus, for most major crustal faults, guided waves propagate only along faults that are continuous between the seismic source and the observation point because a discontinuous fault prevents lateral propagation of guided waves beyond the endpoint of the fault. The presence, continuity, and connectivity of faults can, therefore, be inferred from the presence or absence of guided waves along faults. Such precise exploration can be used to identify or exclude faulting at specific sites.

**Data Processing**

The two data files (north and south fan-shots) were converted and used to plot noise from each geophone channel and the maximum amplitude across the fan from both directions (*Figure 4-4*). The maximum amplitude (y axis) corresponds to the higher frequency observed in the travel-time curves from the Betsy gun’s impact (*Figure 4-5*).

**4.4 Results**

Maximum amplitude plots from the fan-shot guided waves reveal higher frequencies between 390- and 470-meter locations. For both northern and southern shots, the amplitude sharply increases around the 380-meter mark and decreases around 440 meters, aligning with the interpretation that the fault plane is in this vicinity. A second increase begins at the 440-meter mark and decreases around 460 meters.

The refraction survey permitted imaging depths of approximately 25 meters below the surface. P-wave velocity modeling (*Figure 4-3*) reveals the underlying
structure in which the upper 5 meters across the survey range between ~580 and 950 m/s. Downslope to the east, the upper 5 meters is predominately ~580-660 m/s whereas upslope to the west demonstrates a range of ~660-950 m/s. Thus, the tomography model displays a layer of low-velocity material that is interpreted as dry sand (unconsolidated sedimentary fill) from ~580 and 950 m/s. With increasing depth (~15-25 meters), the velocity reaches up to ~1300 m/s at the base of the survey, which is interpreted as saturated sand.

~40 m of depth. This distribution is segmented by an interpretive fault around the 422-meter mark (lateral location). Between 382- and 422-meter marks, the velocity sharply decreases down to 990-1200 m/s, appearing as an asymmetric half-graben formation; a west-dipping, antithetic fault (382-meter mark) appears to mirror the east-dipping normal fault (422-meter mark).

Refraction and fan-shot data suggest a possible interpretation of an asymmetric half-graben bounded by the major east-dipping fault on the western margin of the basin (Figure 4-6). Alternatively, deposition of the alluvial fan may have resulted in a sag formation bounded by the range front.
Figure 4.1: Location of the geophysical survey showing the 198-meter-long refraction line (white line from 324- to 522-meter marks) and the two fan-shot locations across the alluvial fan (north and south, denoted as yellow boxes).
Figure 4-2: Refraction survey design showing relative geophone and shot locations. Red circles represent shot locations, colored triangles represent geophone locations (different colors for field organization purposes).
Figure 4-3: P-wave refraction tomography model. Colored scale bar represents the velocity distribution in the subsurface.
Figure 4-4: Maximum noise and amplitude plots from across the north- and south-directed alluvial fan shots.
Figure 4-5: Travel-time curves from north and south fan-shots compared to the “smoothed amplitude” plot from Figure 4-4. Note how the high frequency shown in the travel-time curves both align with the peak maximum amplitude values between 400 and 460 meters.
Figure 4-6: Schematic cross section of interpreted antithetic fault based on geophysical results.
Chapter 5: Discussion and Conclusions

Late Quaternary deformation along the southern Wassuk Range was investigated with the goal of resolving kinematic questions within the western Basin and Range and Walker Lane as a whole. For the Whiskey Flat study area, fault scarp degradation modeling and seismic refraction imaging were used to examine fault scarp morphology and underlying geometry, respectively.

Through the photogrammetric imaging technique, fault scarp degradation modeling assessed the kinematic evolution and deformation. To calculate dip slip and extension rates via trigonometry, an assumed range of slope angle is assumed to range from 55 to 65° (average for transport-limited slopes; Wallace, 1977). Thus, long-term dip slip rates are estimated from 0.17 ± 0.03 to 0.12 ± 0.02 mm/yr (55-65°, respectively) and 0.31 ± 0.05 to 0.23 ± 0.04 mm/yr (55-65°, respectively). In addition, the horizontal extension rate for Johnston Canyon is approximately 0.78 ± 0.12 to 1.2 ± 0.18 mm/yr (55-65°, respectively), which demonstrates the largest rate for the local section of the fault zone. Furthermore, the southernmost vectors that straddle Whiskey Flat shown in Figure 2-3 represent ~2-4 mm/yr of extension. Significantly, these are nearly orthogonal to the eastern and western sides of the Whiskey Flat area, suggesting mostly normal faulting (i.e., horizontal stretch).

Geologic evidence of right-lateral, strike-slip faults are not observed in the southern Wassuk Range. In contrast, deformation rates north of Whiskey Flat have been documented to include both extensional and right-lateral components of faulting (Wesnousky et al.; 2012, Dong et al., 2014; Surpless and Kroeger, 2015). The central section presents an extensional rate of 0.4-0.8 mm/yr and a right-lateral strike-slip rate of
1.2-1.6 mm/yr, whereas the northern section presents an extensional rate of 0.5-1.3 mm/yr and a right-lateral strike-slip rate of 0.7-1.3 mm/yr (Figure 2-3).

Seismic refraction imaging techniques assessed the structural geometry in the subsurface. Shallow geophysical data collected along the eastern range front aligns with the expectation of higher-angled geometry of fault scarps than farther west, supporting active extensional deformation. Seismic profiling addressed whether there are multiple faults across the alluvial fan surface and if they are imbricated or confined to the fault bounding the range front. Based on refraction tomography modeling, the polarity-opposing, steep velocity drops at 382- and 422-meter marks support the idea of an existing antithetic fault (west-dipping) merging with the east-dipping normal fault, forming an asymmetric half-graben formation.

Although the Wassuk Range is generally defined as a NNW-trending fault system, three separate segments can be further divided—the north demonstrates linear NW-striking faults, the center forms small alternating N- and NE-striking right-steps, and the south is defined by NNW-striking normal faults. Putting the two neotectonic and geophysical methods together, new kinematic observations suggest a slightly slower slip rate within the southern section compared to the northern and central sections and a potential asymmetric graben formation, supporting the idea of a dominant normal fault system that aligns with the overall NW-directed geodetic shear. Extension rates of the southern Wassuk Range may also characterize the nature of the western Basin and Range. And, based on magnitude and surface rupture length relationships (Wells and Coppersmith), Jim Canyon appears to correlate more to the northern rupture zone of WRFZ than Powell Canyon.
A potential explanation for the decrease in deformation rates could be related to eastern faults that may be more responsible for the right-lateral strain accommodation. Since these faults have yet to be mapped locally within Whiskey Flat (Walker Lake basin), it is possible they exist under the surface, which are difficult to detect in basin sediments (Surpless and Thorne, 2021). Another reason could be derived from fault-block rotations due to the left-lateral strike-slip faults that occur at the northern and southern boundaries of Whiskey Flat. Rotational kinematics can produce opposing polarity to larger-scale dextral strain, relating to a lack of evidence for right-lateral strain in the southern Wassuk Range. N-striking grabens have also been documented along north and central Wassuk Range (e.g., Dilles and Gans, 1995; Surpless et al., 2002; Hammond and Thatcher, 2007; Lee et al., 2009). In contrast, however, the geometry of the linear NNW-striking fault segment of Whiskey Flat that is associated with the inferred NE-striking graben formation is consistent with the larger-scale NW-directed dextral motion of the Walker Lane.

Furthermore, the neotectonic period (i.e., current tectonic regime) can start at different times in different regions that ultimately depend on when the modern-day stress field of a region was first imposed. Broad-scale geodetic observations can give insight to future deformation of fault zones, however, may be misguided on smaller-scale kinematics (e.g., individual fault deformation rates). Varied uplift rates are segmented throughout the WRFZ and can change depending on the time scale used for estimation (Surpless and Kroeger, 2015). For example, long-term (>1 Ma; 10^6-yr time scale) uplift rates are faster (~1.1 mm/yr) in the Whiskey Flat area compared to the northern segment of the WRFZ (<0.8 mm/yr). The post-113 ka (10^5-yr time scale) uplift rate is 0.82 ± 0.16
mm/yr for the entire WRFZ. In contrast, Bormann et al., 2016 report a $10^4$-yr time scale (Holocene) slip rate to be 0.3-0.8 mm/yr. This discrepancy may be due to averaging long-term uplift and other deformation rates for different time scales that could introduce over- or under-exaggeration.

Well-documented structural mechanisms driving present-day deformation include Basin and Range extension, the Sierra Nevada uplift, and the transform fault between Pacific and North American plates. As shown in the displacement field from Oldow et al. (2001) (Figure 2-2) and the velocity model from Dong et al. (2014) (Figure 2-3), broad-scale right-lateral shear is dominant. This region yields a complex pattern of faulting due to competing tectonic factors of extensional and dextral components across the system (Bennet et al., 2003). Within this context, the Wassuk Range appears to spatially separate the normal faults on the west (e.g., North Mono Basin) and dextral faults on the east (e.g., Benton Springs) (Figure 2-1). The western domain of the central Walker Lane (west of the WRFZ) demonstrates an active series of subparallel NNW- to NNE-striking and east-dipping, range-bounding normal faults. These fault systems each divide a mountain range to the west from a half-graben formation holding a basin to the east (e.g., Singatse Range) (Pierce et al., 2021) (Figure 5-1). The Singatse Range demonstrates NW- and NE-striking fault scarps that merge to form a NE-striking graben. A similar pattern may exist in the subsurface of the Whiskey Flat region.

Conclusions

Scarp degradation and seismic tomography data permit an active model of the southern Wassuk Range normal fault system. The WRFZ has been previously interpreted
as a rhomboidal pull-apart orientation within the larger strike-slip system of Walker Lane (e.g., Link et al., 1985; Mann, 2007; Faulds and Henry, 2008); and is similar to the step-like pattern along smaller fault systems nearby (Pierce et al., 2021). Synthetic modeling of young scarp profiles along the southern range front suggests multiple late Quaternary surface-rupturing earthquake events between 1631 ± 944 (Powell Canyon) and 3339 ± 435 (Jim Canyon) years with magnitudes of 6.9-7.1, suggesting the most recent event occurring at the southernmost location (Powell Canyon). Furthermore, earthquake events along the southern Wassuk Range result in average recurrence intervals between 687 and 3774 years, suggesting a more frequent activity in the southernmost Wassuk Range (Powell Canyon).

Slower long-term slip rates of 0.10-0.27 mm/yr—compared to prior studies can be justified by observing large-scale geodetic shear orientations (NW-striking) and considering alternative accommodation mechanisms (e.g., vertical axis rotation). Subsurface geophysical imaging also demonstrates the likelihood of an additional antithetic fault in Powell Canyon, in which the graben’s extensional direction also aligns with the NW-trending right-lateral shear (Figure 5-2).

**Implications for Seismic Hazards**

Because of the segmentation and oblique orientation of the Wassuk Range within Walker Lane, deformation is likely to continue, which is significant for future seismic hazard assessments. The Walker Lane was first outlined by Gianella and Callaghan (1934); they noted the similarity of horizontal components of strain between the major structural systems of the Great Basin and the San Andreas fault (SAF) system. Unlike the SAF system, there exists no single throughgoing strand along the Walker Lane.
(Faulds and Henry, 2008; Putirka and Busby, 2011). Structural geology studies suggest that left- or right-lateral strike-slip fault systems should be characterized by a zone of disconnected fault segments during initial stages of development, however, ultimately merge to take up displacement along a principle and throughgoing fault. In this case, the SAF system is at a more mature stage of structural development than the Walker Lane. Furthermore, in regard to assessing the potential hazard within the Whiskey Flat area, the dominant faulting mechanism should be documented as a normal fault system (despite possible dextral faults buried in the basin to the east) without the risk of right-lateral-induced deformation.

**Future Work**

Although neotectonic geomorphology and shallow geophysical methods were combined for a comprehensive model, future research would be beneficial for questions that arose throughout this study. For example, seismic reflection surveying is required to refine the subsurface geometry (e.g., dip angle) within the southern Wassuk Range. Additionally, conducting cosmogenic nuclide dating on footwall samples may estimate the fault scarp’s age more precisely, ultimately constraining more accurate long-term deformation rates that would not depend upon time-scale discrepancies.
Figure 5-1: Structural map showing range-bounding normal fault systems west of the WRFZ (labeled on the right) (modified from Pierce et al., 2021).
Figure 5-2: A) NW-orientation of geodetic shear aligns with the extending normal fault system of Whiskey Flat (denoted as Luckyboy) (modified from Surpless and Thorne, 2021).
References


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