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<https://doi.org/10.15760/etd.7425>

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The Rocky Ledge Fault, Shasta County, NE California: Development and Morphology of
a Quaternary Oblique Normal Fault in Basalt

by

Gregory David Linscott Martin

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

Master of Science
in
Geology

Thesis Committee:
Ashley Streig, Chair
Ray Weldon
Adam Booth

Portland State University
2020

Abstract

Distinct morphology, variable vertical separation, and unique structural geometries are observed along the Rocky Ledge fault (RLF), an east-dipping, oblique normal fault in the tectonically complex Hat Creek Graben, Shasta County, NE California. Situated in the southern Cascade arc, the RLF is located at the boundary of the Klamath Mountains, Basin and Range, and Walker Lane Seismic Belt. The primary goal of this project is to better understand Quaternary deformation along the RLF. I developed detailed maps of geologic units and structures along the ~15 km length of the RLF. Map data informs assessment of fault geometry, scarp morphology, and fault development processes. I define a step-by-step conceptual kinematic fault development model using area-balanced cross section restoration techniques that document the unique geologic structure and scarp deformation style. Offset initiates as a broad monoclinial fault propagation fold that breaks along the upper anticlinal axis as the scarp develops. The RLF has a sub-vertical ($\sim 85^\circ$) near-surface east dip that becomes less steep ($40\text{--}60^\circ$) with depth. West-dipping antithetic faults with scarps that present as along-strike “furrows” or troughs, displace talus material and form uphill-facing benches and breaks in slope in the lower portion of the main RLF scarp. I developed a profile of stratigraphic separation along the RLF fault length from measurements of vertical stratigraphic separation. The RLF is divided into three en-echelon sections. The southern section is ~7 km long with ~74 m maximum vertical separation, the central section is ~3.5 km long with 40 m maximum vertical separation, and the northern section is ~3 km long with 28 m vertical separation. Sections are separated by relay ramps, which span ~175 – 550 m widths between overlapping fault

tips. Future section linkage may occur with slip localizing at these overlapping tip zones. Cumulative vertical separation is considerably higher in the southern section than the central and northern sections. Along strike, vertical separation dramatically decreases over short fault lengths at the endpoints of each section, resulting in steep fault tip taper gradients (offset die-out). Global per-event average fault tip taper gradients range from 0.1 – 2.4 m/km, with 9 of 76 reported values (12%) exceeding 1 m/km (Thompson, 2017). At the RLF, 50% of average per-event displacement gradients exceed 1 m/km. Steep taper gradients suggest the RLF has significant cumulative vertical displacement relative to fault length. Frequent or large slip-per-event earthquakes are necessary to generate the observed cumulative vertical displacement at the RLF. Areas of significant future displacement (such as relay ramps) and the potential for anomalously large earthquakes are important considerations for evaluating fault hazards and associated risk assessment.

Dedication

I dedicate this thesis in part to the memory of friends lost during the completion of this project: Matt Paulson, and Damon, Sarah, and Duncan Brown. We miss you.

I further dedicate this work to my mother, Dr. Judith Linscott Martin, a student and a teacher, a fighter, and a true inspiration. I love you.

Acknowledgements

I am grateful for the mentorship, guidance, and support of my advisor, Ashley Streig, project partner and committee member Ray Weldon, and committee member Adam Booth. Thank you for your tireless efforts and enduring patience. I thank Mr. Cody Holly for excellent field assistance. Thank you to Pacific Gas and Electric, specifically Dr. Bill Page, for making lidar, cosmogenic age date, and other data available.

This project was funded in part by a Geological Society of America Graduate Student Research Grant (2017), Portland State University Geology Departmental Student Research Grant (2017), and through funding from Dr. Streig and Dr. Weldon. Thank you.

Dr. Ben Melosh, USGS, provided ongoing encouragement and academic motivation, for which I am thankful.

I benefitted greatly from time with my graduate student cohort and the faculty at Portland State University; thank you to all. Fellow students Alison Horst, Luna Brett, and Kris Hornsby provided useful insights and constructive suggestions that made this project better.

Education and the pursuit of knowledge are core family values; I owe a special debt of gratitude to my grandparents, Charles and Betty Jo Martin, for making financial arrangements many years ago that allowed my graduate education to happen. I also thank and acknowledge my maternal grandmother, Elizabeth Linscott, for her lifelong commitment to learning.

Thank you to the Martin, Richards, Elwell, and Dyson families for ongoing support, encouragement, and motivation.

I humbly acknowledge and am eternally grateful for the guidance, advice, support, and encouragement provided by my parents, Drs. John and Judith Martin; I could not have done this without you.

To my daughter Elliana, born during the early stages of this project, thank you for moral support and all the laughter!

Finally, for unwavering support, endless encouragement, limitless patience, and unmatched resiliency, I thank my wife, Elizabeth Martin. I love you.

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I. Introduction

Globally, crustal faults exhibit large spatial and temporal differences in rupture behavior primarily as a result of slip rate, fault maturity, and local rheology (Burbank and Anderson, 2012). Historic ruptures and paleoseismic records of coseismic surface displacement on faults reveal complex deformation and fault growth patterns, and seismic analysis of fault rupture behavior and earthquake frequency continue to improve as global databases of fault characteristics expand. These global datasets provide useful empirical relationships for first-order evaluation of fault rupture hazard. Hazard analysis requires data well beyond any specific location or facility, and human safety and critical infrastructure protection underpin the importance of this project. In this study I evaluate cumulative vertical displacement and extension, detailed fault scarp morphology, fault tip taper gradients, and linkage between fault sections to understand the mechanics of the Rocky Ledge fault (RLF).

The RLF is an oblique, normal fault located in the southern Cascade Arc east of the Klamath Mountains, west of the Basin and Range, and north of the Sierra Nevada Mountains and the Walker Lane Seismic Belt. Across the Pit River region, dextral shear from the Sierra Nevada and Walker Lane Seismic Belt transfers to the north toward the Klamath Mountains and Oregon Coast block (Unruh and Humphrey, 2017). The RLF, one of many structures accommodating strain in this complex region, bounds the northwest margin of the Hat Creek Graben, an extensional basin in Shasta County, northeastern California (Figure 1).

Figure 1. Hat Creek Graben (yellow star), general tectonic setting and significant geologic features. The study site is at the junction of six significant tectonic provinces including the Cascadian subduction zone, the Sierra Nevada-Great Valley block, the Klamath Mountains, the Basin and Range province, the Oregon Coast block, and the northern end of the Walker Lane Seismic Belt.

Totaling over 15 km in cumulative length, the RLF north of Burney Mountain is divided into three distinct sections that vary in length, dominant strike, vertical separation, and structural complexity (Figure 2). Several consultant and academic investigations have focused on nearby faults in the area, including the Hat Creek fault

bounding the east side of the graben (Blakeslee and Kattenhorn, 2013). Limited reconnaissance mapping (Piedmont, 2009; Austin and Weldon, 2013) has been conducted on the RLF, and cosmogenic exposure age dating has been carried out on the RLF and the nearby Old Lumber Mill fault (Rood, 2013; Rood et al., 2015; Penna, 2016). No comprehensive mapping or detailed morphological analysis has been completed on the RLF to date.

Figure 2. Regional fault map of the northern Hat Creek Graben showing relative fault activity and significant regional features including the Pit River and the towns of Burney and Fall River Mills (modified from USGS Quaternary Fold and Fault Database, 2006). The Rocky Ledge fault forms part of the northwestern boundary of the Hat Creek Graben.

The primary goal of this project is to better understand late-Quaternary evolution of the RLF by understanding the morphology of along-fault surface deformation in a basaltic terrain. Using lidar data, aerial imagery, and field observations, I generated strip maps of fault units and structural features in ArcGIS to detail the morphological surface expression of the RLF. I use a dense network of surface profiles oriented perpendicular to fault strike to measure the vertical separation along the fault length and generate a length-vertical separation profile, which I use to measure fault tip taper gradients, essentially how rapidly vertical separation decreases approaching an end point along the fault section. Fault tip taper gradients for sections along the RLF are compared to local, regional, and global fault taper tip gradients to evaluate how rapidly slip decreases along strike. I developed structural cross-sections from surface profiles and use area-balanced cross-sections to investigate scarp development processes, fault geometry, vertical and extensional displacements, and structural complexity across three sections of the RLF. I propose a model for Rocky Ledge fault development where offset initiates as a broad monoclinical fault propagation fold that breaks along the upper anticlinal axis as the scarp develops.

This work seeks to evaluate fault development processes and growth mechanisms at the RLF. A detailed understanding of RLF characteristics will also inform the overall understanding of the complex regional tectonics in the western Hat Creek Graben.

1. Geologic Setting

The Hat Creek Graben, in the “Lassen segment” of the southernmost Cascade Range (Muffler et al., 1994), is located to the south of Mount Shasta and the Pit River

and north of Mount Lassen (Figure 1). Located in an extensively faulted volcanic corridor (Figure 2), the morphology of the region reflects intersecting tectonic provinces, faulting, and recurring volcanic activity (Paguican and Bursik, 2016).

Earthquake activity in the Pit River/Hat Creek region reflects the large-scale interaction between the Pacific, North American, Gorda, and Juan de Fuca tectonic plates (Lahontan, 2012). East-west convergence and subduction of the Gorda plate under the North American plate results in arc volcanism as far south as Mount Lassen, 45 km south of the RLF. North-south shortening expresses as east-west structures in the Klamath Mountains west of the arc (Austin, 2013). The Sierra Nevada-Central Valley microplate moves northwest, driving northward motion of the Oregon Coast block relative to stable North America. The Walker Lane Seismic Belt bounds the Sierra Nevada –Central Valley block to the east and allows northwest movement (Unruh and Humphery, 2017). The Modoc Plateau, which bounds the Hat Creek Graben to the east and comprises the northwestern boundary of the east-west extending Basin and Range province, demonstrates extensive basaltic volcanism and extensional faulting (White and Crider, 2006).

Oblique normal faults are prevalent in basaltic terrain in part because of the association of basaltic volcanism and extensional, rifting regimes (Blakeslee and Kattenhorn, 2013). Individual normal faults in the Hat Creek area (e.g. Hat Creek fault, Figure 2) exhibit well-defined left-stepping, en echelon patterns consistent with releasing, extensional geometry and transtensional dextral shear (Lahontan, 2012). The west-dipping Hat Creek fault, the most extensively studied fault in the area, represents the

eastern boundary of the Hat Creek Graben (Muffler et al., 1994). Studies of the Hat Creek fault yield a slip rate of 2.2 - 3.6 mm/year and estimate the fault can generate a $M_w \sim 6.7$ earthquake with a recurrence interval of 667 ± 167 years (Blakeslee and Kattenhorn, 2013). Exposure dating of earthquake-generated antithetic bedrock fault scarps at the Hat Creek fault suggest the most recent ground-rupturing earthquakes occurred around 12.4 ± 0.5 ka and 9.6 ± 1.2 ka, with $> 2.6 - 2.9$ meters of slip per event (Rood et al., 2015).

2. Geology, fault morphology, and long profiles along the Rocky Ledge fault

The RLF, which forms part of the north-western boundary of the Hat Creek Graben (Austin and Weldon, 2013), is a generally north-south trending, east-dipping, oblique normal fault, and offsets the $\sim 214.8 \pm 9.2$ kyr Basalt of Rocky Ledge with an estimated slip rate of 0.35 ± 0.05 mm/year (Rood et al., 2015). The right-lateral component of faults in the Hat Creek Graben and surrounding area is difficult to constrain due to mostly flat, basaltic units being offset. Therefore, I focus on the measurable dip-slip component. The Basalt of Rocky Ledge is a columnar-jointed basalt that inundated low topography between higher remnants of much older (> 1 Ma) volcanoes in the northern Hat Creek Graben (Figure 3) (Muffler et al., 2012). While the thickness of the Basalt of Rocky Ledge is not well documented, it is generally thought to extend at least 5 meters in depth and is much thicker in places. A strong paleotopographic influence exists, where the layer is thicker where paleo channels were filled and thinner on paleo-highs. This low-potassium olivine tholeiitic basalt shows ropey pahoehoe texture at the surface and corresponding pipe-vesicles (gas bubble traces), which indicate paleo-top of boulders and serve as an upward indicator on these basalt flows, as well as

flow breccias that indicate paleo-bottom (Rood, 2013). In the central portion of the RLF, an older volcanic unit is found west of the main scarp and forms a prominent topographic peak, against which the Basalt of Rocky Ledge onlaps and thins (Figure 3).

In the late 1980s, geologists for the State of California documented closed depressions along side-hill troughs within RLF talus, with exposed boulder surfaces appearing “very fresh to significantly weathered” (Wills, 1990). This was interpreted to mean the talus had been over-turned during Holocene time, and the RLF was subsequently zoned active under California’s Alquist-Priolo Fault Zoning Act (CGS, 1991).

Limited data exists regarding earthquake timing at the RLF. Cosmogenic ^3He surface exposure age dating samples were collected from large rockfalls and antithetic fault exposures, and a total of 34 ^3He cosmogenic surface exposure age date estimates have been determined for fault perpendicular transects across the RLF in the southern (18 samples) and northern (14 samples) sections (Rood, 2013; Rood et al., 2015). In the south, exposure dates of ~5 - 52 ka were determined with a cluster at 11.8 +/- 1.5 ka (n = 5) collected from a rockfall, which was interpreted as a possible “most recent” earthquake event around 12 ka at the RLF (Rood, 2013). Understanding earthquake timing helps inform our understanding of possible per-event displacements and fault growth and scarp evolution scenarios.

Figure 3. Geologic setting and lidar coverage of the Rocky Ledge fault and northwestern Hat Creek Graben area. A) Lidar-derived hillshade map showing three distinct fault sections (A – C, south to north). Broad surface profile locations are shown near the middle of each fault section (Figure 4). B) Geologic map of the Rocky Ledge fault and the surrounding area (modified from Muffler et al., 2012). The majority of the western Hat Creek Graben is capped by the Basalt of Rocky Ledge (brl), an approximately 215 ka tholeiitic basalt, with a small outcrop of older volcanic rock (vo) mapped along the central portion of the RLF.

The RLF is divided into three prominent roughly N-S striking sections which step left from the south to the north. In each section, the scarp has a steep upper footwall area west of the primary fault trace, while the lower 1/2 to 2/3's of the scarp consists of a partially collapsed monocline limb which is covered by basalt talus deposited from the eroded cliff face above. The talus-covered slope contains peaks and troughs, which form benches and uphill-facing breaks in slope within the talus and disaggregated basalt bedrock (fault furrows). Fault scarp furrows along the RLF may exhibit antithetic

monoclinial fold deformation without a clearly associated antithetic fault (Piedmont, 2009). Furrows could be a surface expression of a blind (buried) antithetic fault. Piedmont (2009) argues that this may in part be a characteristic of a hanging-wall rollover, and that could indicate shallowing of the RLF dip angle with depth in the near-surface. Austin and Weldon (2013) map offsets along the RLF with high-resolution lidar derivatives and identified a component of dextral shear along the RLF, with northeast-striking segments acting as releasing bends in a dextral system that accommodates vertical offset (Austin and Weldon, 2013). The amount of cumulative dextral displacement along the RLF is currently unresolved. This study resolves cumulative vertical displacement and extension along the RLF, though does not evaluate net displacement including the dextral component of shear.

Figure 4 shows three long surface profiles, oriented perpendicular to RLF strike, which span the available swath of lidar coverage. These profiles reveal a hangingwall rollover east of the scarp in the in the central and southern portions of the study area, where the valley floor drops at the base of the scarp, as well as backtilting of the footwall west of the scarp. Outcrop-scale profiles and cross sections discussed in detail herein do not fully encompass far-field deformation across the RLF. In particular, kilometer-scale tilting of the original Basalt of Rocky Ledge is likely due to additional shallowing of the dip of the fault well below outcrop-scale area-balanced cross sections.

Figure 4. Long profiles across the RLF oriented approximately east-west, perpendicular to RLF strike (Figure 3). In each profile the X-axis is horizontal distance along the profile (m) and the Y-axis is elevation (m). Vertical exaggeration (V.E.) in all profiles is 20 x. A) Profile A – A' shows down-to-the-east vertical separation across the fault. The valley bottom adjacent to the base of the scarp is nearly flat for approximately 500 meters, beyond which the hangingwall dips approximately 2° west, towards the RLF. A broad hangingwall rollover anticline appears present east of the RLF scarp, and backtilting of the footwall is apparent to the west of the scarp. B) Profile B – B' showing east-side down vertical separation along the RLF. A steep drop in the valley floor is located at the base of the scarp and represents a possible hangingwall anticline, beyond which the footwall dips approximately 1.5° west, towards the RLF. Backtilting of the footwall is visible west of the RLF scarp. C) Profile C – C'; east of the scarp the valley floor gradually increases surface elevation eastward, away from the fault.

II. Methods

1. Mapping

Using ArcGIS software, I conducted preliminary mapping of the RLF remotely with publicly available aerial imagery and 1 m resolution lidar coverage of portions of the Pit River and Hat Creek Graben area provided by Pacific Gas and Electric (Figures 3, 5). Aerial photographs clearly show vegetation, which can be indicative of certain units (i.e. the difference between talus and colluvium). Lidar derivatives include slope; aspect (the direction a slope is facing); slope-shade (steep slopes are shaded, and gentle slopes illuminated, regardless of sun angle); and contours (Figure 5). I field-verified primary surface units and structural features along the fault scarp along the northern RLF at a scale of 1:2,000 or better. The lidar dataset is limited by its 1 m resolution, so some fine structures <1 m scale are obscured.

I extracted 142 surface profiles along the length of the fault, spaced semi-evenly and oriented perpendicular to fault strike. I used these topographic profiles to follow subtle contacts and geomorphic features along strike and correlate surface fault expression in profile view, including breaks in slope or up-hill facing scarps. I measured along the profile length to determine the map position of structural features and unit contacts. These observations were combined with map-view lidar derivatives and aerial imagery to map the areal extent of structural features and geologic units.

Figure 5. Example of airphotos and lidar derivatives used to map the RLF. North is up in all six images. A) Overview map of the RLF; images B – F are located on the southern fault denoted by the red box. B) Aerial imagery: GeoEye, USDA orthoimages. C) Slope map, warmer colors indicate steeper slopes (red is very steep), cooler colors represent gentler slopes (green is nearly flat). D) Slope aspect, showing the slope direction (yellow = east facing slopes, red = north, blue = south, and green = west). E) Slope-shade image, a grayscale slope gradient (black is steep, white is gentle slope) with 40% transparency draped on hillshade with 315 azimuth. F) A partially transparent hillshade image draped on the lidar DEM with 2 m contours.

During field reconnaissance I collected strike and dip data on complex, unique, and representative structural features, and I visually observed the entire length of surface

rupture north of Highway 299. I used a Trimble Geo7X handheld differential GPS to document the positions of map features and photographs. The GPS data was post-processed using Trimble Pathfinder software to improve the horizontal accuracy.

2. Stratigraphic and Vertical Separation Measurements and Length-Vertical Separation Profile

Stratigraphic separation of the ground surface across a fault is the distance between projected, unwarped surfaces in the hanging wall and footwall, where bedding defines the slope on each side of a fault (Caskey, 1995) (Figure 6). Vertical separation is the amount of apparent offset measured in a vertical plane that is normal to fault strike (Figure 6). I used 238 lidar derived surface profiles oriented perpendicular to fault strike to measure vertical and stratigraphic separation (Figure 7a). Stratigraphic separation, the vertically offset distance between the top of the Basalt of Rocky Ledge, is used for subsequent evaluation of vertical offset along the fault length. I modified the existing method (Caskey, 1995) to establish an anchor point on the top of the footwall rather than the hangingwall, which is deformed and obscured by talus at the RLF. Fault scarp components and all features used to measure separation are shown on Figure 6.

Figure 6. Vertical separation methodology modified from Caskey (1995) for a complex normal fault scarp. The solid lines are the ground surface on the footwall and hanging wall, stars denote anchor points used to correlate separation of the ground surface across the fault scarp. Slope parallel dashed lines project from anchor points and indicate stratigraphic separation (h), VS_c and VS_m indicate vertical separation across the fault.

A topographic profile from the northern section of the RLF illustrates the approach used to measure vertical and stratigraphic separation (Figure 7). This approach is modified such that vertical and stratigraphic separation can be measured on surfaces that are not oriented parallel or sub-parallel. Where offset surfaces are not parallel or sub-parallel, broad deformation such as footwall back-tilting and hanging-wall roll-over may occur, as shown in the broad profiles (Figure 4). In these complex locations this

measurement technique provides a consistent way to evaluate vertical separation across the fault scarp.

Figure 7. Example of vertical separation measurements along the RLF. A) Locations of 238 surface profiles, oriented perpendicular to fault strike, numbered from south to north. The green cross is the “zero-reference benchmark,” the point from which all fault length measurements were started. B) An example along the northern RLF, location indicated in part A.

Profile locations were measured along the fault strike from the upper ledge of the fault scarp starting from a benchmark placed at the southern extent of the map at the intersection of Mountain View Road and an unnamed N-S oriented road at the base of the RLF scarp shown as the zero reference benchmark in Figure 7 (lat/long 40.8769, -121.6200). Next, the fault section and cumulative stratigraphic separation measurements (h_m) (Appendix A) were plotted by position along the RLF to develop a profile of stratigraphic separation along fault length. Volcanic rock older than the Basalt of Rocky Ledge is mapped on the upper surface of the footwall block south of Highway 299 (Figure 3) and the Basalt of Rocky Ledge is mapped on the hanging-wall. Because the surficial geologic units on either side of the fault are not the same, I cannot use the

standard vertical separation technique described above. In this area, I projected the Basalt of Rocky Ledge surface from the west and used this as the upper surface.

I terminate each fault section where separation goes to zero. North of Section B and south of section C subtle offset is apparent as gentler <1 m high folds and scarps beyond the termination point; these values are not included in the profile of continuous vertical separation along fault length.

3. Fault Tip Taper Gradient

At the end points of each fault section we can measure how rapidly vertical displacement decreases along fault length. The slope of a line from the selected vertical displacement point to the end of the fault tip is the gradient (meters of displacement per length of fault [m/km]). I measured from the initiation of displacement to the vertical displacement one kilometer from the end (referred to as the 1 km taper gradient). I also measured from the tip to the first significant break in the profile slope (the break-in-slope gradient).

4. Area-Balanced Cross Sections

The response of rocks to extension is generally not as well understood as their response to compression (Rowan and Kligfield, 1989). However, the application of restoration and area-balancing principles to structural cross sections allow geologically valid interpretations and provide valuable insights into fault geometry and the processes responsible for scarp evolution. Area-balanced cross sections assume conservation of cross-sectional area of a deformed section in an extensional setting (Gibbs, 1983). A simplified two-dimensional area-balance can be used to estimate both vertical and

extensional separation by taking the current deformed surface (length = l_1) and retro-deforming it to pre-earthquake condition (length = l_0). Dextral slip is not reflected in cross section, although the units have constant thickness along strike, so area balancing can still be applied.

I applied iterative cross section restoration and area-balance techniques to evaluate possible fault geometry and assess fault development models (Figures 8 and 9). I use section 1-1' as an example, which is presented in greater detail in subsequent sections. A simplified area relationship shows the deformed area equals the undeformed area (Figure 8a), and this relationship can be used to evaluate general fault characteristics and estimate a preliminary fault dip angle (Figure 8b). I measure the area of the deformation zone (Figure 6; Area A, Figure 8c) and relate this to the heave (H) and throw (T) (Figure 6; Area B, Figure 8c) (Equations 1, 2).

$$\text{Area A} = \text{Area B} \quad (1)$$

$$H = \text{Area A} / T \quad (2)$$

I then estimate the dip of the fault based on the dip-slip relationship of the vertical and horizontal displacement (Figure 8c). The vertical throw (T) divided by dip-slip (DS) is the sine of the fault angle (dip), θ (Equation 3):

$$\sin^{-1}(T/DS) = \theta \quad (3)$$

Figure 8. Area conservation in deformed sections used to evaluate fault geometry. A) The conceptual framework of cross section area balancing, modified from Gibbs, 1983. In Gibbs' model, block A is before deformation, block B represents post deformation, block C is not affected by faulting, L_0 is the pre-deformation ground surface length, L_1 is the post-extension ground surface length, e is extension and d is the depth to a very low angle detachment fault. My application of this concept does not assume the presence of a detachment fault but does use a general reference frame of heave (H) and throw (T). B) The geometric relationships of heave, throw, and dip-slip (DS) used to estimate preliminary fault dip angle (θ) of the RLF, modified from Caskey, 1995. C) Section 1-1 in the northern RLF. The bold line labeled **a** shows a surface profile derived from lidar. The cross hatched triangle at the top of the fault scarp labeled **b** shows the erosional area of the footwall. The solid black line labeled **c** (about 3/4 of the way up the scarp) shows the mapped RLF location, dip unresolved. Block A shows the area of the deformation zone. The bold hashed wedge at the lower scarp, labeled **d**, depicts the talus cover of the lower scarp slope. The hangingwall area above the elevation of the valley floor is greater than the eroded scarp area of the footwall, indicating the zone east of the fault is composed of both talus material and broken-in-place

bedrock. Block B represents the conceptual pre-deformation zone area and provides a reference frame to evaluate fault geometry.

The approach outlined above and in Figure 8 yields a preliminary RLF fault dip angle but lacks sufficient detail to evaluate the complex scarp morphology and structural geometry of the RLF. Therefore, iterative cross section restoration is applied to improve calculations of the fault dip angle and assess scarp morphology. Area-balance of both eroded and deposited material and gap/overlap of bedrock and fault planes are used to assess fault geometry both in the near-surface (10's of meters) and at depth (100's of meters), and to estimate vertical and extensional displacement (Figure 9). Structural and stratigraphic complexities along the fault include a greater area east (right) of the fault plane compared to the eroded footwall (Figure 8c). A steep (sub-vertical) near-surface fault dip angle appears likely based on the size of the eroded footwall wedge and presence of talus on the lower scarp slope. However, extension is required to create accommodation space necessary for the monocline blocks that accounts for the non-talus footwall component; this requires a less-than-vertical fault dip angle. The RLF has at least two dominant dip angles; very steep in the near surface and less steep at depth. The rate and volume of footwall erosion is not homogenous along the length of the RLF, with some areas experiencing large rockfalls and other areas of near-vertical basalt cliffs remaining largely intact. Conventional scarp diffusion models which assume more uniform erosion do not accurately reflect the variability of RLF scarp morphology. Developing area-balanced cross sections allowed the evaluation of fault geometry, scarp morphology, and possible deformation models. The construction method followed the workflow outlined below.

1. Pick location of interest and create a surface profile from lidar using 3D Analyst in ArcGIS. Set axis scales to 1:1.
2. Plot main and possible antithetic fault locations (refer to map); set dip angles (e.g. 80-85° for main, ~45-50° antithetic) which will be refined to provide balance (Figure 9a).
3. Reconstruct the pre-faulting monocline: measure a monocline surface at a sub-parallel angle to the existing profile ground surface angle (e.g. 25°); project the surface through the eroded upper bedrock area; move the hanging wall monocline limb up the primary fault until the valley top connects to the limb (Figure 9b).
4. Unfold the monocline to get the undeformed, level state; the original surface length (L_0) can be measured here (Figure 9c).
5. The monocline limb (east of the fault) detaches from the footwall along the main near-surface fault and slides down the lower fault (dip determined previously; this allows extension) (Figure 9d).
6. The hangingwall above the ground surface and east of the main fault is a larger area than the area of eroded bedrock from the footwall, west (left) of the fault (Figure 9e). The eroded material from the footwall gains porosity (and therefore volume) as it is deposited as talus on the slope below. The porosity of the talus material ranges from about 60% at the surface to 30-40% at 25 m depth (Scapozza et al., 2015). An estimate of 50% porosity (twice the eroded area) is used for the talus wedge. Adjust the collapsed monocline limb blocks as necessary to accommodate the deposited material. It may be necessary to adjust the fault angles both near-surface and at

depth, and adjustments may also be necessary to steps two and three. Iterate as necessary. Move the partially collapsed monocline limb blocks along the faults (both primary and antithetic) to close the gap created by slip along the lower fault. Overlaps of the blocks (i.e. at the fault contact) should balance with gaps created by the movement along the near-surface and deeper fault.

7. The extension within the scarp can be measured by subtracting the original ground surface length (Figure 9c) from the final surface length (Figure 9f). The vertical displacement is the difference in elevation of the top of the uneroded footwall and the base of the scarp.

Figure 9 (previous page). Cross section restoration and area-balance techniques using section 1-1' as an example. In the figure, presented as sequential steps A through F, the x-axis is always the horizontal distance (meters) along the cross section line, the y-axis is elevation (meters), and there is no vertical exaggeration. A) Using a lidar-derived surface profile, plot the mapped main fault labeled **a** and antithetic fault(s), labeled **b**. Arrows show relative fault motion. The dip is estimated at sub-vertical to the east for the main near-surface fault and approximately 45° to the west for the antithetic faults. The RLF at some depth (labeled **c**) has a preliminary dip calculated using the process described in Figure 8. B) Add shallow marker beds (labeled **a**) to help illustrate the scarp, and reconstruct the footwall at the top of the scarp labeled **b**. A pre-fault monocline surface has a sub-parallel angle to the observed surface angle and is approximately the length between the main fault and the base of the scarp labeled **c**. Incipient antithetic faults can be extended within the hangingwall monocline block. Slide the monocline limb up the main fault to reconnect the ground surface. Some thrusting may occur due to compression from folding near the scarp base (labeled **d**). The interaction of the near-surface main fault, antithetic faults, and main fault at depth are extrapolated and labeled **e**. A deep marker bed labeled **f** illustrates the displacement that has occurred. C) After unfolding the monocline back to a conceptual undeformed state, the pre-deformation ground surface length (Figure 8a, L_0) is measured (labeled **a**). The main fault at depth may be shown (**b**), but no marker beds are offset, indicating surface deformation has not occurred. D) The hangingwall monocline limb breaks from the footwall along a steep near-surface main dip (**a**). The base of the scarp may have a defined antithetic fault (**b**). Slip occurs along the deep fault, which creates accommodation space (**c**). E) The footwall at the upper part of the scarp (labeled **a**) erodes, depositing talus material on the slope below (**b**). The area of the hashed red zone on the footwall is half the area of the stippled green zone at the surface of the hangingwall. Blocks of the partially collapsed monocline limb occupy the space created by the fault movement at depth, and complex subsurface fault-bedrock interactions are depicted as area-balanced gaps and overlaps (**c**). F) The extensional displacement can be measured from the difference of the original surface length (Figure 8a, L_0) labeled **a**, and the post-deformation surface length (Figure 8a, L_1), labeled **b**. Vertical displacement is the elevation difference between the top of the scarp and the bottom of the scarp (labeled **c**).

By conserving area and quantifying erosion and deposition, we can estimate displacement and fault geometry. Section restoration and area-balance provides a way to evaluate fault characteristics such as dip angle and relative displacements, as well as assess possible scarp and fault development scenarios. However, the interaction of bedrock and faults is a complex, dynamic, and unobservable process that occurs at depth.

III. Results

1. Geologic Units and Structures Along the RLF

Fault Units

Four primary geologic fault units are identified along the length of the RLF and detailed in Table 1. Unit 1 is a cliff forming layered basalt flow that forms the free face of the upper fault scarp. Unit 2 is a colluvial talus slope high on the scarp, parallel to the base of the free scarp face. Unit 3, which comprises the lower 1/2 to 2/3 of the scarp face, is a combination of talus deposited from above and bedrock monocline limb broken up in place. Unit 4, at the base of the fault scarp, is broken up Basalt of Rocky Ledge, partially mantled by soil, and is not consistently found along the length of the RLF.

Table 1. Fault Units: Observations and Characteristics	
Name	Description
Unit 1	A cliff-forming layered basalt flow (BRL) with ropey upper surface texture, characterized by a lack of vegetation and steep relief. Observed as a steep topographic drop between the upper valley top and underlying colluvium unit, with near vertical cliffs greater than 10 m high observed in places.
Unit 2	Slope-forming, vegetated layer underlying the prominent cliff-forming basalt bedrock. This unit ranges in thickness from greater than 10-m to non-existent along the trace of the RLF. It is characterized by pulverized, angular bedrock with surface soil development and sparse to abundant vegetation including trees, shrubs, and grasses.
Unit 3	Small (~0.2-m) to very large (>4-m) “mega blocks,” sub-rounded to angular basalt boulders that are distributed along the lower 1/2 to 2/3 of the scarp face. This unit has very little to no soil development evident and is the most extensive observed along the length of the RLF.
Unit 4	Basal scarp unit partially mantled by soil and vegetation; discontinuous along the length of the RLF.

Figures 10 and 11 show representative photographs of fault units along the RLF. Figure 10 shows an example of units exposed in the southern portion of section B, while Figure 11 shows a mega-block from Unit 3.

Figure 10. Representative photograph of mapped fault units taken along the southern portion of the central section (section B) of the RLF. Inset map shows photo location (white star). View is looking to the west at the RLF scarp.

Figure 11. “Mega-block” observed in Unit 3 near the northern tip of the RLF. Inset map shows the photo location (white star). Geologist for scale.

Off-fault Units

Several surface units were mapped above and below the RLF scarp (Table 2). The Valley Top unit, west of the RLF and above Unit 1, is generally flat to hummocky soil mantled basalt with scattered bedrock outcrops and sparse to dense vegetation including trees, shrubs, and grasses. The Valley Bottom unit is similar to the Valley Top but is found below the RLF to the east. Near the central portion of the RLF a layered basalt flow mapped as older volcanics (Muffler et al., 2012) is located above Unit 1 between the RLF and the Valley Top. A circular volcanic vent within the Basalt of Rocky Ledge is located at the southern edge of the RLF.

Table 2. Off-fault Units: Observations and Characteristics	
Name	Description
Valley Top	This unit comprises the top of the footwall, above (and west of) the RLF scarp. A thin soil mantle covers a basaltic surface and displays a low topographic gradient with soil development, grass, and forest cover present. Land use including timber access roads and forestry operations evident throughout this unit.
Valley Bottom	Similar to the valley top unit, this unit includes a thin soil mantle on basalt, vegetation such as trees, shrubs, and grasses, and timber access roads and forestry operations.
Older Volcanics	A layered basalt flow at least 788 ka old (Figure 3) (Muffler et al., 2012).
Volcanic Vent	Circular volcanic vent located at the southern extent of RLF section A and north of Burney Mountain.

Structures

Several geologic structures are identified along each section of the RLF including the primary fault trace, antithetic faults and synclines, and compressional features (Table 3). The primary RLF trace strikes roughly north-south to northwest-southeast and dips to the east, with vertical displacement down to the east. At the base of the slope, a fold axis bounds the scarp, and in places is expressed as a west-dipping antithetic fault that often

separates Units 3 and 4. Within Unit 3, smaller west-dipping antithetic fault scarps are identified where distinct uphill (west) facing benches with prominent peak and trough morphology are apparent (Figure 12). These furrows are generally oriented along strike with the RLF and persist for 10's to 100's of meters. In the lower part of Unit 3 and in Unit 4 compressional features including anticlines are present (Figure 13).

Table 3. Persistent Geologic Structures: Observations and Characteristics	
Name	Description
Primary Fault Trace	The east dipping primary RLF fault trace is observed in the upper $\frac{1}{2}$ to $\frac{1}{3}$ of the scarp, between Unit 1 and Unit 3, and is often coincident with Unit 2.
Main Antithetic Fault	A west-dipping antithetic fault is found at the base of the scarp, often separating Unit 3 and the valley bottom or Unit 4.
Smaller Antithetic Faults	West-dipping antithetic fault scarps found within Unit 3 exist for 10s to 100s of meters along-strike with the main RLF.
Compressional Features	Compressional features caused by localized thrust faulting and likely driven by flexural slip are observed on each of the RLF sections. The majority appear in Unit 4, although some thrust features may be present in Unit 3 as well.

Figure 12 (previous page). Section A, looking along the axis of a disaggregated furrow (visible in the central portion of the image) in Unit 3 from the base of the scarp; view is looking to the north. A) The photograph is annotated to show the furrow trough and peak. B) Map shows the photo location (white star). View is looking to the north-northwest from the base of the scarp.

Figure 13. Annotated photograph of a compressional anticline in Unit 3 on the central portion of section B. Photo looking to the south at the base of the RLF scarp. Photo annotations show parting surfaces in the basalt and the anticline axis shown by the solid blue line. Inset map show the photo location.

Unique structural elements along each of the three RLF sections are identified and summarized in Table 4. This includes fault splays along sections A and B, which show 5-10 m of vertical offset and diminish within 10's of meters of the primary RLF trace (Figure 14). Broad folding is observed north of section B and east of section C (Figures 14 and 17). In the southern portion of section A and the central area of section B, the valley floor drops steeply at the base of the RLF scarp (Figures 15 and 16). A north-south trending down-to-the-east fault scarp not within the Basalt of Rocky Ledge is located west of the southern portion of section A (Figure 14). This western fault scarp is not included in the “active” Alquist-Priolo zoned fault trace and is classified as

“undifferentiated Quaternary deformation” (Figure 2) (CGS, 1991; Sawyer and Bryant, 1995; USGS, 2006).

Table 4. Non-persistent Geologic Structures: Observations and Characteristics	
Name	Description
Fault Splays	Fault splays within Unit 1 trend away from the main fault trace. These features show some vertical offset and diminish quickly (within 10's of meters horizontally).
Broad Folding	Broad monoclinal folds within the Valley Bottom and Valley Top units; generally subtle, low relief topographic features.
Steep Drop of the Valley Bottom at the Base of the Scarp	In the southern portion of section A and the central portion of section B, the valley floor drops steeply to the base of the RLF scarp. This is not observed near Section C, the northern area of the RLF.
Scarp Associated with RLF in Burney Mountain	West of the southern portion of section A, vertical displacement is observed that extends into the base of nearby Burney Mountain (Figure 2).
Isolated Faulting	North of the northern extent of section A and east of south-central RLF section B, a short (~300 m) west dipping fault is observed, which appears to have corresponding east-dipping antithetic faults west of this primary trace. This short, isolated fault cluster is along-strike with RLF section A and approximately parallel to section B.

2. Detailed Mapping Along the RLF

The RLF is subdivided into three main left-stepping sections, subdivided into sections A – C from south to north (Figure 14). Section A is the longest section (7.28 km) with the greatest vertical offset (74 m) and has the best developed structural features (e.g. Table 3) (Figure 15). Section B is 5.24 km long and shows a maximum stratigraphic separation of 42 m (Figure 16). Section C is the shortest (2.76 km) with the lowest vertical offset (28 m) (Figure 17). Total cumulative mapped fault length of all three sections is 15.28 km.

Section A strikes roughly N-S and shows a prominent ~25° right bend ~3 km from the southern edge where the RLF encounters the older volcanic unit (Figure 3), which forms a dominant topographic peak near the central reach of the section (Figure

14). Section B strikes 350° to 330° south to north. A short ~ 350 m long west dipping fault scarp is exposed 200 m east of section B (Figure 16).

Section C strikes $\sim 355^{\circ}$. At its northern tip, the fault is expressed as a prominent monoclinial fold (Figure 17). Several folds are mapped east of section C and north of section B (Figure 14). At the base of the scarp the valley floor drops steeply along section A (Figure 15) and section B (Figure 16), and areas of the footwall at the top of the scarp appear to be backtilted (Figure 4, Figures 14, 15 and 16). Section B is separated by a left step from Section A by a ~ 175 m wide west-dipping relay ramp (Figure 18b). The RLF then steps left to Section C via a ~ 550 m wide gently west-dipping relay ramp (Figure 18c).

Explanation of Map Units

Unit contacts approximate

Fault Units

u1 Unit 1 **u3** Unit 3

u2 Unit 2 **u4** Unit 4

Other Units

Vo Older Volcanics

Vv Volcanic Vent

Explanation of Structural Features

Feature locations solid where well located, dashed where approximate, ball and bar on downthrown block of normal faults

East Dipping Fault Fault Splay

West Dipping Fault

Monocline Anticline

Syncline; shorter arrow tail on steeper limb

Explanation of Additional Features

Population Center Highway

Cross Section Location Pipeline

Strike and Dip Flat Topography

DEM (1 m) Elevation Color Ramp

High: 1048.9
Low: 908.4

Contour
Interval: 2 m

Mag
North
14.8

Map Resources: ESRI, USGS, Google Earth

Figure 14. Overview geologic map of the RLF including surface units, structural features, and nearby towns. Detailed geologic unit descriptions are included in Tables 1 and 2 and morphologic descriptions of structures are included in Table 3. Legend components shown here are also used for Figures 14-17. Inset: simplified RLF map showing sections A, B, and C from south to north as blue, orange, and green, respectively.

Figure 15. Geologic fault map of Section A showing primary units and structures identified in this study. A) The northern portion of section A. The RLF steps to the right, east of the “older volcanics” unit (~788 ka, Muffler et al. 2012). Tens of meters of primary displacement is accommodated along this step, although a cumulative displacement of over 70 m continues to the north before tapering to zero at the northern tip of section A. B) The N-S striking southern portion of section A, where the most pronounced talus furrows are found (near cross section 3-3'). The footwall at the valley top is backtilted in this area. There is a volcanic vent in the Basalt of Rocky Ledge near the southern tip of section A. See Figure 14 for the map legend.

Figure 16. Geologic fault map of Section B. Section B trends roughly 330° - 350° N-NW over 5.24 km. The highest V_s along Section B are observed along the southern portion of this section of the RLF, which then bends ~20° to the NW and V_s decreases to 10 - 20 m before tapering to 0 - 10 m broad monoclinial folding in the north. The footwall at the top of the scarp appears backtilted in the central part of section B, and the valley floor drops at the base of the scarp. An inset map is shown for an area of secondary faulting 250-300 m east of the main RLF trace. The secondary structures trend N-NW and have a primary dip opposite that of the main RLF (to the west). See Figure 14 for the map legend.

Figure 17. Geologic fault map of section C. This is the northern-most section of the RLF, it is the shortest fault length, 2.76 km, with the lowest vertical separation across the fault (28 m). This section trends roughly N-S, with a minor left bend in the center of the section. Vertical separation along the length of the section transitions from brittle scarps to monoclinial folding along the northern 50 - 100 m of the section. Several broad east- and west-dipping monoclinial folds are mapped within 200 meters of both the hanging wall and foot wall. See Figure 14 for the map legend.

Figure 18. Map highlighting relay ramp structures separating overlapping tips of fault sections at the RLF. A) Overview of the RLF, boxes show the locations of relay ramps separating fault sections. B) Relay ramp between sections B and C. C) Relay ramp structure between sections A and B.

3. Stratigraphic Separation Along Strike

Stratigraphic separation values are plotted along strike from south to north in Figure 19. Section A values are blue, section B is orange, and C is green. Cumulative separation is shown as black lines where fault sections overlap. Maximum stratigraphic separation of 74 m is measured approximately 5.1 km north of the zero-reference benchmark, and a second high point of 72 m is located approximately 3 to 3.1 km north of the zero-reference benchmark. Midway between these two high points stratigraphic separation drops to 52.5 m, creating an “M” shape in the profile (Figure 19). Maximum stratigraphic separation measured along section B is 42 m, located 7.22 km north of the zero-reference benchmark. There is 0.58 km of overlap between sections A and B, and a maximum cumulative stratigraphic separation of 50 m along the RLF basalt is located 7.14 km north of the zero-reference benchmark. Along section C maximum stratigraphic separation is 28 m, observed 11.71 km north of the zero-reference benchmark, 1.41 km north of the initiation of section C. There is 1.64 km of overlap between sections B and C, with maximum cumulative stratigraphic separation of 33.9 m located 11.56 km north of the zero-reference benchmark along the RLF (Figure 19).

Figure 19. Profile showing vertical stratigraphic separation along the length of the RLF. Each fault section is shown as a colored line, with cumulative displacement where sections overlap shown as a black line. Vertical offset rises dramatically over relatively short horizontal distances in the southern portion of each section. On the x-axis the zero point corresponds to the zero-reference benchmark.

4. Fault Tip Taper Gradients

All three RLF sections show generally similar vertical stratigraphic separation profiles, with stratigraphic separation decreasing rapidly over short fault distances, tapering steeply at the endpoints of each section, and more gradual changes in vertical separation along the midpoints of the section (Figure 20). Figure 19a is a plot of vertical separation along fault length, solid black lines indicate the 1 km taper gradient measurement and dashed black lines show the break-in-slope taper gradient measurements. Taper gradients range from 6 - 51 m/km with the 1 km measurement method and 12.1 - 148.4 m/km with the break-in-slope method (Figure 20, Table 5). Section A taper gradients are 51 m/km in the south to 29.5 m/km in the north with the 1

km measurement method and 148.4 – 33.8 m/km south to north when measured with the break in slope method. Section B taper gradients range from 30.8 m/km in the south to 6 m/km in the north when measured over 1 km distance, and 80.8 m/km in the south to 12.1 m/km in the north using the break in slope measurement method. Taper gradients for section C range from 24 m/km in the south to 19.1 m/km in the north with the 1 km measurement method and 67.9 m/km in the south to 40.2 m/km in the north using the break-in-slope measurement method. Section A has larger cumulative vertical separation and corresponds with rapid decrease in vertical separation over short along strike distances at the end points of the section, shown by steep taper gradients.

Lower cumulative separation corresponds with more gradual decrease in vertical separation over along strike distances, shown by less steep taper gradients, such as the north end of section B (Figure 19). A plot of all six end point taper gradient values for the RLF versus total vertical separation reveals a good linear fit to taper gradient measurements using the 1 km method, and no apparent trend for taper gradients measured using the break in slope method (Figure 19c).

Figure 20. A) Profile of RLF sections and taper gradient measurements for both 1 km (solid) and break-in-slope (dashed) methods for each section. B) Close-up of the north end of section C to highlight the different measurement methods. C) Plot of vertical separation versus gradient for both measurement methods and linear fit to points.

The taper gradients at the endpoints of each section represent the taper values for cumulative vertical separation along the RLF. Two knickpoints observed in the channel of Burney Creek, each approximately 1 m high, are interpreted as per-event offsets of the two most recent surface rupturing RLF earthquakes (PG&E, 2018). Given this relationship, I estimate per-event taper gradients by dividing the cumulative offset by an average per-event vertical offset of 1 m along the fault length. Average, per-event fault section taper gradients given these assumptions for the RLF are 1.07 ± 0.23 m/km for the 1 km measurement method, and 1.31 ± 0.84 m/km for the break-in-slope measurement method (Table 5).

Table 5. Fault Tip Taper Gradients				
Fault Sections and Endpoint ID		Fault Taper Gradients (m/km)		
		Vertical Separation (m)	Gradient (m/km)	Per-event Gradient^a (m/km)
1 km from endpoint				
Section A	South	46.5	51.03	1.10
	North	29	29.5	1.02
Section B	South	32	30.77	0.96
	North	4	6.04	1.51
Section C	South	24	23.98	1.00
	North	22	19.1	0.87
Mean : 1.07 Std Dev: 0.23				
Break-in-Slope from endpoint				
Section A	South	49.5	148.39	3.00
	North	74	76.2	1.03
Section B	South	42	30.96	0.74
	North	23.5	25.44	1.08
Section C	South	19	22.52	1.19
	North	22	18.5	0.84
Mean : 1.31 Std Dev: 0.84				
^a For assumed 1 meter per-event estimated average displacement				

5. Area-Balanced Cross Sections and Conceptual Fault Scarp Development Model

Sequential restoration of area-balance cross sections from the current scarp morphology to a flat ground surface constrains the fault dip angle near the ground surface and at depth, the approximate depth of change in fault dip angle, the area of talus and broken-in-place bedrock, and relative amounts of vertical and extensional displacement (e.g. Figure 21). Restoration of area-balanced cross sections derived from surface profiles of the RLF scarp allows a sequential fault development model that is geologically reasonable. Three area-balanced cross sections, one from each of the three fault sections, reveal the RLF has a steep (subvertical) fault dip near the surface and becomes less steeply dipping at depth (Figures 22, 23, 24). The hangingwall portion of the scarp is a combination of talus material deposited from the eroded footwall above and bedrock broken up in place via mechanical disaggregation of the monocline limb (Unit 3) (Figures 22, 23, 24). Vertical displacement is approximately three times greater than extension (Table 6).

A conceptual four-step kinematic fault scarp development model resulted from the development of the cross sections and summarizes the general evolution of the RLF scarp from an undeformed surface to the present time (Figure 21). This model highlights the step-wise deformation observed in the retrodeformations for the area-balanced cross sections (Figures 22, 23, 24). The model outlines processes during the development of the RLF and leading to current RLF scarp morphology along all three fault sections (Figures 14, 15, 16, and 17).

Stage one is the undeformed ground surface following the deposition of the Basalt of Rocky Ledge (Figure 21a). The basalt has abundant vertical and horizontal fabric as a result of flows with vesicular tops and bottoms, rubble zones between vesicle pipes, and horizontal layers on cooling fronts. The main RLF may exist at depth but has not encroached sufficiently on the surface to cause observable deformation (Figure 21a). In stage two, broad monoclinal folding develops as the RLF propagates to the surface (Figure 21b). Fold hinges are located at the top and base of the fold; the upper anticline hinge is steeper than the lower syncline hinge. In stage three, the monocline breaks along an anticline breakout at the top of the monocline (between the footwall and hangingwalls) and a syncline breakout at the bottom (Figure 21c). A steep near-surface fault develops and slip along the deeper, more shallow dipping fault opens space as vertical and extensional separation continues. Stage four includes the collapse of the monocline limb and the development of antithetic faults within the monocline limb, which result in the furrow features observed in all three RLF sections (Figure 21d). As the upper part of the footwall erodes (red area, Figure 21d), talus material with more porosity than the intact bedrock is deposited on top of the partially collapsed monocline surface on the hangingwall (green area, Figure 21d). Below the observable ground surface, space created by the interaction of faults and bedrock blocks is accommodated many different ways by localized faulting and folding that cannot be characterized without subsurface observations. This is depicted in all three cross section figures as area-balanced overlaps and space gaps in the highly dynamic fault process zone.

Figure 21 (previous pages). Conceptual kinematic four-stage fault scarp development model. A) Undeformed ground surface (Stage 1). Marker beds help define possible deformation at each stage. B) Broad monoclinical folding with slip along the RLF at depth (Stage 2). C) Folding ceases and subsequent deformation is from fault movement (Stage 3). D) The scarp as we observe today (Stage 4). Unit 1 is blue, Unit 2 is orange, Unit 3 is green, and Unit 4 is purple. The monocline has partially collapsed into the void space created by fault movement, and talus rubble of greater porosity than intact bedrock has eroded from the footwall and blanketed the hangingwall. Antithetic faults develop in the collapsed monocline limb and offset Unit 3.

Cross section 1-1' is located near the mid-point of RLF section C and appeared generally representative of other areas along section C (Figure 17). Figure 22 shows the development of cross section 1-1' using the four-stage scarp development model. Figure 22a shows an undeformed ground surface (such as the Basalt of Rocky Ledge) as a continuous stratigraphic horizon across the cross-sectional area. No fault displacement is apparent at the surface, although there may be pre-existing faults and fold axes at depth. Figure 22b shows broad monoclinical folding developing from slip along the RLF at depth during early large magnitude earthquakes, with an anticline axis developing at the top of the fold and a syncline axis developing at the base of the monocline. Extension at the top of the scarp may occur, although this area is now heavily eroded. A thrust flap has developed east of the base of the fold from compression in the hangingwall near the syncline axis driven by flexural slip within the basalt. Figure 22c shows that subsequent earthquakes result in the monocline breaking along the anticlinal axis, separating the hangingwall and footwall and resulting in a steep (~85°) dip to the east. The hangingwall slips along the RLF at depth, which dips approximately 40° east (Figure 22c). Antithetic faults develop in the hangingwall as the monocline begins to collapse. Between Stages 3 and 4, the upper portion of the footwall scarp (Unit 1, west of the primary RLF trace) begins to erode (Figure 22d, red zone), and blocks of basalt originating from the footwall topple and deposit onto the slope below (Unit 3, Figure 22d, green zone). The area of the

wedge on the lower $\sim 2/3$ of the scarp slope east of the RLF and above the elevation of the valley floor (the hangingwall block and accumulated talus), approximately 200 m^2 , is greater than the eroded wedge from the footwall west of the fault ($\sim 25 \text{ m}^2$) (Figure 22d). Localized compressional features are observed east of the base of the scarp (in Unit 4) and offset within the partially collapsed monocline limb are expressed as furrows within Unit 3. I measure approximately 18 m of vertical displacement and 5 m extensional displacement with this area-balance technique, and the main RLF dip angle shallows from $\sim 85^\circ$ to 40° at approximately 57 m depth (Figure 22d) (Table 6).

Figure 22. Step-wise progression of area-balanced cross section 1-1'. Symbology applies to all stages of RLF development. No vertical exaggeration. A) Undeformed ground surface following the deposition of the Basalt of Rocky Ledge. Marker beds show deformation near the surface and at depth. Dashed lines show possible incipient fold axis. B) Broad monoclinal folding from slip along RLF at depth; compression at the base of the footwall and deformation in the basalt driven by flexural slip. Fold axes have been established; these will evolve to fault planes. C) The hangingwall separates from the footwall along the anticline axis as slip occurs on the RLF at depth. Antithetic faults develop in the hangingwall block as the monocline limb breaks up. D) The RLF scarp as it appears today. Eroded basalt from the footwall block erodes onto the slope below with ~50% porosity, resulting in a partially collapsed monocline limb covered by talus boulders. Antithetic faults in the bedrock offset the talus, resulting in furrows on the lower ½ of the scarp slope. The dashed line around the primary fault depicts the fault process zone, where the fault and surrounding bedrock undergoes dynamic interaction, creating space and breaking apart bedrock blocks in a complex, unobservable subsurface process.

Cross section 2-2' is located near the southern end of RLF Section B (Figure 16). Prior to surface deformation the RLF may exist at depth, although the ground surface is flat (Figure 23a). Incipient fold axes may exist between the propagating fault tip and the ground surface. Early earthquakes result in broad monoclinal folding with slip along the RLF at depth, and the anticline axis at the top (west) of the scarp and syncline axis at the base (east) of the scarp are present (Figure 23b). Brittle fault deformation occurs as the hangingwall block separates from the footwall, resulting in a steep near-surface fault dip (87° at cross section 2) (Figure 23c). As the footwall erodes (between stages 3 and 4), blocks from Unit 1 topple onto the scarp slope below (Unit 3). The area of the wedge on the lower $\sim 2/3$ of the scarp slope east of the RLF and above the elevation of the valley floor ($\sim 470 \text{ m}^2$) is greater than the approximate area of eroded material from Unit 1, west of the RLF ($\sim 145 \text{ m}^2$). Offset along west dipping antithetic faults in the hangingwall results in displaced talus (Figure 23d). Vertical displacement of 41 m and extensional displacement of 15.5 m is observed, with the lower RLF dipping approximately 87° east in the near-surface and shallowing to 54° east dip below 57 m depth from the valley top (Table 6).

Figure 23. Step-wise progression of area-balanced cross section 2-2', symbology applies to all stages. A-C) Stages 1 – 3 of fault development represented by A-C. D) The RLF scarp as it appears today. Eroded basalt from the footwall block erodes onto the slope below with ~50% porosity, resulting in a partially collapsed monocline limb covered by talus boulders. Antithetic faults in the bedrock offset the talus, resulting in furrows on the lower 1/2 of the scarp slope.

Cross section 3-3' is located near the southern-most end of RLF section A, the longest and most vertically offset section with the greatest number of structural features (Figure 15). Cross section 3-3' shows the most vertical separation and the most abundant structural features (specifically furrows) and greatest amount of hanging wall deformation in the partially collapsed monocline limb of the three cross sections. Following the deposition of the Basalt of Rocky Ledge, the ground surface is flat and undeformed (Figure 24a). Movement along the fault at depth results in broad monoclinial folding with hinges at the top and base of the fold (Figure 24b). Folding yields to brittle faulting and the hangingwall separates along the upper fold axis, resulting in a steep ($\sim 86^\circ$) near-surface primary fault angle. Antithetic east dipping faults develop in the hangingwall as the monocline limb begins to collapse into a void created by slip along the RLF at depth, which dips less steeply ($\sim 62^\circ$) than the upper fault (Figure 24c). The primary antithetic fault dips approximately 45° west. The wedge of eroded material on the footwall block west of the RLF is approximately 280 m^2 , while the wedge of material on the lower 1/2 to 2/3 of the scarp slope located east of the RLF and above the elevation of the valley floor is approximately $1,450 \text{ m}^2$. As the monocline limb collapsed, material eroded from the footwall and deposited on the hangingwall on the lower 1/2 to 2/3 of the scarp slope, and was subsequently offset by antithetic faults in the hangingwall block, creating surface furrows in Unit 3 (Figure 24d). Vertical displacement of 50 m and extensional displacement of 13.4 m is observed, with a change in primary RLF dip angle approximately 104 m depth from the valley top (Table 6).

Symbology

- Ground surface
- Shallow marker bed 1
- Shallow marker bed 2
- Deep marker bed
- Fault - arrows show direction of movement
- Incipient fold axis
- Incipient fault
- Anticline fold axis
- Syncline fold axis

0 40 m

Figure 24 (previous page). Step-wise progression of area-balanced cross section 3-3'; symbology applies to all stages of fault development. A-C) Stages 1-3 represented by A-C. D) The RLF scarp as it appears today. Eroded basalt from the footwall block erodes onto the slope below with ~50% porosity, resulting in a partially collapsed monocline limb covered by talus boulders. Antithetic faults in the bedrock offset the talus, resulting in furrows on the lower 1/2 of the scarp slope.

Table 6. Fault Metrics from Balanced Cross Section Analysis						
Cross Section ID	Total Vertical Displacement (m)	Total Extensional Displacement (m)	Ratio of Extension: Vertical components of displacement	Fault Dip Angle – Near Surface (degrees)	Fault At Depth	
					Fault Dip Angle (degrees)	Depth of angle Change (m)
1	18	5	0.28	85	40	57
2	41	15.5	0.38	87	54	57
3	50	13.4	0.27	86	62	104

IV. Discussion

1. Fault Tip Taper Gradients

Fault tip taper gradient increases with the strength of the surrounding rock (Scholz and Lawler, 2004). As slip accumulates in a fault interior, stress builds at the tips until a yield strength (a “threshold”) of the surrounding rock is reached; once this is exceeded, the fault grows laterally (Ellis and Barnes, 2015). The observed fault endpoint taper gradients can be conceptualized in two general ways. In one end member, the fault reaches a quasi-stable length early on as strain localizes and forms the fault, and each subsequent earthquake grows the scarp vertically along the entire length (Figure 25a) (e.g. Manighetti et al., 2001). In this scenario, the observed fault endpoint taper gradients represent cumulative vertical deformation from all surface rupturing earthquakes. The other end member is that each earthquake event both lengthens and grows the fault scarp vertically, so that the measured taper gradient represents only the most recent earthquake event (Figure 25b).

Figure 25. End member scenarios of conceptual fault growth models and corresponding tip taper gradients. A) Each surface rupturing earthquake (numbered 1-4) increases the vertical displacement on a quasi-stable fault length, which is established early on in the formation of the structure. The measured tip taper gradient is the cumulative vertical displacement of all earthquakes that have occurred at this structure. B) Each earthquake (1-4) both lengthens and vertically grows the fault scarp, so that the measured taper gradient is representative of the most recent earthquake event.

The relationship of per-event and cumulative fault tip taper gradients for each RLF section is similar regardless of the specific per-event displacement; per-event

displacement tip taper gradient values are comparable among all fault tips despite steeper cumulative gradients in more offset sections. This suggests steeper cumulative gradients represent more surface rupturing earthquakes or more slip per event, with the most having occurred in section A, the most vertically offset of the three RLF sections. Despite varying cumulative gradients, the per-event gradient relationship suggests that the RLF has similar characteristics to the growth scenario represented in Figure 25a. However, more coseismic displacement data along the RLF would clarify the relationship between fault lengthening and the distribution of vertical displacement along strike (i.e. whether vertical displacement is uniform along the full fault length versus a scenario with greater vertical displacements in the south and smaller displacements in the north) (e.g. Figure 25b).

The RLF shows generally similar morphology and comparable per-event taper gradients to the Hat Creek fault at the eastern edge of the Hat Creek Graben, with a per-event taper gradient of $\sim 0.5\text{--}1$ m/km. The RLF yields lower per-event taper gradients than the Long Valley Mountain fault, located approximately 2 km west of the RLF, with a per-event taper gradient of $\sim 3\text{--}10$ m/km, (PG&E 2018). Taper gradients along the RLF can also be compared with a global database of per-event endpoint taper gradients of compiled by Thompson (2017).

This database includes per-event fault tip taper gradients for 13 historic earthquake events along 38 faults or fault sections, primarily strike slip and oblique faults, with gradient measurements at both tips (76 total). Average per-event tip taper gradients for the global compilation range from $0.1\text{--}2.4$ m/km, with 9 of 76 (12%) taper

gradients exceeding 1 m/km, and maximum per-event gradients range from 0.1 – 4.2 m/km (Thompson, 2017). At the RLF, 50% of average per-event tip taper gradients exceed 1 m/km (1 km method). Few of the 38 faults and fault sections in the Thompson (2017) database occur in basaltic (or partially basaltic) terrain, and none of these are regional faults in the Burney, CA area. For these reasons, the database differs from taper gradient observations along the RLF.

Fault tip taper gradients along the RLF average roughly 1 m/km and appear to be greater (steeper) than the global average and are generally consistent with regional fault taper gradients. Steeper than average fault tip taper gradients indicate that the RLF (and comparable nearby faults) have more cumulative vertical offset to fault length ratios compared to the global database, and therefore offset dies out (tapers) more quickly along fault length. Areas with higher offsets may have experienced more surface rupturing earthquakes or slip in these areas may have been greater than sections to the north. If the growth scenario presented in Figure 25a is dominant at the RLF (as suggested by steep per-event tip taper gradients), then fault lengthening is less likely, and future displacement will be primarily vertical. Alternately, slip is greatest in the south, but the total number of earthquakes is consistent along the entire fault length, and the fault is growing with each successive surface rupturing earthquake to the north (Figure 25b). Section linkage within the RLF and coseismic rupture with other faults in the area play important roles in fault growth and fault displacement history.

2. Profile Shape and Fault Growth – Linked Segments

Fault geometry and fault growth are intimately linked; fault length and maximum displacement are key geometric relationships that inform our understanding of fault growth (Childs et al., 2017). For the RLF, I use stratigraphic separation as a substitute for displacement. These measurements were made in a systematic, reproducible fashion. A plot of stratigraphic vertical separation along fault length highlights how vertical offset varies across all three RLF sections. Fault zones result from the displacements along strike and linkage of component sections (Peacock and Sanderson, 1991). Many normal faults consist of complex zones of overstepping, linked sections, where displacement is transferred between overlapping fault sections dipping the same direction by tilted beds forming relay ramps and by the development of minor faults (Peacock, 2002). The RLF shows three distinct east dipping overlapping sections separated by relay ramps (Figure 18). Figure 26 shows a fault growth model using the evolution of a displacement-length profile to show how overlapping fault segments can become linked through the breaching of relay ramps by minor faults (Peacock and Sanderson, 1991). The distribution of slip along fault length is shown in an idealized semi-elliptical shape; actual length/displacement shapes are variable, and the factors controlling profile shape are complicated and not investigated in this project. During stage 1, two similarly-dipping, separate fault sections are not overlapping (Figure 26a). As the faults grow the tips overlap, a relay ramp develops between the two sections. (Figure 26b). Further development leads to a ramp-breaching connecting fault across the relay ramp, mechanically linking the previously separate fault sections (Figure 26c). The fault has a

defined bend at the former relay ramp location, and there is a decrease in vertical displacement at the point where the linkage occurred (Figure 26d).

Figure 26. Schematic map view diagrams of stages of fault development and corresponding vertical separation profiles along the fault length. A) Offset along non-overlapping faults. B) Minimally overlapping, linked faults. C) Overlapping, linked faults connected by a faulted relay ramp. D) Well-developed singular fault trace of previously discrete sections, where the bend (lateral ramp) is reflected in the vertical separation profile as a decrease in the vertical displacement profile. Figure modified from Peacock and Sanderson, 1991.

Along the southern RLF, a prominent “M” shape in the vertical separation vs. fault length profile is present (Figure 19) that coincides with a change in fault strike (Figure 14). Section A is currently one continuous section and may represent two previously discrete sections, which subsequently became mechanically linked. This is analogous to the scenario presented in Figure 26c, where two individual fault sections

have linked and the resulting vertical displacement along the linkage zone is significant. The relay ramps separating sections A and B and section B and C are zones of interest for potential future fault section linkage as slip localizes in these overlap zones during large earthquakes. A natural gas pipeline transects the section A-B relay ramp area, and a major east-west highway is located just south of this overlap zone (Figure 14). Significant localized displacement at the relay ramp could severely damage important infrastructure and jeopardize human safety.

3. Fault Geometry and Scarp Development

Area-balanced cross sections along the RLF reveal two distinct fault dip angles on the primary fault. To explain current fault morphology, the RLF dip is sub-vertical near the surface and less steeply dipping at depths ranging from 57 – 104 m (Figures 22, 23, and 24, Table 6). Studies of normal fault development in basalt have shown that slip on the fault at depth early in fault evolution (i.e. RLF stage 2; Figure 21) drives folding at the free surface into a monocline and tensile stress concentrations that result in the opening of pre-existing cooling joints in the footwall ahead of the fault tip (Bubeck et al., 2018). The layered Basalt of Rocky Ledge shows distinct vertical and sub-vertical jointing in cliff exposures. As the RLF propagates upward and ultimately breaches the surface, jointing controls the near-surface fault dip angle. As fault propagation folding yields to brittle fault deformation, the anticline breakout hinge dividing the footwall and hangingwall evolves to the primary RLF trace we observe today (RLF stages 3 and 4; Figure 21). Future studies focused on far-field hangingwall deformation may further constrain the dip angle at greater depth away from the base of the scarp, where a possible

rollover anticline due to crustal shallowing of the main RLF has been proposed (Piedmont, 2009).

Area-balanced cross sections show the wedge of material in the hangingwall downslope of the RLF and above the elevation of the valley floor is a greater area than the amount of eroded material from the footwall, upslope of the RLF (Figures 22, 23, and 24). This suggests that the lower 1/2 - 2/3 of the fault scarp (RLF Unit 3) is comprised of partially collapsed monocline limb (remnant of fault propagation folding) blanketed by talus material eroded from above (RLF Unit 1; Figure 21). West-dipping antithetic faults initiate in the monocline limb to close space created by extension along the RLF at depth and offset the surface talus material. The resulting structural features are the along strike peak-and-trough furrows observed in Unit 3 (Figure 12, 14). These features may initially form during a single earthquake event but may also grow over time with subsequent events.

Applying restoration to area-balanced cross sections, essentially retrodeforming the current fault scarp to a flat, undeformed surface, is a valuable investigative tool. A better understanding of the development of mapped fault units (such as Unit 3, a combination of deposited talus and broken up bedrock monocline limb), fault dip geometry, relative extensional and vertical displacements, and possible fault scarp development processes are possible. However, this technique is limited; complex interactions of faults and bedrock blocks, which create the accommodation space required for scarp evolution, as well as the subsurface fault geometry, are more complicated than can be modeled in cross section without direct, first-hand observations. In addition, both

vertical and extensional displacement outside of the outcrop-scale reference frame of the cross sections affects the scarp morphology. For example, the steep drop of the valley floor (Figures 14 and 15) and backtilting of the footwall block (Figure 4) may influence the observed vertical separation at the scarp. Finally, horizontal fault deformation from a possible dextral component of slip is unresolved and is not reflected in cross section. Despite these limitations, restoration and balancing techniques are an effective tool for assessing fault geometry and possible scarp development models.

4. Cosmogenic Age Dates

Cosmogenic ^3H exposure dating samples were collected along RLF sections A and C from the top of Unit 3 and base of Unit 1 on cliffs and blocks interpreted as coseismic rockfall, as well as lower on the scarp, from talus boulders in Unit 3 (Rood, 2013; Rood et al., 2015; Penna, 2016). Twelve cosmogenic samples were collected near the central portion of section C yielded three age population groups of 19.0 ± 2.4 ka ($n=3$), 33.5 ± 2.9 ka ($n=5$) and 45.5 ± 2.5 ka ($n=2$) (Penna, 2016). Two samples were not able to be matched these age groups. An average time span of 13.3 ± 1.7 ky is present between these populations of cosmogenic samples (Penna, 2016). Eighteen samples were collected near the southern tip of RLF section A (Rood, 2013; Rood et al., 2015; Penna, 2016). A prominent cluster of ages around 11.8 ± 1.5 ka result from 5 samples; this cluster of ages is interpreted to be the most recent surface rupturing earthquake on the RLF (Rood, 2013).

The cosmogenic exposure age dating completed to date is the only empirical data available regarding the most recent earthquake activity and possible recurrence intervals

at the RLF. However, coseismic rockfalls may not occur during every earthquake event (Valagussa et al., 2014). Therefore, these data may not reflect timing of all surface rupturing earthquakes on the RLF. Establishing earthquake timing helps inform our understanding of fault activity, fault growth, and per-event displacements. For example, if we know there is a long recurrence interval at the RLF, we may surmise that fault growing earthquakes are infrequent yet anomalously large (given the cumulative displacement and fault length). This informs our assessment of risks posed by fault hazards.

5. Empirical Scaling Relationships

Using empirical scaling relationships between surface rupture length and magnitude (M_w) for surface rupturing earthquakes on normal faults, an independent rupture of the entire 15.28 km length of the RLF would result in a M_w 6.5 earthquake with average per-event displacement of 0.3 m and maximum per-event displacement of 0.6 m (Wells and Coppersmith, 1994). Alternate empirical scaling relationships of surface rupture length and M_w developed for normal faults reveal that an independent rupture of the 15.28 km RLF length would result in a M_w 6.7 earthquake with average and maximum per-event vertical displacements of 0.45 m and 1.37 m, respectively (Wesnousky, 2008). The maximum cumulative vertical offset at the RLF is 74 m (Figure 19) and the age of the Basalt of Rocky Ledge ~ 215 ka (Rood et al., 2015). A range of 0.3 – 0.45 m for average per-event displacements and 0.6 -1.37 m for maximum per-event displacements yields a range in earthquake recurrence of 874 to 1,744 years between surface rupturing events given the Wells and Coppersmith (1994) regressions and 1,300

to 4,000 years with the Wesnousky (2008) regressions. Both scaling relationships suggest a much shorter recurrence interval than indicated by cosmogenic age dating.

The maximum cumulative vertical separation of 74 m along section A, the ~215 ka age for the Basalt of Rocky Ledge (Rood, 2015), and the estimated recurrence interval (RI) of 13.3 ± 1.7 ky (Penna, 2015), yields a per-event vertical displacement of 4.5 m. For the geologically constrained maximum displacement of 4.5 m, empirical scaling relationships with surface rupture length and Mw from Wells and Coppersmith (1994) reveal that a rupture length of up to 55 km is required, which would generate an earthquake Mw of 7.1. Similarly, empirical scaling relationships with surface rupture length and Mw from Wesnousky (2008) indicate a surface rupture length of 50 km is required to generate 4.5 m maximum vertical displacement and a Mw 6.9 earthquake.

For the maximum total vertical separation of 28 m along section C and the age and recurrence interval provided above the per event maximum vertical displacement along this section is 1.7 m. Empirical scaling relationships of surface rupture length, Mw, and maximum displacement reveal a required surface rupture length 28.8 km, which would generate a Mw 7.1 earthquake (Wells and Coppersmith, 1994). Alternately, empirical scaling relationships of surface rupture length, Mw, and maximum per-event displacement of 1.7 m reveal a required fault length of 18.8 km, which would generate a Mw 6.8 earthquake. These empirical scaling results require a greater rupture length relative to the scarp heights for the RLF. These empirical relationships suggest that either the RLF ruptures coseismically with the northern segments of the Hat Creek fault or with numerous smaller faults in closer proximity (Figure 2). Alternately, the recurrence

interval may be incorrect, or these scaling laws may not be appropriate for a fault in basaltic terrain (Stirling et al., 2013).

An average per-event displacement of 1 m has been suggested for the RLF based on field evidence, an intact knickpoint in Burney Creek interpreted as having formed during the most recent earthquake event (PG&E, 2018). A 2 m maximum per-event displacement (twice the average) is possible (Hempill-Hailey and Weldon, 1999). Using empirical scaling relationships of maximum displacement, M_w , and surface rupture length, a required fault length of 32.3 km could generate a M_w 6.9 earthquake (Wells and Coppersmith, 1994). Alternately, empirical scaling relationships of surface rupture length, maximum displacement, and M_w by Wesnousky (2008) indicate a 22.2 km rupture could generate a M_w 6.8 earthquake.

An estimated surface rupture length of 22.2 - 32.3 km, based on a maximum per-event displacement suggested by field evidence at the RLF, is suggested by empirical scaling relationships (Wells and Coppersmith, 1994; Wesnousky, 2008). This could indicate that the RLF ruptures coseismically with other nearby faults in the area, possibly the Old Lumber Mill (SRL = 6.5 km, RI = 3 $\pm$ 0.3 ky, maximum displacement = 0.53 m (Penna, 2016)), Burney Spring Mountain Fault (SRL = 3 km (LCI, 2013)), or Fault 3432 (SRL = 2 km (LCI, 2013)). Trenching studies as part of the Pit 3 Dam investigation have suggested that Fault 3432 has a per-event maximum displacement of approximately 0.5 m, which empirical scaling relationships also suggest is disproportionate for its relatively short length (LCI, 2013).

V. Conclusions

The Rocky Ledge fault consists of three main N/S-striking left-stepping sections and totals ~15 km cumulative length. I map each section in detail and investigate scarp morphology and fault geometry with area balanced cross sections. Distinct surface morphology includes a steep upper scarp face, partially preserved monocline structures covered by talus on the lower scarp slope, and antithetic fault scarps that create along-strike peak and trough-like furrows in the hanging wall. Area balanced cross sections and retrodeformation for all three sections of the RLF reveal early monoclinial fault-propagation folding yields to brittle faulting as the RLF tip approaches and daylight at the surface. Extension is approximately 27-38% of total vertical displacement, and ranges from 13.4 m where 50 m of vertical displacement is observed (~27%) to 15.5 m where 41 m of vertical displacement is observed (~38%). In the near surface, preferential fault growth along pre-existing cooling joints in the basalt influence a sub-vertical primary fault dip angle, while the RLF at depth (~10's to 100's of meters) is less steep (40° - 60°), allowing the extension necessary for the morphology observed at present.

A profile of total vertical stratigraphic separation along the length of the fault reveals steep fault tip taper gradients which are similar to other regional normal faults in basalt and are steeper than the global average; 50% of RLF average per-event tip taper gradients exceed 1 m/km, while 12% of average per-event tip taper gradients in the global database exceed 1 m/km (Thompson, 2017). Consistency of per-event taper gradient values between RLF sections indicates that the more vertically separated fault

sections with steeper gradients have experienced more surface rupturing earthquake events or larger amounts of slip per-event.

The southern section of the RLF has mechanically linked across a ~500 m wide overlap zone from previously discrete sections in the past. Two relay ramps ~175 – 550 m wide exist at overlapping fault tips and represent future section linkage zones. Over time, the RLF sections could link at the surface, with slip localizing in the overlap zones leading to significant displacement in these areas. Areas of significant future displacement and the potential for anomalously large earthquakes are important considerations for evaluating fault hazards and associated risk assessment.

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Appendix A – Stratigraphic Separation Measurements

Figure A1. Map of surface profiles used for vertical stratigraphic separation measurements.

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
1	5	0.06	A
2	17	0.11	A
3	20	0.18	A
4	25	0.24	A
5	48	0.30	A
6	51	0.37	A
7	50	0.45	A
8	48	0.53	A
9	48	0.62	A
10	50	0.67	A
11	48	0.72	A
12	49	0.76	A
13	49	0.80	A
14	50	0.85	A
15	53	0.89	A
16	57.5	0.94	A
17	55.5	0.98	A
18	54.5	1.03	A
19	54	1.09	A
20	56	1.15	A
21	55	1.21	A
22	54	1.24	A
23	56.5	1.27	A
24	55.5	1.32	A
25	55.5	1.38	A
26	56	1.43	A
27	54	1.47	A
28	53	1.49	A
29	54	1.53	A
30	55	1.58	A
31	56	1.60	A
32	58	1.74	A
33	58	1.88	A

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
34	58	2.01	A
35	62	2.14	A
36	63	2.29	A
37	66	2.43	A
38	70	2.64	A
39	70	2.80	A
40	69	2.91	A
41	72	3.00	A
42	72	3.13	A
43	66	3.24	A
44	52.5	3.35	A
45	59	3.54	A
46	60	3.66	A
47	55	3.80	A
48	57	3.94	A
49	58	4.07	A
50	61	4.17	A
51	59	4.25	A
52	62	4.46	A
53	60	4.59	A
54	64	4.72	A
55	68	4.86	A
56	70	4.99	A
57	74	5.09	A
58	72	5.19	A
59	65	5.35	A
60	66	5.46	A
61	63	5.56	A
62	53	5.79	A
63	46	5.89	A
64	44.5	5.95	A
65	41	6.10	A
66	36.5	6.19	A

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
67	29.5	6.28	A
68	32	6.33	A
69	30	6.38	A
70	31.5	6.42	A
71	30	6.45	A
72	30.5	6.48	A
73	32	6.52	A
74	32	6.56	A
75	28.5	6.60	A
76	27	6.65	A
77	25	6.67	A
78	25.5	6.68	A
79	24	6.72	A
80	23.5	6.75	A
81	24	6.77	A
82	23.5	6.81	A
83	20	6.84	A
84	17.5	6.87	A
85	16	6.89	A
86	14.5	6.91	A
87	14	6.94	A
88	10	6.97	A
89	6	7.00	A
90	6.5	7.02	A
91	6.5	7.04	A
92	5	7.06	A
93	5.5	7.08	A
94	4	7.10	A
95	3.5	7.12	A
96	3	7.15	A
97	2.5	7.18	A
98	1.5	7.22	A
99	2	7.25	A

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
100	0	7.28	A
101	0	6.70	B
102	4	6.75	B
103	9.5	6.80	B
104	19	6.88	B
105	25	6.95	B
106	29	7.01	B
107	31.5	7.07	B
108	36	7.14	B
109	42	7.22	B
110	39	7.31	B
111	40	7.39	B
112	39	7.46	B
113	38	7.54	B
114	36	7.58	B
115	32	7.66	B
116	32	7.74	B
117	36	7.82	B
118	36	7.89	B
119	35	7.97	B
120	37	8.04	B
121	36	8.11	B
122	37.5	8.20	B
123	36.5	8.26	B
124	35	8.37	B
125	32	8.49	B
126	37	8.58	B
127	27	8.64	B
128	27	8.69	B
129	29	8.75	B
130	30	8.80	B
131	30.5	8.85	B
132	29.5	8.90	B

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
133	25	8.93	B
134	30	8.97	B
135	26.5	9.01	B
136	26	9.06	B
137	25	9.11	B
138	25	9.14	B
139	23	9.16	B
140	24.5	9.21	B
141	21.5	9.24	B
142	24.5	9.29	B
143	22.4	9.38	B
144	22.5	9.43	B
145	22.8	9.53	B
146	23	9.61	B
147	21	9.69	B
148	23.5	9.79	B
149	23.5	9.88	B
150	23.5	9.95	B
151	22	10.02	B
152	21.5	10.11	B
153	18	10.21	B
154	13	10.26	B
155	14.4	10.33	B
156	14.5	10.38	B
157	11.5	10.44	B
158	11	10.52	B
159	11	10.60	B
160	9.2	10.68	B
161	7.3	10.76	B
162	6	10.82	B
163	4	10.87	B
164	5.8	10.93	B
165	7.1	10.99	B

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
166	7.5	11.07	B
167	6.4	11.14	B
168	4.9	11.18	B
169	6.5	11.23	B
170	2.7	11.29	B
171	5.7	11.36	B
172	4.5	11.42	B
173	3.5	11.46	B
174	4	11.51	B
175	3.9	11.56	B
176	6.2	11.62	B
177	6.4	11.68	B
178	1.7	11.76	B
179	1.2	11.83	B
180	1.8	11.89	B
181	0	11.94	B
182	0	10.30	C
183	3.5	10.35	C
184	5.7	10.40	C
185	8	10.43	C
186	15	10.48	C
187	19	10.53	C
188	19	10.58	C
189	20	10.63	C
190	20	10.68	C
191	21	10.73	C
192	22	10.78	C
193	22	10.83	C
194	21.5	10.88	C
195	21.5	10.93	C
196	26.5	10.98	C
197	26	11.03	C
198	25.5	11.08	C

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
199	26	11.13	C
200	25.5	11.18	C
201	26	11.23	C
202	23.5	11.23	C
203	23.5	11.28	C
204	24.5	11.33	C
205	23	11.39	C
206	26	11.46	C
207	27	11.51	C
208	27.5	11.56	C
209	27	11.61	C
210	27	11.66	C
211	28	11.71	C
212	23.5	11.76	C
213	21	11.81	C
214	19	11.86	C
215	20	11.91	C
216	18.7	11.96	C
217	20.5	12.01	C
218	23	12.06	C
219	18.8	12.11	C
220	17	12.16	C
221	19	12.21	C
222	18.2	12.26	C
223	18	12.31	C
224	20	12.36	C
225	20	12.41	C
226	18.5	12.46	C
227	17.8	12.51	C
228	18.5	12.56	C
229	22	12.61	C
230	19.5	12.66	C
231	17.5	12.71	C

Table A1. Vertical stratigraphic separation measurements by section, Rocky Ledge fault

Profile ID	Measured Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark	Section ID
232	17.5	12.76	C
233	17.7	12.81	C
234	16	12.86	C
235	9.1	12.91	C
236	9.3	12.96	C
237	3.5	13.01	C
238	3.9	13.06	C

Table A2. Vertical stratigraphic separation measurements – Cumulative, Sections A and B, Rocky Ledge Fault

Cross Section ID – Section A	Cross Section ID – Section B	Cumulative Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark
76	101	27	6.70
77	102	29	6.75
78	103	35	6.80
79	104	43	6.88
82	105	48.5	6.95
83	106	49	7.01
84	107	49	7.07
87	108	50	7.14
90	109	48.5	7.22
95	110	42.5	7.31
96	111	43	7.39
97	112	41.5	7.46
98	113	39.5	7.54

Table A3. Vertical stratigraphic separation measurements – Cumulative, Sections B and C, Rocky Ledge Fault

Cross Section ID – Section C	Cross Section ID – Section B	Cumulative Vertical Stratigraphic Separation (m)	Position along RLF, (km) Measured from zero-reference benchmark
182	155	14.4	10.30
183	156	18	10.35
185	157	19.5	10.43
186	158	26	10.48
187	159	30	10.53
189	160	29.2	10.63
190	162	26	10.68
191	163	25	10.73
192	164	27.8	10.78
194	165	28.6	10.88
195	166	29	10.93
196	167	32.9	10.98
198	168	30.4	11.08
199	169	32.5	11.13
200	170	28.2	11.18
203	171	29.2	11.28
204	172	29	11.33
205	174	27	11.39
206	175	29.9	11.46
207	176	33.2	11.51
208	177	33.9	11.56
211	178	29.7	11.71
212	179	24.7	11.76
214	180	20.8	11.86
215	181	20	11.91