The Geometry, Kinematics, and History of the Thousand Lake Fault System, Central Utah

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The Geometry, Kinematics, and History of the

Thousand Lake Fault System, Central Utah

A thesis submitted in partial fulfillment of the requirement for the degree of
Bachelor of Science in Geology
From the College of William and Mary in Virginia,

by

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Accepted for ___________________________
(Honors, High Honors)

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April 29, 2014
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Plate 1: Geologic map of Lyman 7.5’ quadrangle (1:24,000)
Abstract

The High Plateaus of central Utah form a transition zone between the physiographic provinces of the Basin & Range and Colorado Plateau. The High Plateaus are characterized by a system of steeply-dipping normal faults and associated seismicity. My research focuses on understanding the movement and history of the Thousand Lake Fault (TLF) system, which is the easternmost major fault of the High Plateaus province bounding the Colorado Plateau. The main strand of the TLF dips westward and strikes N-S and NW-SW. Kinematic evidence suggests down-to-the-west normal slip on the TLF and total offset of 800-1000 m, with displacement decreasing to the northeast as displacement is transferred west to the Paradise Fault system. The TLF displaces volcanic rocks of Tertiary age from the top of Thousand Lake Mountain to an elevation up to 500 m lower on the hanging wall. The TLF offsets Quaternary boulder deposits near the Yellow Ledges, providing a minimum age constraint for most recent fault activity in the Quaternary.

Brittle deformation features in the fault zone suggest a seismogenic history for the fault. However, relative smoothness of the longitudinal profiles of channels crossing the fault reveal that mass movement controls slope topography and the most recent fault rupture is obscured by surficial deposits. Stratigraphic relations and a previously dated boulder fan exposure age demonstrate that recent movement on the TLF occurred in the last 200 ky. The large displacement on the fault (as great as 1,000 m) indicates that the fault was extremely active for a protracted period fault and is therefore an older structure along the boundary of the Transition Zone. Based on active extension patterns of the Great Basin, the fault may have initiated in the Late Miocene in response to Mid-Cenozoic stresses.
Introduction

Understanding the tectonic history of the region between the largely stable Colorado Plateau and the active rifting of the Basin & Range is critical to understanding intracontinental extension of the North American craton (Figure 1). The history of the geologic transition zone between the Colorado Plateau and the Basin & Range remains poorly understood. Though not a plate boundary, the intermountain western United States is located in a region of active deformation and seismicity. The mechanisms behind the complex deformation history of the interior western US remain disputed, but have significant implications for the study of large-scale extension in continental interiors.

Central Utah lies along the Intermountain Seismic Belt, a zone of increased seismicity that extends from southern Montana to northern Arizona (Figure 2). Utah experiences hundreds of small earthquakes every year, and large earthquake events occur approximately every 150 years (Utah Geological Survey, 1997). This zone of seismic activity occurs largely at the boundary between the geologic provinces of the Basin & Range and the Colorado Plateau, which in central Utah are separated by the High Plateaus (Anderson and Barnhard, 1986). The High Plateaus of Utah form a transition zone between the Basin & Range Province and the Colorado Plateau. This transition zone (Figure 1) is characterized by crustal extension due to late Cenozoic normal faulting, late Tertiary and Quaternary basaltic volcanism, and active seismicity (Wong and Humphrey, 1989), and contains numerous young north-northeast striking normal faults.

Neotectonics, the study of tectonic movements of Neogene and Quaternary age (younger than ~35 million years), is relevant to understanding current seismic activity and modern topography as well as the history of older geologic processes.
Figure 1. Map of American southwest highlighting the Basin & Range, Colorado Plateau, and Transition Zone.
Figure 2. Map of all earthquakes in Utah greater than magnitude 1 since 1973. The black lines mark the boundaries of the Intermountain Seismic Belt. Study area shown in yellow on the margin of the ISB.
Stresses within the Earth cause faults to slip, resulting in earthquakes. Seismic activity can be highly disruptive and potentially dangerous, and generate ground shaking, soil liquefaction, slope failure (landslides), and surface fault rupture. The US Geological Survey considers a fault active if it has slipped within the last 10k years.

The Thousand Lake Fault (Figure 3) is the easternmost major fault in the transition zone in central Utah (Stokes, 1977; Anderson and Barnhard, 1986; Arabasz et al., 2007; Bailey et al., 2007), and it marks the boundary between two very different geologic regions: the Awapa and Fish Lake Plateaus to the west and the Colorado Plateau to the east (Figure 3). The Fish Lake Plateau is a 1500 km$^2$ region of the High Plateaus located northwest of Torrey and southeast of Salina. Dutton (1880) first named this fault in his monograph on the geology of the High Plateaus of Utah. The Thousand Lake Fault (TLF) is a poorly understood normal fault of Quaternary age with unknown seismic potential located along the western side of the Thousand Lake Mountain (elevation 3400 m).

The purpose of my research is to determine the geometry, kinematics, geologic history, and potential hazards associated with the Thousand Lake fault system. Detailed maps of the fault with structural measurements and cross sections will elucidate the fault’s displacement and extent. Additionally, I discuss the effects of the TLF slip in regard to the landscape evolution of the High Plateaus.
Figure 3. Overview map of Utah illustrating the transition from Basin & Range to the Colorado Plateau and a shaded relief map of the High Plateaus region. TL- Thousand Lake fault system, F – Fremont Fault, P- Paradise Fault, JV- Joes Valley fault system.
Geologic Setting

A tectonic boundary exists in the western United States between the Colorado Plateau and the Basin & Range (Figure 1). The Basin & Range is the widest active rift zone in the world and is characterized by high heat flow, mafic magmatism, and ongoing lithospheric extension (Wannamaker et al., 2001). In contrast, the Colorado Plateau is a tectonically stable block generally unaffected by deformational forces other than Cenozoic uplift and plutonism. Between these two geologic regions lies the 100 km-wide Transition Zone (Wannamaker et al., 2001). The Transition Zone experienced extensional and contractional deformation similar to the Basin & Range, but also displays many characteristics of the Colorado Plateau such as high elevation and high elastic thickness of the crust (Wannamaker et al., 2001).

In central Utah, the geologic transition zone between the Colorado Plateau and the Basin & Range is known as the High Plateaus, and this physiographic region lies within the Intermountain Seismic Belt (ISB) (Figure 2). The Thousand Lake Mountain region lies astride the eastern boundary of the ISB, which is a zone of seismicity in the interior western United States extending from southern Nevada and northwestern Arizona to southeastern Idaho and western Montana. Extensive research exists on the seismic hazards present in the ISB, especially in the highly populated Wasatch Fault region near Salt Lake City (e.g. Hylland, 2007). Intraplate extension is the dominant tectonic mechanism driving seismicity in the ISB (Mason, 1996). The seismic belt is structurally and morphologically more similar to the Basin & Range than to the tectonically stable Colorado Plateau (Mason, 1996).
**Regional Deformation**

The southwestern United States (Figure 1) has experienced many deformational processes since the late Mesozoic. The crustal shortening that occurred as a result of the collision of the Farallon and North American plates in the late Cretaceous caused both the Laramide and the Sevier orogenies. The two orogenies therefore overlap in both time and space, but display different deformation styles. The Sevier orogeny caused thin-skinned deformation and occurred further west than the Laramide. The Sevier orogeny shortened basement metamorphic and igneous rocks, then shortened thick Paleozoic and Mesozoic sedimentary rock in an eastward stepping sequence of thrust faults. To the east of the Sevier orogeny the Laramide orogeny (80-45 Ma) uplifted basement rocks along with overlying sedimentary strata (Maxson and Tikoff, 196; Willis, 2000).

Mason (1996) asserts that the east-directed thrusting during the Sevier orogeny created north-south structural fabrics against the west margin of the stable and pre-existing Colorado Plateau may have allowed for the late Cenozoic development of the ISB in central Utah. Velasco et al. (2010) utilize seismic reflection data to understand the geometry of high-angle normal faults in the Wasatch region that become listric with depth (curve to horizontal). They interpret these listric normal faults as reactivated Sevier-age structures that are consistent with extension.

To the east, the Colorado Plateau experienced several deformation events since the Late Cretaceous. The horizontal compression of the Laramide orogeny caused contraction in the Colorado Plateau, with crustal-scale thrust, reverse, and oblique-slip faulting and folding (Davis, 1999). Deformation occurred in the Miocene 25-19 Ma as the plate convergence rates slowed from Laramide rates ~100 mm/yr to ~50 mm/yr.
The shallow subduction of the Farallon plate rolled back to a steeper angle, and subduction-induced magmatism produced features like the laccoliths of the Henry Mountains and the Marysvale volcanic field (Davis, 1999). Basin & Range extension initiated ~15 Ma and continues today, producing high-angle normal faults along the western margin of the Colorado Plateau (Davis, 1999). These deformation events on the Colorado Plateau may have caused the ~2 km uplift of the plateau during the Cenozoic (Flowers, 2010). Many theories exist to explain mechanisms of uplift, including lithosphere removal, volatile addition, magma extraction, lithosphere warming, asthenosphere upwelling, and crustal thickening (for complete list of citations see Flowers, 2010).

**Stratigraphy**

The Fish Lake Plateau is underlain by a thick (up to 700 m) Tertiary-age volcanic sequence that unconformably overlies sedimentary units of Eocene to Cretaceous ages (Figure 4) (Dutton, 1880; Carbaugh and Bailey, 2009). Fish Lake volcanic rocks include Oligocene to Miocene alkali-rich porphyritic trachyandesite (Johnson Valley trachyandesite- Tjv) and trachyte ash-flow tuff as well as younger basalts from local volcanic activity (Ball et al., 2009). These volcanic units overlie the Tertiary Flagstaff Formation and North Horn Formation, which crop out on the Fish Lake Plateau. The Flagstaff Formation (Tf) is an Eocene to Paleocene lacustrine limestone/sandstone unit (Sperry, 1980; Gierlowski-Kordesch, 2004).

To the east, the Thousand Lake Mountain region of the Colorado Plateau, a much thinner (approximately 100 m) volcanic sequence unconformably overlies Jurassic-age and older strata (Smith et al., 1963; Doelling and Kuehne, 2007). The Moenkopi
Figure 4. Simplified stratigraphy of the Fish Lake Plateau (High Plateau region) and Thousand Lake Mountain region (Colorado Plateau). The Fish Lake Plateau is underlain by a much thicker suite of volcanic rocks, and the strata of the Colorado Plateau represents much older deposition. Fault displacement is approximate.
Formation (Trm) is the oldest unit exposed along the Thousand Lake Fault, and consists of red and brown thinly–bedded mudstones and sandstones (Smith et al., 1963).

Unconformably overlying the Moenkopi Formation is the Chinle Formation (Trc), which consists of six members deposited in a fluvial-deltaic-lacustrine system (Dubiel, 1987). The Shinarump Member of the Chinle Formation is the lowest member, characterized by white to yellow/gray medium- to coarse-grained and conglomeratic sandstone with large-scale cross-stratification and horizontal laminations (Dubiel, 1987). Other members of the Chinle Formation consist of mottled sandy siltstone and sandstone, mudstones, and limestones (Dubiel, 1987).

The Glen Canyon Group overlies the Chinle Formation and includes (in ascending order) the Wingate Formation (JTrw), Kayenta Formation (Jk), and Navajo Formation (Jn). The Wingate Formation is a fine-grained, reddish-brown, cliff-forming crossbedded sandstone (Smith et al., 1963). The Kayenta Formation is a white to reddish-brown siltstone, conglomerate, and sandstone (Smith et al., 1963). The Navajo Formation is a red and white, thick, crossbedded quartzose sandstone of eolian origin (Peterson and Pipiringos, 1979).

Above the Glen Canyon Group lies the San Rafael Group, of which two members (the Carmel and Entrada Formations) crop out within the study area (Smith et al., 1963). The Carmel Formation (Jc) contains limestone, shale, gypsum, and sandstone, while the overlying Entrada Formation (Je) is primarily a reddish-orange crossbedded sandstone and silty sandstone (Peterson and Pipiringos, 1979).

**Past Work**

The Thousand Lake Fault (TLF) (Figure 5) was first recognized and named in
Dutton’s 1880 monograph on the High Plateaus of Utah. The TLF extends 25 km from south of the Capitol Reef area northeast to join the Paradise Fault (Smith et al., 1963; Williams and Hackman, 1971) (Figure 3). Based on differing elevations of volcanic rocks, Smith et al. (1963) estimated a total vertical displacement of 750 m along the fault zone west of Thousand Lake Mountain and noted that in the south there is less displacement (~120 m) on the fault along the west side of Boulder Mountain.

The TLF is considered the eastern boundary of the Basin & Range/ Colorado Plateau transition zone and the western edge of the Colorado Plateau (Wannamaker et al., 2001). Rowley et al. (1979) suggest that most of the faulting in the High Plateaus of Utah took place at 7 Ma. Smith et al. (1963) argued that the TLF reactivated after the Miocene and again after the deposition of early Wisconsin (~85,000 ka) terrace gravels along the Fremont River.

Anderson and Barnhard (1986) report a lack of well-developed fault slip indicators on the Thousand Lake Fault’s main strand. Rake angles on the main strand were 70 degrees or more, with a paleostress consistent with normal faulting and a west-northwest (285°) neotectonic extension direction. They conclude the fault displays features observed along other major faults bounding blocks on the western edge of the transition zone.

Nelson (1989) reports field and geochronological evidence near Geyser Peak north of the Thousand Lake Mountain suggesting that local faulting may have occurred there after 5 Ma. Foley et al. (1986) and Hecker (1993) report similar offsets on basalts of age 4-5 Ma and link this offset to the Paradise/Joes Valley fault system to the north (Figure 3).
Figure 5. Detailed satellite imagery showing the locations Thousand Lake Fault and surrounding regions.
East of the Thousand Lake Mountain Fault, Wong and Humphrey (1989) observed a spatially isolated cluster of earthquakes near Capitol Reef National Park between December 1978 and January 1980. They associated the seismic activity with a reactivation of Laramide basement faults, and connected the earthquakes to the Transition Zone characterized by crustal extension.

Marchetti et al. (2007) map the fault’s extent on the western side of Boulder Mountain and note that glacial and debris flow deposits cover much of the fault trace. Based on the lack of offset or rupture in the young deposits, they conclude that no recent (younger than Last Glacial Maximum) fault movement has occurred near Boulder Mountain or its western scarp. However, Marchetti et al. (2005) found evidence for Quaternary slip on the Thousand Lake fault east of Bicknell with Helium-3 exposure ages on scarp boulder surfaces of 83-213 ka, which provide a minimum age estimate for most recent offset on the fault. The rate of slip of the fault is unknown, but estimated at less than 0.02 mm/year (Black and Hecker, 1999).

Methods

My research included data and sample collection in the field, petrographic analysis of thin sections, digital mapping, and analysis of morphologic indices. Fieldwork in Utah from June 6 to July 1, 2013 yielded the majority of data for the project. I mapped in the Lyman 7.5’ quadrangle at a scale of 1:24,000 and south in the Bicknell 7.5’ quadrangle at a 1:10,000 scale, a combined study area of approximately 140 km$^2$. I recorded a station at locations of rock type change, at contacts between units, and along the fault. Each station was recorded on a Garmin GPS 72 unit, which has an associated error of less than 10 m. At each station, I recorded detailed notes and took structural
measurements of bedding, lineations, and fault strike and dip where measureable. In the field, I collected hand samples for petrographic analysis.

After returning from the field, I plotted station locations, rock type, and structural measurements in Adobe Illustrator on GeoPDFs of the Lyman and Bicknell 7.5’ NAD83 quadrangles. I used aerial imagery, digital elevation models, and field data to draw contacts between rock units and fault locations. From the stratigraphic relations and fault geometry, I created five cross sections of the study area.

Active tectonics shape landforms by forming boundaries, controlling drainage patterns, and developing variable relief. In order to quantify the effects of the Thousand Lake fault system on the landscape, I looked at geomorphic indices along the fault trace. Morphometry (the measure of landscape shape) is a useful tool in understanding active tectonic deformation (Keller and Pinter, 2002). Using 10m DEMs of the TLF region, I analyzed 9 longitudinal profiles with RiverTools in order to locate potential knickpoints across the TLF.

Additionally, I collected samples for future Helium-3 cosmogenic nuclide dating from 5 boulders on a boulder fan offset by the TLF west of the Yellow Ledges (Figure 6). Cosmogenic nuclide dating is a valuable technique for the study of neotectonic movement because it can constrain the age of the most recent fault movement. A Terrestrial Cosmogenic Nuclide (TCN) is “a nuclide produced by the interaction of secondary cosmic radiation with exposed target atoms in earth-surface materials,” and refers to those cosmogenic nuclides produced in situ in Earth minerals (Gosse and Phillips, 2001). Cosmic rays interact with the Earth’s atmosphere and produce neutrons that bombard the Earth’s surface and create cosmogenic isotopes (Yeats et al., 1997).
Fault scarps exposed after a rupture can be sampled to provide a detailed rupture history, limited by erosion and nuclide production rates (Ivy-Cohs and Kober, 2007). Helium-3 is useful for dating rocks of ages $10^3$-$10^7$ years and has a well-calibrated production rate (Schaefer and Lifton, 2007). Pyroxenes, olivine, and garnet retain $^3$He, and while some studies use $^3$He dating on quartz, it often diffuses too quickly (Schaefer and Lifton, 2007).

To maximize precision of the $^3$He dating, I selected several samples from boulder surfaces that fit criteria for TCN exposure sampling (Figure 6). The ideal geometry of a rock or landform surface must be sufficiently extensive (samples collected at least 50 cm from an edge or second face), flat, and horizontal (modeling cosmic ray flux on horizontal surface is straightforward) (Gosse and Phillips, 2001). I located sampling sites with a lack of shielding, and will attempt to minimize the effects of erosion.

Optically Stimulated Luminescence (OSL) is another valuable dating technique for Quaternary material. A small amount of light can be obtained from mineral grains (primarily quartz and feldspar) when stimulated by a beam of light in a laboratory (Huntley et al., 1985). This emitted light can be used to determine years that have elapsed since the grains were last buried. The date obtained, therefore, is the last deposition of sediment at which the grains were exposed to sunlight, when the bleaching set the latent signal to near zero (Aitken, 1998). The latent signal builds up with exposure to weak natural flux of nuclear radiation from sunlight (Aitken, 1998). Samples of quartz in colluvium from the slopes of the Yellow Ledges will be dated with OSL to bracket the age of the fault movement.
Figure 6. Examples of boulder sample sites. (a) Sample location HB-88; large, flat boulder of andesite porphyry, abundant in pyroxene. (b) HB-86 sample site; boulder ~2.6m x 1.5m x 0.9m.
Results

Stratigraphic Relations

Field data from the Lyman and Bicknell 7.5’ quadrangles (Figure 7) were compiled in maps with scales ranging from 1:10,000 to 1:24,000 incorporating structural measurements on and around the TLF. The TLF is a major structural feature in the eastern Lyman quadrangle (Plate 1). Surficial deposits from mass movements off the eastern slope of the Thousand Lake Mountain including slumps, debris flows, and landslides as well as alluvial deposits covered much of the study area. In the Lyman quadrangle, the surficial deposits typically cover the fault surface (Plate 1).

In the Lyman quadrangle, the TLF displaces volcanic rocks of Miocene age (Tjv, 26.01± 0.04 Ma) (UGS Open File Report, 2012) from the top of Thousand Lake Mountain to an elevation up to 500 m lower in the Rabbit Valley Salient. The TLF offsets Quaternary boulder deposits near the Yellow Ledges, providing a minimum age constraint for most recent fault activity (Figure 8). The boulder fan below the Yellow Ledges (Jurassic Carmel Formation) (Figure 9) has no source from the slopes of the Thousand Lake Mountain. A small cap of volcanic boulders overlies the Carmel Formation, providing an offset on the TLF at this location region of ~130 m (Figure 10).

Farther south, fault strands displace Mesozoic units (Figure 11) from one another in a series of westward-stepping N-S striking fault strands near Sunglow Campground. The stratigraphic units of the Carmel Formation and the Navajo Formation (Jurassic) are brought down to the west against the Wingate Formation and Chinle Formation (Late Triassic/early Jurassic). Several small fault strands place the Shinarump Formation below the Chinle Formation, about 15 m below its stratigraphic position above the
Moenkopi Formation (Figure 12b). The westernmost fault strand places Jurassic units of the Carmel and Navajo formations against Tertiary volcanic rocks (Figure 12a) and Tertiary sedimentary units (Figure 13b) in addition to boulder fans (Figure 13a). Among the rocks offset by the fault is a biotite-rich ashy sandstone (Tas, Figure 12a), a volcanic unit that underlies the Johnson Valley Reservoir trachyandesite. Smith et al. (1963) previously mapped this unit as the Flagstaff Formation, but based on stratigraphic relations observed in the field, we map this ashy sandstone as a separate unit (Plate 1). Ages on biotite collected from field samples in an earlier study show that the minimum age for these rocks is 36.53± 0.14 Ma (UGS Open File Report, 2012).

**Fault Geometry and Kinematics**

The main strand of the TLF dips westward and strikes N-S in the southern part of the Lyman quadrangle. The strike changes to 020° near 38.42° and parallels the orientation of the Paradise and Fremont faults to the NW. Kinematic evidence suggests down-to-the-west normal slip on the TLF and total offset of ~80 to >500 m. Displacement on the TLF decreases to the northeast, and may be transferred to the Paradise Fault system (Figure 7).

In the Bicknell 7.5’ quadrangle, the TLF zone contains several anastomosing strands striking N-S and NW-SE. The fault is well-exposed in the region north of Sunglow campground where it displays an en-echelon, left-stepping pattern of displacement transfer. Measurable strikes and dips yielded a mean fault measurement of 358° 66° W (Figure 14). Slickenline measurements on fault planes in show fault movement with a displacement to the northwest (Figure 14).
Figure 7. Satellite image illustrating the location of the Lyman and Bicknell 7.5’ quadrangles.
Figure 8. Boulder fan offset near the Yellow Ledges. Note the colluvium from the Yellow Ledges unruptured by the fault displacement. Unit symbols: Jn- Navajo Formation, Jc- Carmel Formation, Qb- Boulder fan, Qmm- Mass movement deposit, Qc- Colluvium
Figure 9. Eastward view of the Yellow Ledges, illustrating colluvium covering the fault, overlying the boulder fan (Qb), which is downdropped by the TLF (dashed line). Imagery from Google Earth.
Figure 10. Cross sections demonstrating fault displacement at the Yellow Ledges. Thickness of Quaternary units exaggerated.
Figure 11. Stratigraphic relations in Mesozoic rocks. (a) Wingate (JTrw), Kayenta (Jk), and Navajo (Jn) formations on the footwall of the TLF in Crescent Canyon. (b) Wingate (JTrw) and Chinle (Trc) formations on the footwall of the TLF.
Figure 12. Views of strands of the TLF displacing Mesozoic sedimentary units. (a) The TLF downdrops a sequence of steeply dipping Tertiary volcanics to west, against Jurassic Carmel formation. (b) Strands of the fault displacing the Shinarump formation and Triassic Chinle formation.
Figure 13. The TLF displacing Cenozoic rocks. (a) Boulder fan down-dropped against Navajo Formation south of the Yellow Ledges with a fault measurement of 353°70′W. (b) Limestone of the Flagstaff Formation downdropped against Navajo Formation west of the Crescent Canyon in the Bicknell quadrangle. Fault surface covered by colluvium.
Figure 14. Stereograms of structural measurements. Arrows demonstrate slip direction based on trend and plunge of slickenlines. (a) Six fault measurements along strand of TLF north of Sunglow Campground. Mean fault orientation is 358º 66º dipping west. (b) Two slickenlines measured on fault surface in Navajo formation north of Sunglow Campground. (c) Two slickenlines measured on fault surface in Shinarump Formation south of Bicknell shooting range at HB-124.
**Fault Zone Structures**

Several indicators of brittle deformation and paleoseismicity exist in the fault zone near Sunglow Campground in the Bicknell quadrangle. An injection vein at HB-26 has an orientation of 356° 48° E at its origin at the top of the outcrop, and wraps around the entire outcrop, curving to horizontal (Figure 15). The main strand of the TLF is located in a gully 3m west of the outcrop at HB-26. The extensional stress normal to the greatest stress create a dilational opening, allowing saturated sediment with large, angular clasts to fill the fracture (Figure 16).

A fault breccia contains more than 30 vol-% angular fragments in a fine-grained matrix, and forms through brittle processes by fault propagation through rock along older planes of weakness (Passchier and Trouw, 2005). Fault breccia occurred at HB-25 and as float near HB-14 (Figure 17). Cohesive breccias form in the pressure-temperature conditions where brittle deformation dominates, which is the upper 10 km of the Earth’s crust. The cohesion of the breccia is due to precipitation of minerals like quartz or calcite from fluid flow (Passchier and Trouw, 2005).

Fracture sets in the fault zone occur in the Jurassic Navajo Sandstone (Figure 18). These fractures occur in the orientation of the TLF, indicating that they either formed as deformation structures in the fault zone, or preexisted as planes of weakness along which the fault propagated.
Figure 15. Photos of an injection vein located on the TLF at HB-26. (a) Outcrop view of injection vein in an outcrop of Navajo Formation. (b) Vein becomes horizontal, demonstrating downward movement of fill material. (c) Detailed view of vein with rounded and angular clasts of Ashy Sandstone (Tas), Navajo Formation (Jn), Johnson Valley Tracyandesite (Tjv), and Lake Creek Trachyte (Tlc) poorly cemented in a muddy matrix.
Figure 16. Schematic overview of injection vein formation. A dilational opening allowed saturated sediments to flow downwards quickly, filling fracture during seismic activity.
Figure 17. Limestone fault breccia from HB-25. (a) Outcrop photo of cohesive breccia with large, angular clasts. Iron oxide staining visible on surface. (b) Thin section photo in plane-polarized light. Clasts are angular and primarily limestone in a matrix of quartz and calcite.
Figure 18. Fracture sets in the Navajo Formation from HB14 and HB16. Note the predominant group of N/NNW strikes, with a second set of NE-striking fractures.
**Geomorphic Indices**

Longitudinal profiles of the Fremont River flowing east across the TLF illustrate the downward movement of Bicknell Bottoms on the hanging wall of the fault (Figure 19). The topography at Bicknell Bottoms, located southwest of the town of Bicknell and west of the Red Gate (Figure 5), is extremely flat with a number of braided and meandering channels of the Fremont River. At Red Gate, the river crosses the TLF as one meandering channel, demonstrating no knickpoint (Figure 19). An examination of longitudinal profiles of channels flowing west across the fault reveals concave, smooth profiles inconsistent with disruption by tectonic movement (Figures 20 and 21). Channels are deeply incised in many places, cutting through mass movement deposits, older alluvial fans, and previous alluvial deposits.
Figure 19. Longitudinal profile of the Fremont River through Rabbit Valley and Bicknell Bottoms. Notice the flat profile of Bicknell Bottoms as the fault lowers the topography on the western hanging wall.
Figure 20. Longitudinal profiles of channels flowing west over the TLF. Note the lack of knickpoints at the locations where the channels cross the fault.
Figure 21. Location of channels with longitudinal profiles shown in Figure 20 shown on a colorized digital elevation model. High elevations shown in red, low elevations in green. The Thousand Lake Fault is shown as a white line flanking the Thousand Lake Mountain.
Discussion

Kinematics and Geometry

The TLF is a steeply-dipping normal fault zone with an orientation consistent with the extension direction of the Transition Zone and the Basin & Range province. Slip on the TLF is down-to-the-west, with a total displacement 800-1000 m (Figure 22). Displacement decreases to the north, as offset is transferred west to the Paradise and Fremont Faults. The main strand of the fault strikes in two distinct directions: N-S in the south, and NE-SW in the north. Only one strand of the TLF is apparent in most of the Lyman quadrangle, though surficial deposits may cover and obscure inactive strands. At Pole Canyon in the north, two strands are visible in an anastomosing pattern (Plate 1).

The two directions of dominant strikes indicate the presence of two segments of the fault. Seismic events are therefore unlikely to propagate past the fault bend, so the two segments may have different ages of most recent seismic activity (DePolo et al., 1989). The bend in the fault’s direction of strike may represent an oblique component of slip.

Rock units across the region are tilted east towards the TLF (Figure 22). The tilting indicates rotation of units towards the fault by slip along a curved, listric fault surface. The TLF therefore has controlled the landscape evolution of the Fish Lake Plateau during its protracted history.

Fault History

The TLF offsets boulder deposits near Yellow Ledges, providing a minimum age for fault movement. The boulder fan is a weathered diamicton resulting from a debris flow deposit with meter-scale weathered boulders of Johnson Valley Reservoir.
trachyandesite (Tjv). Based on He-3 dates from a similar boulder fan south of Sunglow Campground, the minimum age is less than 213 ka (Marchetti et al., 2005). A fan of colluvial material from the Yellow Ledges covers the TLF, constraining the most recent movement to older than the colluvium deposition. The colluvium on the slope may also represent a colluvium wedge of coeval deposition with the last rupture of the fault (McCalpin, 1987), so an exposure age of the sediment would record the last seismic event.

The fault zone near Sunglow Campground north of the Red Gate has many fault strands. Displacement there offsets Mesozoic sedimentary units against other sedimentary units as well as Mesozoic rocks against Quaternary boulder fans and Tertiary trachyandesite. Fault zone structures like the injection vein at HB-26, fault breccia, and fractures demonstrate a seismogenic history for the fault. Earthquakes likely controlled the large displacement of the fault surface, though no seismic activity has occurred within the Holocene.

The relative smoothness of the longitudinal profiles of channels crossing the fault (Figure 20) reveal that mass movement occurs more frequently than tectonic processes, controlling slope topography. Channels from the western flank of the Thousand Lake Mountain erode debris flows and landslide deposits rather than fresh bedrock of fault scarps. Channels flowing along and across the fault trace incise deeply into underlying surficial units, depositing younger alluvium on older alluvium and debris flows. The older surficial units could represent material transported as a result of the most recent fault rupture, so more modern incision may have occurred after the last seismic event.

Thousand Lake Mountain and Boulder Mountain (Figure 3) were likely originally connected as one block, as they are both capped by pyroclastic flow deposits of
trachyandesite dated to ~26 Ma. The Fremont River drainage has eroded between these peaks, crossing the fault as it flows west across the down-dropping hanging wall to the upthrown footwall at Red Gate. The motion of the fault has caused a ponding effect at Red Gate, creating the topographic low at Bicknell Bottoms (Figure 18). At times when large displacement occurred on the fault, the Fremont River likely dammed at Red Gate, creating a closed basin with a lake, which eventually incised across the fault again to drain. Thinly-bedded deposits of possible lacustrine origin located near the town of Bicknell provide possible evidence for ponding caused by fault movement.

While the most recent movement on the TLF occurred in the last 200k years, the fault is a much older structure along the boundary of the Transition Zone (Figure 23). The large displacement on the fault (as great as 1,000 m) indicates that the fault was extremely active for a protracted period. An olivine basalt flow near the Forsyth Reservoir on the eastern edge of the Fish Lake Plateau dated to 5 Ma (USG Open File Report, 2012) are extruded along the fault zone and offset by the fault (Bailey et al., 2007). The basaltic volcanism was likely contemporaneous to fault movement, so the fault must have been actively slipping 5 Ma. Based on active extension patterns of the Great Basin, the fault may have initiated in the Late Miocene in response to Mid-Cenozoic stresses (Wannamaker et al., 2001). The TLF displaces Miocene volcanic rocks (26 Ma) from the peak of Thousand Lake Mountain, making the Late Miocene a plausible age for initial upper-crust rupture. Slip on the TLF may represent a reactivation of a Sevier orogeny structure or zone of crustal deformation.
Figure 22. Regional cross section from the northwestern Fish Lake Hightop to the southeastern flank of the Thousand Lake Mountain. Note the large offset of Tjv (Johnson Valley Reservoir trachyandesite) ~1000 m from the TLM to the Fremont River.
Figure 23. Geologic history of the TLF region with selected events pertinent to the fault zone development.
Conclusions

The Thousand Lake Fault system is a steeply-dipping (~70°) normal fault zone that downdropped the Fish Lake Plateau block to the west against the Colorado Plateau block to the east. The fault strikes N-S in the Bicknell and southern Lyman quadrangles, and the strike changes to 020° near latitude 38.42°. The strike bend may indicate a zone of slip with an oblique component. In the south the fault anastomoses, displaying several fault strands that displace both Mesozoic and Cenozoic formations. Only one fault strand is visible through most of the Lyman quadrangle, due to burial by surficial deposits or displacement transfer to the Paradise and Fremont faults.

The TLF displaces Miocene volcanic rocks from the Thousand Lake Mountain to an elevation 500 m lower in the Rabbit Valley Salient. Regionally the TLF and other similar normal faults have a displacement greater than 1,000 m. Most recent movement on the fault displaces boulder fans, demonstrating that the fault moved during the Quaternary.

Brittle deformation features in the fault zone including tectonic breccia, an injection vein, and abundant fractures demonstrate that the fault has a seismogenic history. Seismic rupture produced the large displacements on the fault, though no field observations suggest Holocene seismic activity. The magnitude of displacement on the TLF indicates that the fault system is a major regional structure that likely initiated in the Miocene as an easternmost expression of Basin & Range extension. The fault is likely a very deep and listric structure, curving to horizontal at depth and tilting hanging wall strata towards the TLF. The Thousand Lake Fault as a transition zone structure has had a
major regional impact on the deformation active at the margin of the Colorado Plateau in the last 15 million years.

Future Work

Future work in the field includes collection of quartz samples from colluvium on the fault at Yellow Ledges for OSL dating and continued mapping in the Lyman quadrangle. Samples of porphyritic andesite will be dated with Helium-3 cosmogenic nuclide dating. Forthcoming ages will further constrain the age of most recent movement on the TLF.

Acknowledgements

My research was funded by a generous Honors Fellowship from the Roy R. Charles Center at the College of William & Mary. Summer fieldwork and mapping in the Lyman 7.5’ quadrangle were funded by a USGS Educational Mapping grant.

I am indebted to several individuals for their support of my work. First, I would like to thank the Wayne Wondermonkeys (Erika Wenrich, Zach Fleming, and Peter Steele) for their teamwork during fieldwork in Utah. Their positive attitudes and field skills made our time traipsing through the Lyman and Bicknell quadrangles both highly enjoyable and productive. Dave Marchetti also provided valuable field assistance and advice for this research in his role as honorary Wondermonkey. Additionally I would like to acknowledge King Shasta for his magnificent (though aloof) presence.

I would not have been able to complete this thesis without the support and assistance of my advisor, Chuck Bailey. I’m grateful for his encouragement and ability
to address my many questions over the last year, as well as his willingness to help me with the many thesis-writing difficulties over the last few months.

Finally, I’d like to express my appreciation for the Geology department at William & Mary. The friendly and supportive community that exists in the department between both faculty and students have made my time as a geology major such a joy and fostered my passion for the earth sciences. Late nights in the TC were made much more bearable when surrounded by such a great group of people!
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