Introduction and Purpose

There are a number of factors that influence the formation and evolution of normal faults, including: the orientation, and changes in orientation, of the principal stress directions; heterogeneities in the crust, such as differences in layering or grain size (Crider and Peacock, 2004); and pre-existing structures, e.g. veins and joints (Crider and Peacock, 2004). Pre-existing structures may actually promote faulting, especially in the early stages of extension, by weakening the crust (Buck, 2007, and references therein). While examples of fully evolved normal fault systems are ubiquitous in the Basin and Range, North Sea, and elsewhere, the initial stages are more difficult to find. Yet these early stages of extension are important to understand, as they are typically characterized by higher crustal heat flow (Buck, 2007), faults and their surrounding fracture zones influence fluid migration in the subsurface by creating both barriers and conduits (Caine, J.S. et al., 1996). This combination of faulting and high crustal heat flow creates an environment favorable for geothermal energy development, seen in many young extensional regions. The northwest Basin and Range (NWBR) is an area currently under exploration for geothermal potential (Benoit et al., 2005). The purpose of this study is to determine the factors that influence the initiation, evolution, and orientation of faults in the northwest Basin and Range, evidence that could be used to predicatively model fault interactions that influence fluid flow.

Mature stages of extension are commonly exposed across the Basin and Range, in the form of large fault-bounded ranges separated by long linear basins; however, the earlier stages of extensional faulting are harder to find. Due to a comparatively lower rate and magnitude of extension, the northwest margin of the Basin and Range is an excellent place to evaluate models for fault initiation and
growth (Figure 1). Like the rest of the Basin and Range, most of the extension in this northwest region is
accommodated by large-offset (≥ 150 m) faults trending N to NNE (Pezzopane and Weldon, 1993); unlike
the rest of the Basin and Range, the NWBR also contains a second set of numerous minor-offset faults
that trend NW (Figure 1) (Scarberry et al., 2009; Trench et al., 2012; Pezzopane and Weldon, 1993).
Based on cross-cutting relationships and the age of the units faulted by both sets, the minor-offset NW
faults have been interpreted to be coeval with the larger offset NNE set, forming as fractures along the
propagating tips of the NNE faults (Scarberry et al., 2009; Trench et al., 2012). Due to similarities
between the fault orientations and older dike alignments, both fault sets may represent reactivation of a
pre-existing fracture system (Scarberry et al., 2009). The exact nature of the relationship between the
two fault sets is not yet well constrained.

Figure 1: Northwest Basin and Range, with areas of previous studies noted. Location of this
study outlined in red.
The Larkspur Hills, east of Surprise Valley in northeast California (Figure 2), provides an ideal location to add to the existing work in the NWBR, since this appears to be a location where the dominant regional fabric changes. As this area is in initial stages of development, it is an ideal place to

Figure 2 – Initial fault map of the Larkspur Hills. Geochronology from Carmichael et al. (2006). LiDAR DEM not shown, but extent of that DEM in the southwest of study area is outlined (dashed line).
further constrain the relationship between the two fault sets, as the early stages of fault initiation and
growth are well preserved. The hills are formed by young faults that cut, tilt, and offset 3 – 8 My basalts
(Carmichael et al., 2006). The basalts are tilted about ~15° to the west, and are offset up to several
hundred meters (Egger and Miller, 2011). The area surrounding the Warner Range has undergone
relatively little extension, about 12-15 %, most of which has been accommodated on the Surprise Valley
fault (Egger and Miller, 2011). Therefore, the faults in the Larkspur Hills are in various early stages of
development. The Surprise Valley is filled with 1-2 km of sediment (Egger and Miller, 2011), obscuring
structures at depth, but seismic (Lerch et al., 2009) and magnetic (Glen et al., 2013) imaging both reveal
significant and continuous faults in the basin. A detailed understanding of the faults visible at the
surface is critical for understanding subsurface geometries of buried faults, which is important for
determining fluid pathways for geothermal exploration. Detailed mapping and analysis of the faults in
the Larkspur Hills will be used by the USGS to aid development of 3D models of the basin’s subsurface
structures. These models will be available to guide local decision making in geothermal exploration.

My research will focus on detailed mapping and analysis of faults in the Larkspur Hills (Figure 2).
Preliminary work shows fault orientations in the southern hills differ from those in the northern hills,
and there are one or two significant NNE-trending faults (Figure 2). Faults to the south of these larger
structures are closely spaced and trend N-S, while to the north the faults trend NW. Both sets appear to
be truncated by the larger-offset structures. This preliminary analysis raises the following questions:
1 – How do the fault orientations relate to the regional stress field over time? One hypothesis is that
they mark a change in the orientation of the principal stresses over time, while another possibility is that
the NW-trending faults exploit a pre-existing fabric.
2 – What controls the change in the fault orientations from south to north? This could be due to fault
growth from south to north, typical of the NNE trending NWBR faults, such as the Surprise Valley fault
(Egger and Miller, 2011) and Abert Rim fault (Scarberry et al., 2010), with the northwest faults forming
as fractures along the propagating tip of a NNE developing fault (Trench et al., 2009). Alternatively, this could mark a point where there is a change in the underlying fabric; this could involve a large continuous structure at depth that is controlling the development of the faults in the southern portion.

**Background:**

**Fault initiation and growth**

In continental settings, extension initially results in the accommodation of strain in a set of diffuse faults and fractures (Gupta, 1998). Over time, strain becomes more localized and some faults become inactive while others connect and evolve into larger, through-going structures. This involves a change in growth mechanisms; isolated faults first grow through tip-line propagation (Figure 3), and then as faults overlap, they begin to link; linking is the dominant factor in the development of larger faults, rather than growth along tip-lines (Crider and Peacock, 2004). The linking process commonly involves the formation of a relay ramp (Figure 4) within the zone of overlap; further growth of the overlapping faults causes the ramp to fracture, and ultimately break. This breaching of the ramp can first occur anywhere along its vertical extent. Once fully breached, the two original faults connect as one large fault. This process is described in detail in Peacock and Sanderson (1994).

![Figure 3 – Fault growth along tip-lines. From White and Crider (2006).](image)
Fault growth and linkage has been studied both in the field and by constructing sandbox models. Field studies (e.g. Crider, 2001; Crider and Peacock, 2004; Peacock and Sanderson, 1994) typically focus on structures with small amounts of slip, as these capture the early stages of faulting. The results from field studies of small-scale faults compare favorably to more developed systems. In the lab, factors influencing fault initiation and development can be controlled using sandbox models (e.g. Hus et al., 2005, and Henza et al., 2011). These factors include: the amount and direction of extension, the thickness and composition of the layers, and multiple phases of extension. By manipulating these variables, geologists have been able to reproduce surface patterns seen in nature, and draw conclusions regarding the factors controlling fault geometries. Results of these studies also compare favorably to

![Figure 4](image_url)
fault systems in the field. One advantage of studying fault geometries using small-scale features, both in the lab and in the field, is that measurements of length, offset, and spacing between structures can be easily made. Among these measurements, fault displacement along strike is useful for creating displacement profiles; comparisons of the slip distributions across relay zones using displacement profiles (Figure 5) have resulted in distinct patterns that can indicate the degree of linkage (Peacock and Sanderson, 1994; Soliva and Benedicto, 2004). Profiles constructed from both field and lab studies indicate that faults usually have an elliptical or bell shaped displacement profile, and as individual faults link, the combined profile for the two faults will begin to resemble the profile of a single fault (Figure 5).

Figure 5 – Displacement profiles for overlapping faults. The top is a map view of fault traces, with elevation contours; the bottom is the displacement profile, with displacement for each fault shown. The displacement is summed in zone of overlap. Modified from Peacock and Sanderson (1994).
The existence of pre-existing or precursory structures, such as veins or joints, plays a critical role in the initiation and evolution of faults (Crider and Peacock, 2004). Rifting can also involve reactivating a large coherent structure at depth; the rupturing of this structure through subsequent cover can then appear as segmented normal faults at the surface (Giba, et al., 2012). Without data at depth, it can be difficult to determine how large faults evolved in mature regions, as resulting surface traces can be the same for different growth mechanisms. High quality 3D seismic data (e.g. Giba et al., 2012; Long and Imber, 2012) has shown that faults have complex subsurface geometries associated with fault growth, linkage, and reactivation. Long and Imber (2012) created displacement profiles for faults with known subsurface geometries, and suggest that these profiles may be useful to constrain the degree of fault linkages in the absence of subsurface data.

I am drawing on the body of previous studies of fault initiation and growth in order to determine the possible controls on the fault geometries in my study area by comparing patterns of surface traces, displacement profiles, fault distribution, as well as the nature and extent of linkages in the study area to those seen in previous field and lab studies. This helps me to limit the possible factors affecting fault formation and growth in the Larkspur Hills, which can then be tested.

Background: Field studies of the northwest Basin and Range

While most of the extension in the northwest Basin and Range is accommodated along large offset NNE trending faults, there are numerous diffuse NW trending segments with topographic relief lower than that of the longer, larger offset NNE faults (e.g. Trench et al., 2012; Scarberry et al., 2009; Crider, 2001; Pezzopane and Weldon, 1993). The Larkspur Hills east of the Surprise Valley marks a zone of transition for the NW fault set. In the vicinity of the Warner Range, there are prominent individual NW trending faults (Figure 1), whereas in the Larkspur Hills, the NW faults are more closely spaced, more numerous, and have less offset. These NW faults become more pervasive and dominant in
number north of this area into Oregon (Figure 1), where the NWBR terminates in the Brothers Fault Zone, which consists almost entirely of NW faults (Pezzopane and Weldon, 1993; Trench et al., 2012). An early interpretation of the NW faults, particularly in the Brothers Fault Zone, was that they were right-lateral strike-slip faults (Lawrence, 1976); however, this interpretation was based on satellite images and not verified in the field. Later field studies in southeast Oregon by Crider (2001) and Trench et al. (2012) indicate the faults have dip-slip or oblique-slip motion. Crider (2001) observed that the two fault sets appear to be coeval, based on map relationships. In the Summer Lake area, Crider (2001) indicated that the NW oblique-slip faults were likely the result of reactivation of basement structures, but could be the result of the influence of a pre-existing fabric.

Crosscutting relationships between the two fault sets in Oregon show a change from NNE-trending faults cutting the NW-trending set in the south, to mutually cross-cutting relationships towards the north; based on these observations, Trench et al. (2012) concluded that the NW faults develop along the fault tips of the NNE faults, with the NNE faults ultimately growing through (cross-cutting) the NW set (Trench et al., 2012).

Scarberry et al. (2009) found that the magnitude of extension on the NNE fault set decreases northward, consistent with the growth of NNE faults from south to north within the northwest Basin and Range. While Scarberry et al. (2009) acknowledge that regional studies have shown that the NW set formed either prior to, or coeval with, NNE-trending faults, along the Abert Rim fault they assert that the NW set formed at the northward propagating tip of the fault, and they interpret this as the formation of dilational fractures associated with fault tip propagation.

The existence of a pre-existing fabric is supported by findings of Scarberry et al. (2009); early Miocene (16.4 - 23.8 Ma) dike alignments of 5-10° and 290-315° in the Abert Rim fault region (Figure 1) are similar to both late Miocene (5-16 Ma) fault sets, which have average trends NW and NNE. Based on these orientations, Scarberry et al. (2009) conclude that faulting after 8.7 Ma may have reactivated a
pre-existing fracture system. Crider (2001) considered the reactivation of basement structures more likely, at least in the Summer Lake area, due to exposed complex older structures to the east and west which may also characterize the basement in the southeast Oregon volcanic plateau.

Previous work in the NWBR has led to a better understanding of the factors influencing fault patterns and orientations; however, the exact relationship of the two fault sets is still unknown, as is the main factor influencing their formation: either pre-existing fabric or reactivation of basement structures. This is important to constrain, as different factors controlling fault formation, interaction, and growth affect the subsurface geometries, and ultimately the location and flow paths of subsurface resources, such as geothermal fluids.

**Planned work**

I plan to contribute to the previous work by testing the hypothesis that the NW faults are fractures resulting from fault growth, examining the influence (if any) that one set has on the development of the other, and determining if the sets are coeval, or if they just appear that way due to volcanic cover. If one set formed before the other, the surface traces may be the result of initial formation of one set, and the reactivation of the other; this would appear as coeval faults due to both sets cutting the same units exposed at the surface.

I will do a detailed analysis of the faults in the Larkspur Hills by first mapping the surface structures in the ESRI GIS program ArcMap 10.1, using 2 digital elevation models (DEM}s). The first covers the southern part of the field area, and was generated from high resolution (1 pixel = 0.5 m) LiDAR point cloud data collected from aerial swath mapping conducted in July 2012; data was processed by Dr. Heezin Lee of the National Center for Airborne Laser Mapping (NCALM) at UC Berkeley. In order to map a wider extent, a DEM from digitized topographic maps at 3 m spacing was obtained from the USGS National Elevation Dataset. The DEMs were used to generate hillshade maps (as in Figure 2) for
the purpose of identifying fault traces, which is initially done by locating prominent cliffs on the
hillshade model. Where surface traces are not well defined, visual analysis is augmented by drawing
profiles across the faults. This involves interpolating a line perpendicular to strike, and then generating
an elevation profile. This is repeated along strike to identify distinct signs of fault offset, and typical
elliptical shape to fault offsets along strike (as in Figure 5).

In order to determine offset along fault traces, I will export fault data and associated DEMs to
send to Thomas Morrow, a graduate student at the University of Idaho. He has written a code for
Matlab that will calculate offset at a specified interval along strike, using the fault data and DEMs
imported from ArcMap. I will then correct for the effects of erosion, which causes fault scarp retreat,
and the maximum offset on each fault will be determined. The data will also be used to construct
displacement profiles for each fault. I will compare the displacement profiles for overlapping, and
apparently linked, faults to determine the potential extent of fault linkage, following the linkage
criterion for segmented normal faults of Soliva and Benedicto (2004) (Figure 6). The fault map will also
be compared to magnetic data to correlate surface traces to structures at depth. The combination of
the two methods will place tighter constraints on the subsurface geometries of the faults.

Figure 6 – Displacement profiles for overlapping faults.
(a) Open relay ramp.
(b) Relay ramp beginning to breach.
(c) Fully breached relay ramp.
Modified from Soliva and Benedicto 2004.
To determine the possible stress direction(s) for fault formation, I will use Rose diagrams, which are 360° histograms for sorting linear and planar features by their azimuth (Figure 7). The azimuths of fault segments are exported from GIS into StereoNet (Allmendinger et al., 2012), and sorted into bins on a Rose diagram. The azimuths are generated by drawing straight best-fit lines along mapped fault segments. The segment lengths are normalized to their associated fault lengths. Using the Rose diagram, the average azimuth can be estimated visually, or calculated. These diagrams also show groups of orientations, and so are useful in determining if there is more than one dominant orientation. Fault data can be sorted and plotted based on length of segments, location, or amount of offset. The average orientation for a fault set is indicative of the stress orientation at the time of fault formation, as the faults in an extensional regime will form perpendicular to the least principal stress direction.

I will also use stereonets to do a kinematic analysis. Fault plane data will be exported from ArcMap, and the program will calculate the poles to the planes, plot the resulting extension axes, and contour those axes using the method of Kamb (1959) (Figure 8). If the fault sets share a single extension axis, then they are kinematically compatible. If they do not, then the faults may represent different deformation events.

Figure 6 – Rose Diagram for fault segments from Larkspur Hills. Diagram includes segments that make up > 50% but <100% of fault length, total of 25 segments in bins of 10°.

Figure 7 – Example of a contoured stereonet from Emanuele et al. (2006).
Using the high-resolution DEM, the tip-lines of faults will be examined for indications of fault propagation folds (Figure 3) (White and Crider, 2006), and signs of NW trending fractures along tip-lines of N-NNE faults. Folds propagate along tip-lines as faults grow (White and Crider, 2006), so this process may be causing slip on pre-existing NW fractures as the NNE faults grow. I will use both remote data and field analyses to examine cross-cutting and truncating relationships between fault sets, in order to determine their relationship geometrically and temporally.

**Anticipated Results**

Based on previous studies in the region, and initial observations of the distribution and orientations of faults in the field area, I anticipate that the overall range of orientations is the result of a pre-existing NW fabric (of either faults or fractures) that formed under a different stress orientation, and that this underlying fabric is either being reactivated under the current stress field, or by localized perturbation of stress caused by the growth of large offset NNE faults, which grow from south to north. I suspect the N to NNE trending faults in the southern part of the field area are stemming from the reactivation of a continuous structure at depth. This is based on changes in fault patterns and distribution to either side of the larger structures, suggesting these structures may be barriers to rupture on one or both sets of faults to either side.

**Significance of research**

Through my research, I will generate a detailed fault map of the Larkspur Hills, determine stress orientation(s) of fault formation, and provide better constraint on the relationships of the two fault sets. This will contribute to our understanding of the extensional evolution of the northwest Basin and Range. Patterns in surface traces will be compared to subsurface patterns inferred from magnetic data (Figure 8) (Glen et al., 2013) to aid 3D modeling of basin structures by the USGS; determinations of how surface
Traces relate to fault linkages from the exposed faults will also be useful in 3D modeling of basin structures, where only the traces of subsurface structures are known. The results of this modeling will be available to local agencies for geothermal exploration.

Figure 8 – Comparison of initial magnetic data (Glenn et al., 2013) to initial surface mapping. Red dots on map are locations of hot springs.
References
### Schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 2013</td>
<td>- Complete initial mapping using remote data (LiDAR, DEM)</td>
</tr>
<tr>
<td></td>
<td>- Fault analysis – determine: offsets, average fault dip, average tilt of lava flows</td>
</tr>
<tr>
<td></td>
<td>- Target field sites for analysis and mapping</td>
</tr>
<tr>
<td></td>
<td>- Prepare field maps</td>
</tr>
<tr>
<td>Summer 2013</td>
<td>- Fault analysis – construct and compare displacement profiles, measure fault spacing</td>
</tr>
<tr>
<td></td>
<td>- Field Session: 2 - 3 weeks, 10 Jun – 30 Jun</td>
</tr>
<tr>
<td></td>
<td>- Analyze field data</td>
</tr>
<tr>
<td></td>
<td>- August: submit abstract to GSA for poster presentation – based on initial findings</td>
</tr>
<tr>
<td></td>
<td>- Field Session: 2 weeks, 26 – 7 Sep (UAS magnetic data)</td>
</tr>
<tr>
<td>Fall 2013</td>
<td>- Develop maps and figures</td>
</tr>
<tr>
<td></td>
<td>- Create poster for GSA based on initial results</td>
</tr>
<tr>
<td>Spring 2014</td>
<td>- Complete thesis: results and conclusion, revise abstract</td>
</tr>
<tr>
<td></td>
<td>- Defend thesis</td>
</tr>
</tbody>
</table>

### Budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Detailed cost</th>
<th>Total Cost</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 WD Truck Rental</td>
<td>3 weeks @ $225.00 per week</td>
<td>$675.00</td>
<td>High clearance 4WD vehicle needed for roads in field area. Vehicle cost will be split between myself and grad student working in the same area.</td>
</tr>
<tr>
<td>Lodging</td>
<td>3 nights @ $55 per night</td>
<td>$165.00</td>
<td>Local campsites are free, but one night per week at the hotel is needed for shower and laundry</td>
</tr>
<tr>
<td>Per diem</td>
<td>28 days @ $20 per day</td>
<td>$560.00</td>
<td>Covers all meals, snacks, and bottled water.</td>
</tr>
<tr>
<td>Fuel for vehicle</td>
<td>1284 mi 19 mi/gal 68 gal @ $4.00/gal</td>
<td>$272.00</td>
<td>Fuel not covered in vehicle rental - cost will be split between myself and grad student working in the same area.</td>
</tr>
</tbody>
</table>