

**A. Proposal Information Summary  
USGS Earthquake Hazards Program Grant**

1. Panel Designation: IMW – Intermountain West
2. Project Title: **Collaborative Research with Brigham Young University and Utah Valley University: Timing, Rate, and Mechanisms of Slip along the Clear Lake Fault, Millard County, Utah**
3. Principal Investigator(s):  
PI Dr. Nathan A. Toké (UVU)  
Co-PI Dr. Michael P. Bunds (UVU)  
PI Dr. Stephen T. Nelson (BYU)  
Co-PI Dr. John H. McBride (BYU)  
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5. Amount Requested: **\$29,496 to UVU** (\$38,004 to BYU for a total of \$67,500)
6. Proposed Start Date: March 15<sup>th</sup> 2016
7. Proposed Duration: 12 months
8. New Proposal : Yes for UVU, No for BYU
9. Re-submittal Proposal: No for UVU, Yes for BYU
10. Has this proposal been submitted to any other agency for funding, if so, which? No

## Abstract

The seismic hazard of active fault zones immediately adjacent to the Colorado Plateau-Basin and Range Transition Zone and the Wasatch Front urban and transportation corridors remains poorly understood. Infrastructure in central Utah continues to develop southward as part of the rapid population growth in the state. The Clear Lake Fault Zone (CLFZ), a ~30-km long and broad zone of faulting, dominates the neotectonic and seismic hazard setting of this region. Nevertheless, information on timing and degree of Holocene fault offsets related to its earthquake history is lacking. Although this portion of Utah is sparsely populated, major infrastructure lifelines include a 1.5 GW electrical generating facility, electrical transmission lines, railroads, freeways, dams and reservoirs, as well as a major natural gas transmission line. The exact mechanism of earthquake-related faulting is also not well understood. This lack of information makes it difficult to estimate parameters critical to seismic hazard evaluation such as the distribution of geologically recent faulting, recurrence interval for faulting episodes and earthquakes, time of latest fault motion, and amount of fault offset possible for an event.

We have recently acquired seismic reflection (compressional and shear wave) and ground-penetrating radar (GPR) profiles across the main fault of the CLFZ, known as the Clear Lake fault, and used these profiles to derive high-resolution structural interpretations of faulting at various scales (our surveys have extended the original USGS and COCORP seismic reflection studies of this region from the early 1980s). These results indicate a major zone of offset and accumulated sediments, which can be traced from just below the ground surface at the Clear Lake fault scarp to several hundred meters depth. We interpret the results to indicate a possible zone of aseismic creep, based on the thick accumulation of apparent growth strata in the hanging wall of the fault; however, we still lack precise information on the timing of offset reflectors (because we cannot “date” reflectors) and confirmation on exact offsets in the near surface (because of the difficulty in measuring small, shallow offsets from geophysical remote sensing).

Our approach to solve these problems is to develop a paleoseismic site along the Clear Lake fault scarp near our previous geophysical profiles. Information obtained from the paleoseismic trenches will complement the geophysical data and complete our objective to create multi-scale cross sections from the ground surface to over 500 m depth. They will also serve to test our preliminary geophysical interpretations of the magnitude of fault displacements and provide data about the timing and mechanisms of the most recent faulting events (rupture vs creep). A second objective is to characterize the heterogeneity of fault tectonics along the Clear Lake fault site by using information from two additional suites of geophysical profiles as well as low-altitude aerial photography producing high resolution decimeter-scale DEMs of the Clear Lake fault scarp. Because of the clear expressions of fault-related structure on the geophysical profiles and the presence of a prominent fault scarp at the site, we are confident that the trenches will provide definitive information on the timing, magnitude, and style of Holocene faulting events. These results will be useful for constraining revised seismic hazard estimates for this under-studied area of the eastern Basin and Range. Further, the integration of trenching and three levels of geophysical resolution, proceeding from GPR, to shear wave, to compression wave (i.e., from finest/shallowest to coarsest/deepest) will provide a template for approaching other potentially hazardous fault zones in this region, in preparation for anticipated increased population pressure.

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**B. UVU BUDGET SUMMARY <sup>1</sup>**Project Title: **Collaborative Research with Brigham Young University and Utah Valley University:****Timing, Rate, and Mechanisms of Slip along the Clear Lake Fault, Millard County, Utah**Principal Investigator(s): **Nathan A. Toké**Proposed Start Date: March 15<sup>th</sup>, 2016Proposed Completion Date: March 14<sup>th</sup>, 2017

<b>COST CATEGORY</b>	<b>Federal First Year</b>	<b>Federal Second Year<sup>2</sup></b>	<b>TOTAL Both years<sup>2</sup></b>
1. Salaries and Wages	\$9,723		
<b>Total Salaries and Wages</b>	<b>\$9,723</b>		
2. Fringe Benefits/Labor Overhead	\$ 1,729		
3. Equipment	\$ 450		
4. Supplies	\$ 1,300		
5. Services or Consultants	\$ 3,060		
6. Radiocarbon or other Dating	\$ 7,520		
7. Travel	\$ 2,662		
8. Publication Costs	\$ 0		
9. Other Direct Costs	\$ 0		
<b>10. Total Direct Costs (items 1-9)</b>	<b>\$ 23,461</b>		
11. Indirect cost/General and Administrative (G&A) cost	\$ 3,621		
12. Amount Proposed (items 10 & 11)	\$ 29,496		
13. Total Project Cost (Total of Federal and non-Federal amounts)	\$ 29,496		

<sup>1</sup> *The BYU Budget Summary is within their separate submission, but the detailed portion is listed below.*

**Detailed Budget.**

**Detailed Utah Valley University (UVU) Budget**

**Salaries and Wages**

Dr. Nathan Toké (PI), 1.5 months' salary @ \$6,720/mo (40% of time)	=	\$4,032
Dr. Michael P. Bunds (Co-I), 1.5 months' salary @ \$7,175/mo (25% of time)	=	\$2,691
Undergraduate Student 1, 6 weeks @ 12.5\$/hr * 20 hrs	=	\$1,500
Undergraduate Student 2, 6 weeks @ 12.5\$/hr * 20 hrs	=	\$1,500
<b>Total Salaries and Wages:</b>		<b>\$9,723</b>

**Fringe benefits/labor overhead.**

Fringe on Faculty Salary (22.6%)	=	\$1519
Fringe on Student Wages (7%)	=	\$210
<b>Total Fringe:</b>		<b>\$1,729</b>

**Equipment.** *No major equipment will be purchased*

**Supplies.**

Supplies for radiocarbon collection and collection of other samples	=	\$50
Paleoseismic Supplies (new scrapers, nails, etc)	=	\$250
Helium for helikite for collecting high resolution digital imagery/DEMs	=	\$150
<b>Total Supplies:</b>		<b>\$450</b>

**Services or consultants.** *The primary cost will be paleoseismic trench excavation.*

Excavation and Backfilling – 3 work days (24 hours @ \$125/hour)	=	\$3000
Shipping of Radiocarbon Samples	=	\$60
<b>Total Services:</b>	=	<b>\$3,060</b>

**Ages.**

*Radiocarbon: We will use Woods Hole Oceanographic Institute's AMS Facilities for <sup>14</sup>C ages:*

*WHOI: <http://www.who.edu/nosams/contact>*

*Susan Handwork: [shandwork@who.edu](mailto:shandwork@who.edu), phone: (508) 289-2469*

Radiocarbon Samples (10 samples @ WHOI \$332/sample)	=	\$3,320
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*OSL: We will use the Utah State University Luminescence Laboratory for OSL ages:*

*USU LL: <http://www.usu.edu/geo/luminlab/contact.html>*

*Tammy Rittenour: [tammy.rittenour@usu.edu](mailto:tammy.rittenour@usu.edu), phone: 435-213-5756*

OSL Samples (6 samples @ USU LL \$700/sample)	=	\$4,200
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**Total Geochronology Cost = \$7,520**

**Travel.** *Travel is justified in more detail within the project plan section of the proposal:*

**Field Work (Travel to the paleoseismic site from Orem, UT six times in two vehicles)**

Mileage (\$0.38/mile x 2 vehicles x 200 miles/trip x 6 trips) =	\$912
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Per Diem Food (\$40/day x 24 days) =	\$960
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**Presentation at an Annual Meeting (one of SSA/GSA/AGU) (1 student)**

Airfare	\$300
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Hotel (Shared) \$75/night x 4 nights =	\$300
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Meeting registration	\$100
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Per Diem food during meeting (\$30/day x 3 days) =	\$90
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**Total Travel Costs = \$2,662**

**Publication costs.**

Printing and Page Charges will be paid by UVU and BYU	\$0
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**Other direct costs.** **\$0**

**Total direct costs.** **\$25,144**

**Indirect cost/general and administrative (G&A) cost.** (38% on Salary/Fringe Only) **\$4,352**

**Amount proposed.** **\$29,496**

**Total project cost.** **\$29,496**

**Detailed Budget.**

**Detailed Brigham Young University (BYU) Budget.**

**Salaries and Wages**

Dr. Stephen Nelson (PI), 1 months' salary	=	\$8,000
Kevin Rey (Research Staff), 96 hrs @ \$25.75/hr	=	\$2,541
<b>Total Salaries and Wages:</b>		<b>\$10,541</b>

**Fringe benefits/labor overhead.**

Fringe on Dr. Nelson is 35.6%	=	\$1,504
Fringe on Mr. Rey is 36.7%	=	\$501
<b>Total Fringe:</b>		<b>\$2,005</b>

**Equipment.**

*No major equipment will be purchased.*

**Supplies.**

*Incidental Supplies will be minimal or are already owned by BYU.*

**Services or consultants.**

*These costs will be paid by UVU (excavation).*

**Ages.**

*Detailed on the UVU portion of the budget*

**Travel.**

*Travel itemized by geophysical project components, additional paleoseismic travel cost indicated on UVU budget.*

**SH Wave Acquisition**

Lodging – 3 rooms @ \$100/night for 2 nights	=	\$600
Per Diem Food – 3 people @ \$30/day for 2 days	=	\$180

**P-wave Acquisition**

Lodging – 5 rooms @ \$100/night for 4 nights	=	\$2000
Per Diem Food – 5 people @ \$30/day for 4 days	=	\$600

**MASW Acquisition**

No lodging required—day trip		
Per Diem Food—3 people @ \$30/day for 1 day	=	\$90

**Paleoseismic Logging**

Lodging – 3 rooms @ \$100/night for 20 nights	=	\$6000
Per Diem Food – 3 people @ \$30/day for 20 days	=	\$1800

**Vehicle Use**

Mileage (\$0.38/mile x 10 round trips x 2 vehicles x 200 miles/trip)	=	\$1520
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**Total Travel: \$12,790**

**Publication costs.**

*BYU will bear the burden of any additional publication costs in collaboration with UVU.*

**Other direct costs.** None **\$0**

**Total direct costs.** **\$25,336**

**Indirect cost/general and administrative (G&A) cost.**

50 % **\$12,668**

**Amount proposed.** **\$38,004**

**Total project cost.** **\$38,004**

## Proposal

### Significance of the Project

Whereas the seismic hazard of the Wasatch fault zone has been studied extensively (e.g., Chang and Smith, 2002), areas immediately to the west, along the transition between the Basin and Range and the Colorado Plateau Transition Zone, have received relatively little attention. This is despite the fact that infra-structure has been steadily pushing westward in Utah from the Wasatch Front in response to increased population pressure.

We propose to use trenching to determine slip rates and offset for a major Quaternary-Holocene fault, the Clear Lake fault, located outboard of the Transition Zone in central Utah in an area of important and expanding infrastructure. Further, we propose to determine whether displacement along the fault proceeds by aseismic creep or discrete fault slip or some combination of the two. Our analyses will be constrained by geophysical subsurface data, previously acquired by us and by others, as well as by new geophysical data, acquired as part of this proposal. A similar version of this proposal was submitted last year with encouragement to resubmit. The primary feedback on that submission was to establish collaborations with another PI having experience in opening, logging, and closing trenches. We have accomplished this through a collaborative submission with Utah Valley University faculty. In particular, Professor Nathan Toké has this requisite expertise.

The Basin and Range Province is a large region of the western U.S. consisting of fault-bounded mountain blocks separated by basins filled with fluvial and lacustrine sediment and volcanic rocks (Eaton, 1982). The 8,000 km<sup>2</sup> Sevier Desert is a large basin in central Utah just west of the seismically active Transition Zone, having a broad floor underlain by thick sedimentary fill that thins toward basin margins (Oviatt, 1989), with a high concentration of Quaternary volcanic features and fault scarps in what is known as the Clear Lake fault zone (CLFZ) (Figs. 1, 2).

A deep seismic profile across the Sevier Desert Basin by the COCORP (Consortium for Continental Reflection Profiling) suggests the basin is underlain by a putative low-angle normal fault called the Sevier Desert detachment (Allmendinger et al., 1983; McBride et al., 2010). The detachment, which has been suggested to possibly be seismically active (e.g., Srisutthiyakorn, 2010), dips ~12° to the west, extends more than 120 km east to west, and has been traced as deep as 15-20 km. It is thought by many geologists to accommodate crustal extension beneath the Sevier Desert Basin, although this interpretation is controversial (McDonald, 1976; Wernicke, 1981; Anderson et al., 1983; Von Tish et al., 1985; Mitchell and McDonald, 1987; Planke and Smith, 1991; Anders, 1993; Anders and Christie-Blick, 1994; Wills and Anders, 1995; Wills et al., 1997; Wills and Anders, 1999; McBride et al., 2010). Thus, the faults in the CLFZ may be genetically related to this structure. Earthquakes in the CLFZ have been associated with 1-3 m of vertical displacement along moderate-to-high-angle normal faults (Hecker, 1993).

The surface expression of active faults in the CLFZ are well-developed in a variety of structural settings, including exposed scarps in both Quaternary sediments and basalt lava flows (Figs. 1, 2). The best-studied fault in the zone is the Clear Lake fault proper, which bounds the zone on the west. Multiple volcanic eruptions (Hoover, 1974; Oviatt, 1989; Oviatt, 1991; Hintz, 2008) place time constraints on fault movement to be Pleistocene to Holocene in age, with ash layers and fluvial and lacustrine sediments indicating recent deformation in the shallow subsurface. Recent high-resolution geophysical profiles across this fault (Heiner, 2014), discussed below, suggest that this major structure may have deformed by aseismic creep throughout the Holocene Epoch. Thus, the primary goal of the proposed research is to characterize the mode(s) of slip and slip rates on this structure.

The abundance of young fault scarps in the CLFZ suggests a significant seismic hazard in this region (Fig. 2). The area is sparsely populated. Millard County, UT has a total population of about 12,500 (US Census, 2014), mainly concentrated in the Delta and Fillmore, UT areas. However, both these cities are located near mapped Quaternary faults, as well as the 1.5 GW coal-fired Intermountain Power Plant

(IPP) that delivers electricity to southern Utah and California (IPA, 2014), such that many county residents and important infrastructure are exposed to substantial risk from multiple seismic faults.

Sevier Desert Basin extension appears to be related to the onset of local volcanism (Lindsey, 1982; Oviatt, 1991), with eruptive activity throughout the last 2 Ma. Nelson and Tingey (1997) concluded that recent volcanism in the Sevier Desert (Fig. 1) resulted from lithospheric melting induced by extension that reached a maximum in this area. Condie and Barsky (1972) defined several different volcanic clusters in the southern part of the Sevier Desert (locally, the Black Rock Desert) from 2.35 Ma to 11 ka, the majority of which are <1 Ma. Relevant to this proposal, volcanic activity includes the 15.5 ka Pavant Butte, a 270 m high cone of fine cinders and the largest volcanic edifice in the basin (Fig. 1; Condie and Barsky, 1972). Also included are the 14.3 ka Tabernacle Hill edifice, which consists of a tuff ring and basalt flows, and the 660 a Ice Springs (Fig. 1) cinder cones and a basalt flow (Fig. 1; Oviatt 1991). Hintz (2008) provides an excellent compilation of existing radiometric ages of these extension-related volcanic rocks.

Oviatt (1989) noted that extensive piedmont alluvial fans at the margins of the Sevier Desert Basin are lacking, suggesting that uplift has been generally absent for the last ~5 Ma. GPS studies show extension rates of 2.8 +/- 0.8 mm/y for central Utah (Thatcher et al., 1996), where Quaternary faults in the Sevier Desert and elsewhere tend to occur across broad zones. Historical seismicity in the Basin and Range Province suggests a surface rupture earthquake magnitude threshold of M 6-6.5 (Arabasz et al., 1992; Hecker, 1993).

*Target Structure—Clear Lake Fault.* The longest continuously mapped structure in the region, the Clear Lake fault, a primary structure in the Clear Lake fault zone (CLFZ), is located in the center of the Sevier Desert Basin (Fig. 1). At a ~26 km length, the CLFZ proper is one of the longest late Quaternary (Holocene?) faults in Utah outside the Wasatch fault zone. At the proposed study site, the Clear Lake fault scarp is about 3 m high, and is a down-to-the-east north-south striking normal fault (Fig. 2A, 3). Furthermore, interpretations of a COCORP deep seismic reflection profile (Allmendinger et al., 1983; McBride et al., 2010) suggest that the Clear Lake fault may continue even further north, at least 23 km north of the study site and further north by at least 8 km beyond where mapped by the U.S.G.S. Quaternary Fold and Fault Database (USGS, 2010) has limited it. Thus, the Clear Lake fault is likely longer than presently recognized, perhaps due to obliteration of scarps by agricultural activity.

Some knowledge of age constraints can be gained from geologic surface mapping over the fault and surroundings. Eolian silt covers the surface of both blocks of the Clear Lake fault, with deltaic/braid plain sands and gravels from the Beaver River in the footwall and sag pond marls in the hanging wall (Figs. 3, 4). As these gravels were deposited in the regressive phase of Lake Bonneville, the fact that they appear to be truncated by the fault (Fig. 3) indicates that considerable slip post-dates lake regression. It has been suggested that the Clear Lake fault is kinematically linked to the Sevier Desert detachment, intersecting it at a depth of about 3.5 km (Crone and Harding, 1984; Oviatt, 1989; and Hecker, 1993). However, no existing subsurface data clearly and definitively link the two features.

Recent work by one of our students (Heiner, 2014<sup>1</sup>), augmented by additional analysis by us, suggests that the Clear Lake Fault has the potential to produce M 7+ earthquakes. We have characterized the shallow architecture of the Clear Lake fault by vectorizing and post-stack reprocessing the U.S.G.S. seismic reflection profile that crosses the fault (Crone and Harding, 1984), as well as acquiring high-resolution geophysical data via ground-penetrating radar, horizontally polarized shear-wave (SH) reflection profiles, and conventional P-wave reflection profiles augmented by logging shallow hand-augered borings (Figs 4 & 5) (see Heiner, 2014 for details).

*Augering.* Direct shallow subsurface geologic data are necessary in order to guide the

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<sup>1</sup> We have recently re-submitted a revised manuscript (*Neotectonics of the Sevier Desert basin, Utah as seen through the lens of multi-scale geophysical investigations*) to *Tectonophysics*. We anticipate that this paper will soon be in press.

interpretation of the geophysical data and constrain age and offset estimates of fault slip. In the footwall of the Clear Lake fault, a bucket auger hole was completed to a depth of 2.64 m where refusal occurred at a gravelly sub-surface layer (Fig. 4). Silt and sand dominated the section with minor marls and gravels. The lower half of the log shows two fining-upward groupings reflecting higher-energy conditions that are probably stream sediments. This is consistent with mapping (Oviatt, 1989; Hintze and Davis, 2002) that indicated the presence fluvial and deltaic sands and gravels in the footwall of the Clear Lake fault (Fig. 3). Overall, the sediment is similar to that found by Bucknam and Anderson (1989a) who excavated a 1 m test pit into the Clear Lake fault scarp, describing loose lacustrine and eolian sediment with sparse suspended pebbles.

The bucket auger hole in the hanging wall was completed to a depth of 8.9 m (Fig. 4) through considerable effort. Silt was encountered near the surface and the rest of the boring was dominated by gray to dark gray and green marl. Several horizons contained organic-rich sediments, including several cm near the bottom that were dark brown to black and rich in organic matter, showing that suitable material exists for  $^{14}\text{C}$  ages to establish the slip history. Absent such organic matter, quartz in marl will provide an excellent analytical matrix for OSL (optically stimulated luminescence) ages. Foot- and hanging-wall stratigraphy matches geological mapping results (Oviatt, 1989; Hintze and Davis, 2002) placing lacustrine/playa silts, marls, and calcareous clays in the hanging wall (Fig. 3). The auger location in the hanging wall is interpreted to represent a sag pond where wet climate episodes promoted plant growth reflected in organic-rich horizons. As discussed below, this interpretation is consistent with the geometry of reflectors.

The ground surface of the footwall hole is 2.5 m above the elevation of the hanging wall boring. The larger-grained river (medium to gravel) sands at the bottom of the footwall hole appear at a depth of 1.8 m. This package of stream sediments is not found in the hanging wall boring. With the close proximity of the holes to each other it is assumed that these sediments are present in the hanging wall, but below the depth obtainable by hand excavation. This suggests that there are more than 9.6 m of offset on stream sand and gravels at this site.

Following the empirical relationships between mean slip and moment magnitude (Wells and Coppersmith, 1994), and assuming the >9.6 m slip represents 4 or 5 events or more, multiple moment magnitude 7+ events may be recorded on this structure, much of it during Holocene time. The offset fluvial sands and gravels were deposited during the regressive phase of Lake Bonneville (Oviatt, 1989), inferring this more than 9.6 m of throw has accumulated in less than 15 ka for a vertical strain rate of at least 0.6 mm/a.

*Seismic Reflection Profiles & GPR Data.* In order to assess the ability of different geophysical techniques to image fault-related structure beneath the area of the surface scarp on the Clear Lake fault, we recently conducted seismic and ground-penetrating radar (GPR) surveys at this and other sites in the CLFZ. On the P-wave seismic reflection profile, coherent reflectors appear at about 50 m depth and continue to at least 500 m (Fig. 5). Deeper, but weaker reflections extend to about 900 m. Disruptions, including vertical offsets of reflectors, were interpreted as faults. Disruption appears just below the surface at the scarp and continues downward exhibiting down to the east displacement. The apparent dip is  $70^\circ$  starting at the surface and decreases somewhat with depth.

The enhanced resolution of the profile due to closer CDP (common depth-point) sampling is apparent when compared with the partially coincident USGS P-wave reflection profile (Fig 6). Crone and Harding (1984) suggested several antithetic faults initiating from the Clear Lake fault at depth, continuing upward to the east up to the surface. However, these features are not readily apparent in the higher resolution profile (Fig. 5).

Coherent SH-wave reflections begin at 5 m depth and continue to about 90 m (Fig. 7), providing enhanced shallow resolution due to the shorter wavelengths from the inherent slower speed of S waves compared to P waves (Woolery et al., 1993). Similar to the P-wave profile, a zone of disruption extends from the top of the profile directly below the scarp, continuing downward with down-to-the east

displacement. A second fault is seen within the footwall 110 m to the west of the main Clear Lake fault, indicating that the total architecture is more complex than a single fault associated with one surface scarp.

The results of the GPR surveys were excellent at this location (Fig. 8), likely due to well-layered sediments and removal of clay-rich, saline surficial materials from the roadbed. Vertical resolution is close to a decimeter and imaging is clear to a depth of ~2 m. The profile shows possible evidence of deformation in footwall that could also be sedimentological in origin (Fig. 8A, location 1). Another fault just west of the scarp with a down to the east offset shows clear evidence of very shallow disruption with a synthetic sense of displacement (Fig. 8A, B), location 2). Directly beneath the scarp are diffractions implying a small-wavelength disruption (Fig 8B, location 3). The scarp also marks the western margin of a small sag basin (Fig 8B, location 4). Shallow disruptions observed in GPR records are consistent with Holocene activity on the Clear Lake fault (Condie and Barsky, 1972; Bucknam and Anderson 1979 Crone and Harding 1984; Oviatt, 1989; and Hecker, 1993). The three geophysical techniques all confirm the ability to image critical features of fault zone geometry at different scales and depths.

Overall, the fault zone is not only recognized by the offset of reflectors above a depth of 80 m in the SH profile, but also deeper where reflectors are deflected downward away from the fault in the P-wave profile at depths from 90 m to 250 m. The upward concavity of these reflectors is likely due, in part, from fault drag during slip, where the degree of drag suggests that faulting occurred in weak sediments. In order for such weak (near surface?) sediments to be observed so deep in the section implies that overall fault movement was fairly rapid. The greater vertical separation between reflectors in the hanging wall suggests these are growth strata, whereas upward concavity of reflectors in the hanging wall suggests the presence of sag ponds. Adjacent to the fault, drag reverses the fault-ward tilt and thickening of strata in the sag pond of the hanging wall. These features suggest that the fault may have deformed by aseismic creep, possibly punctuated by rapid fault movement. If deformation has been by creep alone, the scarp reflects subsidence in the hanging wall that is greater than sedimentation rates, a phenomenon that has been observed elsewhere (e.g., Ferreli et al., 2002).

Inferences of creep on a fault that seems to exhibit high slip rates poses critical questions for seismic hazard and risk assessment. Absent creep, a high apparent slip rate of the Clear Lake fault would indicate a substantial hazard for large events with a relatively low recurrence interval. However, if creep is the dominant mechanism for accommodating strain, evaluating strain rates by the throw alone may lead to overestimation of hazard and risk. More broadly, it raises the possibility that analogous structures in extensional regions, including the Intermountain West (IMW), may elevate apparent seismic hazard estimates.

*Recognizing Slip Modes.* Aseismic creep is commonly recognized or postulated in fault zones (e.g., Stenner and Ueta, 2000 or Toké et al., 2011), including normal faults, from studies of slip at considerable depth (e.g., Bos et al., 2000; Collettini and Holdsworth, 2004; Hreinsdottir and Bennett, 2009; Sabadini et al., 2009; Smith and Faulkner, 2010; Velasco et al., 2010; Takeshita and El-Fakharani, 2013) to surface strain observations (e.g., Pavlides, 1996; Koukouvelas et al., 1999; Vanneste and Verbeeck, 2001; Ferreli et al., 2002; Stemberk et al. 2007; Avila-Olivera and Garduno-Monroy, 2008; Sabadini et al., 2009;). Thus, the inference of creep made from our high-resolution geophysical studies begs further investigation. The indicators of sag-pond and creep interpreted from our seismic images and borings match the expected stratigraphy of a creeping fault as described by Ferreli et al. (2002) from trenches.

A key to the success of this project is the successful recognition of aseismic creep versus episodic slip features observed in fault trenches. Ferreli et al. (2002) noted that creeping faults have been poorly described in terms of exposed stratigraphic and structural features. However, some trench features of both episodic slip and creep can be anticipated. It has long been understood that rapid slip events will offset strata and paleosols accompanied by erosion of footwall scarp material onto the hanging wall, producing colluvial wedges and diminished scarps. The absence or diminution of these features should accompany continuous creep on normal faults (Ferreli et al., 2002). This is discussed in greater detail in the Project

Plan.

*Reducing Seismic Losses.* As discussed above, vertical slip rates on the Clear Lake fault may exceed 0.6 mm/a, exceeding guideline thresholds of 0.1 mm/a for faults in urban and 0.2 mm/a in rural areas, as referenced in NEHRP documentation. Trenching the Clear Lake fault will allow confirmation or modification of slip rate estimates to be used in revising local seismic hazard maps. Trenching will reveal the relative importance of discrete slip events versus creep due to the comparative thickness and geometry of beds in the hanging and footwalls, as well as the presence or absence of colluvial wedges in the hanging wall adjacent to the fault scarp, accompanied by fine-grained sedimentation, thickened strata, and concave upward bedding (e.g., Ferrelly et al., 2002) like that seen in the Clear Lake fault at deeper levels.

Although the population of Millard County, UT is low, the cities of Delta, and Fillmore are ~30, and ~35 km away, respectively, relative to the location of our geophysical studies and proposed trenching. The Intermountain Power Plant (IPP) and a solution mine for natural gas storage are somewhat further at ~46 km. However, the fault scarp can be traced northward 15 km from the site of our geophysical studies, such that Delta and the IPP are quite close to the surface expression of the fault (Fig. 1), and as discussed above, the fault likely extends even further north. Also, within the Delta, UT area are two important earthen dam impounded water bodies, the DMAD ( $12.3 \times 10^6 \text{ m}^3$  volume; UDWQ 2014a) and Gunnison Bend ( $6.2 \times 10^6 \text{ m}^3$  volume; UDWQ 2014b) Reservoirs, which deliver irrigation water from the Sevier River to Utah's largest agricultural area that surrounds Delta (Fig. 1).

A major railroad bisects the Clear Lake fault, and has a spur that delivers coal to the IPP. Current planning calls for replacing coal with natural gas at the IPP by 2025 (IPA, 2013), and a natural gas storage facility is currently under construction via solution mining in a nearby salt dome (WEH, 2014). Conversion to natural gas may require construction of a secondary pipeline from the Kern River pipeline, which also transects the region. The Kern River pipeline delivers natural gas to Barstow, CA from southwestern Wyoming (KRGTC, 2014), and provides 80% of the natural gas consumed in Las Vegas, NV (LVRJ, 2010). Electricity generated at IPP is carried by a HVDC powerline to Adelanto, CA and then dispersed to metropolitan Los Angeles, CA (Fig. 1).

On a population-only basis, the Clear Lake fault appears to pose a high hazard accompanied by low risk. However, the high hazard translates to high risk for important local and regional infrastructure. Ground shaking or other ground failures could interrupt the delivery of electricity to Los Angeles by a number of modes: interruption of coal or gas supplies, damage to generation facilities, or disruption of power lines. Natural gas is an increasingly important resource given modern extraction methods and low prices. Thus, interruption of gas deliveries to Las Vegas and Bakersfield would be economically damaging. Finally, in addition to local ground shaking and other ground failure modes, failure of earthen dams in the Delta area could be destructive.

We expect that trenching will: a) confirm that creep is the dominant strain mechanism on the Clear Lake fault, or b) that episodic slip is the chief failure mode, or c) a mixture of modes is indicated. Resolving the slip behavior of the fault will reduce the uncertainty in hazard and risk assessments to local populations and regional infrastructure.

More generally, a greater understanding of the rate and nature of slip on the Clear Lake fault will improve overall understanding of analogous structures in extensional terranes where both seismic and aseismic processes may be operative. For example, work by us on other fault scarps in the Sevier Desert suggests a range of deformational styles where multiple slip events, rather than creep, seem to be recorded on a given fault (Heiner et al., 2013; Heiner, 2014). Thus, fault scarps of similar height and length in the same region may reflect greatly different hazards.

*USGS/EHP Research Priorities.* Under IMW Element I, the proposed research will contribute to the refinement of hazard and hazard maps impacted by the Clear Lake fault based upon a much-improved record of its slip history. This will impact Delta and Fillmore, Utah, as well as surrounding communities, and permit evaluation of the earthquake risks to regional infrastructure. Specific to the IMW program, this

work addresses a fault with an apparent minimum estimated slip rate three times higher than the 0.2 mm/a cited for rural faults. In addition to evaluating slip mode, we will attempt to evaluate all related criteria, such as “*the time of the last earthquake, slip rate, recurrence times, and slip per event, including uncertainties.*”

Element III will be addressed by an improved understanding of the range of near-surface expression of strain on large, active normal faults. In addition to trenching, we will conduct an MASW (Multi-channel analysis of surface waves (Park et al., 1999; Park et al., 2007)) experiment across the fault to document  $V_{s30}$  of foot and hanging wall sediments at the site of our existing geophysical profiles. Preliminary MASW profiles performed by us in the Sevier Desert (and compared with results in other volcanic terranes) confirm the feasibility of this technique for determining shallow shear-wave velocity structure (Nelson et al., 2012; Yaede et al., 2015). Along with documentation of the stratigraphic properties in the trench wall, corresponding  $V_{s30}$  values of these materials will provide analogue values for similar deposits in the area as well as regionally. Also, we will conduct analogous geophysical experiments to those already conducted at the trenching site to assess along-strike variability in deformation styles.

## **Project Plan**

*Conceptual Model.* As noted above, prior high-resolution, shallow geophysical investigations (Heiner et al., 2013; Heiner, 2014) suggest that Quaternary faults in the Sevier Desert exhibit both episodic slip and aseismic creep. The specific goal of this study is to expose shallow deformation features of the Clear Lake fault by trenching, wherein we will log the trench and collect samples for radiocarbon and OSL ages. Because the age of Beaver River gravels can be estimated, hand augering has revealed organic-rich horizons in the hanging wall, and quartz-rich marl is present, we are confident that geochronological data will permit estimation of slip rates. As mentioned above, Beaver River gravels are present in the footwall of the Clear Lake Fault. These fluvial deposits were left as the Beaver River wandered and prograded basin-ward during the final regression of Lake Bonneville after about 15 ka. We will (if possible) locate these gravels beneath sag pond sediments in a deep test pit in the trench, thereby calculating the total throw on the fault over the last 15 ka.

Figure 9 illustrates possible endmember stratigraphic and structural relationships in the trench based on hand borings and the geophysical records. Given our working hypothesis of aseismic creep, east-dipping fine-grained marls are anticipated to abut the fault, where the east dip is due to drag. Further east, correlative strata are expected to thicken within the sag pond, with sedimentary horizons becoming horizontal. Given a trench of sufficient length in the hanging wall, beds might show westward, shallow dips further from the fault. Within the sag pond proper, we do not expect a 6-7 m deep trench to penetrate to the depth of offset stream gravels seen at shallow depths in the footwall. A deep track hoe test pit may be able to penetrate to gravel horizons to permit the calculation of the total throw of Beaver River gravels.

We expect that past wet climates produced episodic growth of wetland macro- and micro-flora, as indicated by observed organic-rich horizons in hanging wall sag ponds. Thus, ample material for  $^{14}\text{C}$  age control of the slip history should be present. Otherwise, marls should be suitable for OSL ages. While the trench is open, opportunistic detailed sampling of sag pond stratigraphy will be made to enable future paleoclimate and paleolimnological histories in this part of the Bonneville basin using sedimentological, stable isotopic, and microfossil (ostracodes and diatoms) proxies.

Although Figure 9 illustrates our conceptual model for the shallow subsurface of the Clear Lake fault, we recognize the possibility that this fault may solely exhibit episodic slip, or alternate or creep—slip behavior. We will reevaluate our conceptual model as required by relationships in the trench.

*Data Collection.* We propose to construct a 50 m east-west trench with a maximum depth of ~7 m adjacent to existing geophysical profiles (Fig. 1), excavating 15 m into the footwall and 35 m into the hanging wall. Greater horizontal exposure of the hanging wall will reveal information regarding the

nature of slip. We plan to widen the east end of the trench to allow a track hoe to excavate a test pit to an additional ~7 m depth in an attempt to reach Beaver River gravels. We have begun discussions with the BLM Fillmore office regarding land access and intend to place the trench as close (and parallel) to the road and geophysical profiles (Fig. 1) as land access and engineering considerations permit.

Our collaborators on the cooperative UVU proposal have considerable experience in mobilizing, constructing and logging fault trenches. In particular, Professor Nathan Toké will take the lead on mobilizing excavation contractors as well as logging the trench. UVU Professors (Bunds and Toké) will lead an effort to collect high resolution, overlapping low altitude aerial photography that we will process using Structure from Motion photogrammetry methods combined with RTK GPS ground control. We will produce ultra-fine scale (~5-10cm grid), high accuracy (ca. 5-10cm error) DEMs at multiple one to two kilometer long swaths spaced strategically along the CLFZ. One of the DEMs will be produced for the trench site. This data will aid in geomorphic analysis of the area and appropriately siting the trench next to the geophysical surveys. The other DEMs data sets will be widely spaced along the strike of the CLFZ; multiple scarp profiles will be pulled from each data set to produce high accuracy averaged scarp profiles and scarp heights along the CLFZ. Slip distribution geometry may be used to infer displacement curves during paleoearthquakes and help refine earthquake magnitude estimates. Additionally, cm-scale DEMs will be produced at the mapped endpoints of the CLFZ to determine if there is any geomorphic evidence of the fault having ruptured into the now developed agricultural area just southwest of Delta, UT and further than previously mapped at the southeast end of the fault.

Trench logging will be done with the utmost focus on trench safety, while also trying to achieve 6-7 meters of vertical paleoseismic record. We will achieve those depths through benching the trench and excavating a wide swath of the ground allowing us to go deeper through several vertical cuts. We will use ground-based structure from motion techniques to create orthoimagery mosaics and accurate 3D archives of the trench exposures. These millimeter-scale records of the fault exposures will be used for mapping relationships between the stratigraphy and fault zone structure as well as for accurate documentation of the location and character of geochronology samples.

BYU has conventional  $^{14}\text{C}$  counting facilities in-house. However, due to the potential for limited sample size and for increased precision, we will obtain AMS ages from the Woods Hole Oceanographic Institute laboratory.  $\delta^{13}\text{C}$  values of dated materials will be determined in our laboratories at BYU at no cost to the grant. Nelson and Toké will determine calibrated ages using CALIB (Stuvier et al., 2014). Preliminary hand-augered holes suggest the presence of organic matter in the hanging wall of the fault. However, their subsurface distribution cannot be guaranteed so we have budgeted for OSL ages to be determined at Utah State University in order to ensure a complete and well-constrained chronology from the trench.

The interpretation of the trenching results at the Clear Lake fault scarp area will be guided by the previously collected P-wave and SH-wave seismic reflection and ground-penetrating radar (GPR) data at the site, discussed above. We hope the trenching can be located within about 10 meters of these geophysical profiles at Site 1 (Fig. 1). In order to provide better constraints on the along-strike variability of structures observed in these profiles and in the trench, we propose to collect a second suite of P-wave and SH-wave seismic reflection and GPR profiles along two transects located 2.9 and 2.5 km north and south, respectively, of the trench that would cross the mapped fault trace. Both areas are accessed by dirt roads on public property and cross the fault at a high angle so that surveys can be mounted with minimal environmental impacts.

The suite of geophysical profiles will be acquired with the same parameters as used previously to afford exact comparison. This second suite will allow us to test the hypothesis that the near-surface (0-500 m) structure of the fault zone is consistent along strike, which would be expected if rupture occurred from major (e.g.,  $M > 6.5$ ) earthquake events. For example, is there along-strike variation in the offset of near-surface reflectors between the two sites? Does the amount of accumulated sediment in the hanging wall of the fault differ? Likewise, will we see a different degree of sedimentation on the footwall of the fault? Variations in the amount of sediment accumulation and offsets might be related to variations in

rupture mechanisms (e.g., aseismic creep) along the fault. Data processing will be performed using software identical to that used for processing previous profiles (Halliburton SeisSpace (ProMAX)).

At Site 1 we will also re-occupy the geophysical line and conduct an MASW (Park et al., 1999) experiment. We have recently conducted numerous MASW surveys on Oahu and have the necessary equipment at BYU (Nelson et al., 2012; Yaede et al., 2015). Once this survey is completed, we will have maximized the opportunity to correlate GPR and SH wave reflectors, as well as material stiffness via  $V_{S30}$  measurements, to subsurface stratigraphy exposed in a trench. A schedule for the proposed work is presented in Figure 10.

*Responsibilities.* Level of effort and duties of major project personnel are described below:

- Professors. Stephen Nelson and Nathan Toké
  - PI's for direction of project
  - Coordinate trenching operations, logging, and geological interpretations
  - Oversee acquisition and interpretation of  $^{14}\text{C}$  and OSL data to determine slip rates and ages of earthquakes or creep events.
  - Primary authors of project report & journal submission
  - 40% of total effort
- Professors John McBride and Mike Bunds
  - Co-PI's for direction of project
  - Oversee acquisition and interpretation of seismic and GPR data.
  - Oversee acquisition and interpretation of sub-decimeter-scale structure from motion digital elevation models.
  - 25% of total effort
- Mr. Kevin Rey
  - Technician trained to assist in the acquisition of geophysical data, surveying, and laboratory analysis
  - 35% of total effort

*Final Report and Dissemination.* The PI's and co-PI's have extensive experience in the timely publication of research results in appropriate journals. We are committed to fulfill the expectation that results of this study be published. We will also submit the required financial and final technical reports as outlined in Attachment D of the application instructions document.

*Related efforts.* Concurrent to the preparation of this proposal, we are preparing a manuscript for publication based on the work of Heiner (2014). As noted above in a footnote, we have recently re-submitted a revised manuscript (*Neotectonics of the Sevier Desert basin, Utah as seen through the lens of multi-scale geophysical investigations*) to *Tectonophysics*. The initial peer review requested moderate revision, which we believe we have addressed. We anticipate that this paper will soon be in press.

## Project personnel and bibliography of related work.

### **Nathan A. Toké**

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### **Education**

Ph.D.	Geological Sciences, 2011	Arizona State University	Advisor: J Ramón Arrowsmith
M.S.	Geological Sciences, 2005	Arizona State University	
B.S.	Geology (Cum Laude), 2003	University of Vermont	Advisor: Paul Bierman.

### **Select Academic Honors**

Dean's Award for Excellence in Scholarship, UVU College of Science and Health, 2014-2015  
NSF IGERT Fellow in Urban Ecology (ASU 2006-2010)  
Troy L. Péwé Award for Quaternary Geology (ASU 2006)

### **Teaching related to the proposed project**

Geologic Hazards (GEO 3200)	Earthquake and Landslide Processes along the Wasatch Front
Geomorphology (GEO 3500)	Process-based Interrogation of Landforms

### **Select Relevant Publications and Presentations**

- Nelsen, M., **N.A. Toké**, S.A. Fellows, and J.W. Jackson "GIS Analysis of the Types and Spatial Extents of Volcanic Hazards in Millard County, Utah" Submitted to the 67th Annual Rocky Mountain Regional Geological Society of America Meeting, May 21-23rd, 2015.
- Toké, N.A.**, C.G. Boone, and JR. Arrowsmith (2014) "Seismic Hazard, Regulations, and Social Vulnerability in Los Angeles, California – Turning Geologic Hazards into Urban Amenities" *Earth's Future*. Vol. 2, no. 9 440-457. DOI: 10.1002/2014EF000241
- Toké, N. A.**, Arnoff, M., Thomas, J., and M. Bunds. "Documenting Recent Rupture Traces and Paleoseismic Exposures from the Northern Provo to the Southern Salt Lake city Segment of the Wasatch Fault" Basin and Rang Province Seismic Hazards Summit III, January 12-16th, 2015.
- Toké, N. A.**, Carlson, J.K., Barnum, E., Das-Toke, S., Dastrup, D.B., Ivie, H.A., Judd, E., Selck, J., Stuart, K., and J. Whitaker. "Evidence for Multiple Surface Ruptures with 0.3-1.5 Meter Slip-Per-Event Along Structures Between the Salt Lake City and Provo Segments of the Wasatch Fault" *Geological Society of America Meeting Abstracts with Programs*, Vol. 45, No. 7, Paper No. 238-3, Denver, Colorado, October 29, 2013.
- Haddad, D. E., Akçiz, S. O., Arrowsmith, J R., Rhodes, D. D., Oldow, J. S., Zielke, O., **Toké, N. A.**, Haddad, A. G., and Mauer, J., (2012) "Applications of airborne and terrestrial laser scanning to paleoseismology" in: *Seeing the True Shape of Earth's Surface: Applications of Airborne and Terrestrial Lidar in the Geosciences themed issue, Geosphere*, v. 8, no. 4, p. 771-786, DOI: 10.1130/GES00701.1.
- Toké, N.A.**, JR. Arrowsmith, M.J. Rymer, A. Landgraf, D. Haddad, M. Busch, J. Cohan, and A. Hannah (2011) "Late Holocene slip rate of the San Andreas Fault and its accommodation by creep and moderate magnitude earthquakes at Parkfield, California" *Geology*, 10.1130/G31498.1
- Toké, N.A.** and JR. Arrowsmith (2006) "Reassessment of a slip budget along the Parkfield segment of the San Andreas Fault" *Bulletin of Seismological Society of America* 96, 339-348.

## Michael P. Bunds

Associate Professor and Department Chair

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### Education

Ph.D. in Geology, 2001, University of Utah, Ronald Bruhn Advisor

M.Sc. in Geology, 1994, University of California, Davis, Sarah Roeske Advisor

B.A. in Geological Sciences, 1984, University of California, Santa Barbara

### Teaching Related to Proposed Project

Structure and Tectonics (GEO 3700) Structural geology, tectonics, mechanics of earthquakes and landslides

Geospatial Field Methods (GEO 4100) Application of GPS, total station, and digital imagery in geoscience

### Select Relevant Publications and Presentations

**Bunds, M.P.**, Toké, N. A., and Walther, S., in prep, Accuracy Assessment of Structure from Motion (SfM) in Applications related to Neotectonics, Fluvial Processes, and Landslide Assessment.

**Bunds, M.P.**, Horns, D.A., in prep, Implications for the Effect of Water Table Height on Displacement Rate, Slump Geometry, and Hazard Assessment from Long-Term Monitoring of the Sherwood Hills Slump, Provo, Utah

**Bunds, M.**, Toké, N. A., Fletcher, A. and M. Arnoff. "Applications of Structure from Motion for use in Earthquake Geology Investigations: Examples from the Wasatch and San Andreas Fault." Basin and Rang Province Seismic Hazards Summit III, January 12-16th, 2015

**Bunds, M.P.**, Emerman, S.H., Bhattarai, T.N., Anderson, R.B., Adhikari, N., Karki, K., and Palmer, M., submitted, A new lichen apparent growth curve for the Nepal Himalaya, with applications to dating GLOFs, major landslides and mani walls.

**Bunds, M.P.**, Horns, D.A., Ungerman, B., 2013, Improved Hazard Assessment, Effect of Water Table Height on Landslide Displacement Rate, and Failure Plane Rheology from Nine Years of Monitoring of the Sherwood Hills Slump, Provo, Utah, *Geological Society of America Abstracts with Program*, v.45, no.7.

Carlson, J.K., Kemp, T.L., Gautam, T., **Bunds, M.P.**, Emerman, S.H., 2012, Terrace evolution and incision rates along the uppermost Langtang River, Nepal Himalaya, *Geological Society of America Meeting Abstracts with Programs*, Vol. 44, no. 6.

**Bunds, M.P.**, Emerman, S.H., Bhattarai, T.N., Anderson, R.B., Adhikari, N., Karki, K., and Palmer, M., 2010, Using lichenometry to assess long term GLOF and landslide frequency in the Nepal Himalaya: Proceedings of the 11th IAEG Congress, Williams, A.L., Pinches, G.M., Chin, C.Y., McMorran, T.J., and Massey, C.I., eds.

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**Bunds, M.P.**, 2001, Fault strength and transpressional tectonics along the Castle Mountain strike-slip fault, Alaska: *Geological Society of America Bulletin*, v. 113, n. 7, p. 908-919.

Parry, W.T., **Bunds, M.P.**, Bruhn, R.L., Hall, C.M., and Murphy, J.M., 2001, Mineralogy,  $^{40}\text{Ar}/^{39}\text{Ar}$  dating and apatite fission track dating of rocks along the Castle Mountain fault, Alaska: *Tectonophysics*, v. 337, p. 149-172.

## Utah Valley University Institutional qualifications.

### ***Personnel, Institutional Support and Student Involvement***

Utah Valley University's (UVU) Department of Earth Science is a growing program of twelve faculty dedicated to training undergraduate students through active research. Collectively we are well connected to organizations which are vital to using and disseminating the results of this type of research. Drs. Horns, Bunds and Toké are members and regular contributors at the annual meeting of the Utah Quaternary Fault Parameters Working Group and are in active communication with the State Geological Survey and the USGS about paleoseismic research collaborations. We are also a participating institution in the Southern California Earthquake Center. During this project two of us will be collaborative PIs (Drs. Toké and Bunds). Additionally, Dr. Daniel Horns, Associate Dean of the College of Science and Health will participate in the research when available.

Undergraduate research is a vibrant part of our program. We will involve at least two of undergraduate students as research assistants. We will involve more students in the research as a part of upper division classes and their associated labs/field trips (Geospatial Field Methods and Geologic Hazards). We have strong financial support for student involvement from the College of Science and Health's Scholarly Activities Committee and UVU's Summer Undergraduate Research Fellowships for engaged learning. If awarded this grant we will be able to leverage these resources to help fund additional student involvement beyond the scope of the included budget, thereby helping to train future earthquake scientists and geotechnical professionals.

### ***Relevant Departmental Resources***

Our Department shares equipment and space among faculty. We maintain four labs with space available for working with sediment cores and geochronology sample preparation including drying ovens, sieves, chemical hoods, and microscopes. We have separate equipment and sample storage rooms. The department operates a computer lab with 24 dual-monitored i7 workstations for use with ArcGIS, MatLab, Trimble Business Center, Agisoft Photoscan, Adobe Creative Suite, and Microsoft Office. We have all of the basic field equipment necessary to conduct earthquake geology investigations. Additionally, we have an especially robust suite of geospatial data collection equipment and new resources for collecting and processing centimeter-scale structure from motion digital imagery and elevation models. Below is a list highlighting the most relevant resources.

- Three devices for acquiring cm-scale GPS positions: Trimble GeoExplorerXH, Trimble R8 and TSC3 data collector, and a Trimble 5700 RTK system with base station, rover and radio.
- Trimble M3 2" Total Station and field radios for communication during surveys.
- 2m<sup>3</sup> Helikite and 24 megapixel Sony A5100 camera in concert with a 12 mm lens.
- Three multicopter (DJI S900 and Phantom II) equipped with high resolution cameras.
- Agisoft Photoscan for processing digital terrain models from photogrammetry systems.
- A Bruker Portable XRF.
- Intel Atom quad core windows 8.1 tablets running ArcPad for mobile GIS applications.
- A portable Wifi hotspot with a Verizon 4G plan for use with tablets and GPS VRS systems.
- Five i7 Hexacore Workstations with one to two graphics cards and 32- 64 GB RAM for processing structure from motion digital models and making trench mosaics.
- Two field laptops with ArcGIS, TBC, Agisoft Photoscan, and Adobe Creative Suite.
- 3 digital field cameras (one ruggedized, one wide angle, and one DSLR).
- A full suite of trenching tools (e.g., shovels, nejiro gama scrapers and gridding supplies).
- Three soil augers and coring collection supplies.
- Charging solutions and camping supplies for efficiently staying at the field site.

### UVU Current support and pending applications.

Drs. Toké and Bunds currently have one collaborative external grant and together they have received seven small internal awards by Utah Valley University. Dr. Toké is submitting a second proposal during the 2016 NEHRP solicitation, the pending award title and funding request is listed below.

#### **Current Support for UVU PIs**

##### External

**2014-2015 iUtah:** Innovative Urban Transitions and Aridregion Hydro-Sustainability – Research Catalyst Grant, collaborative at UVU with **Drs. Bunds, Toké, Walther, and Zanazzi**, and Drs. Moore and Power at Univ. of Utah: Multi-disciplinary Investigation of the Timing and Impact of Major Watershed-Damming Landslides in the Central Wasatch: Little Cottonwood and City Creek Canyon Case Studies, Submitted December 1st, 2014: \$18,310. (1 summer month each during 2015)

##### Toké Internal Support

**2015 CSH Scholarly Activities Committee Faculty Research with Students:** Developing a long (~3000 yr) paleoearthquake record for the west-central Denali Fault at the Nenana River, Alaska – UVU Collaboration with Dr. Bemis and Kade Carlson at the University of Kentucky: \$3,360. (1 summer month 2015)

**2015 CSH Scholarly Activities Committee Faculty Research with Students:** Quarter Faculty Summer Salary Support for N.A. Toké: 6 Collaborative Projects Involving Students: \$1,795.

**2015 Undergraduate Research, Scholarly, and Creative Award:** Mentoring Bret Huffaker: GIS analyses, Structure from Motion, and Paleohydrology of Pleasant Creek, Capitol Reef NP: \$2,000

**2014 CSH Scholarly Activities Committee Faculty Research with Students:** Continued Investigation of the northern Provo Segment of the Wasatch Fault: \$4,100.

##### Bunds Internal Support

**2015-2016 CSH Scholarly Activities Committee Faculty Research with Students:** A Collaborative Effort Involving Students to Re-address Four Outstanding Questions in Regional Geoscience Using Ultra-high Resolution Topographic Mapping from Structure from Motion: \$1,180.

**2015 Student Summer Undergraduate Research Fellowship:** Mentoring Preston Fackrell: Augmented Reality Sandbox: Developing and Assessing an Innovative New Technology to Aid Geoscience Education: \$1,500

**2014-2015 CSH Scholarly Activities Committee Faculty Research with Students:** Support for collaboration with USGS on SfM/high resolution mapping along the Borah Peak Rupture: \$1,488.

#### **Pending Applications by UVU PIs**

**2016 National Earthquake Hazards Reduction Program (NEHRP) Grant:** Collaborative Research with Brigham Young University and Utah Valley University: *Timing, Rate, and Mechanisms of Slip along the Clear Lake Fault, Millard County, Utah*, \$61,682 (**This Proposal: \$27,082 to UVU**):

1.5 summer months for **Toké** in 2016

0.5 summer months for **Bunds** in 2016.

**2016 National Earthquake Hazards Reduction Program (NEHRP) Grant:** Characterizing the timing of ruptures crossing between the boundary between the Provo and Salt Lake City segments of the Wasatch Fault, \$33,578 to UVU:

1 summer month for **Toké** in 2016

#### Past USGS-supported projects.

**2007 National Earthquake Hazards Reduction Program (NEHRP) Grant**, co-written with JR. Arrowsmith (PI), Paleoseismic characterization of earthquakes at Parkfield, **\$43,000**.

This award helped fund Dr. Toké's PhD research and led directly to a paper published in *Geology* (Toké et al., 2011). The work has been cited in Appendix B of UCERF 3 (Field et al., 2013).

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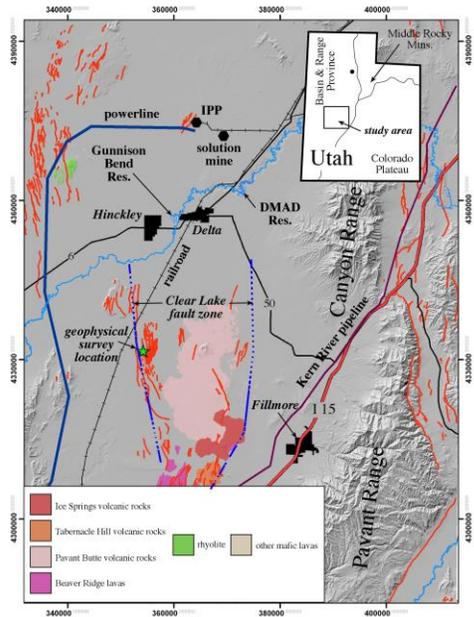


Figure 1. Index map for seismic reflection profile/trench location in central Utah. Important municipalities and infrastructure elements are indicated. Faults (red lines) are from U.S. Geological Survey (2010). Quaternary lava are from Hintze and Davis (2002) and Hintze et al. (2003). UTM coordinates 12N, NAD83.

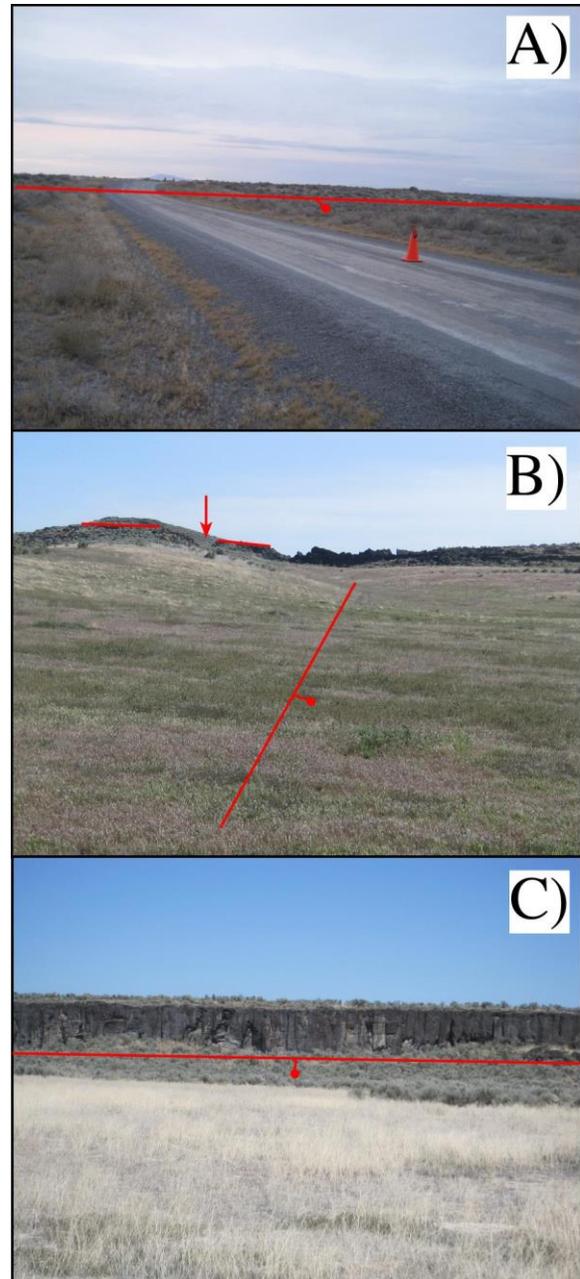


Figure 2. Annotated field photos of scarps. A) Clear Lake fault scarp shown with red line drawn at base of the scarp. Photo taken looking west. B) Western Tabernacle Hill scarp looking south with red line drawn at base of scarp. Red arrow indicates where corresponding fault cuts lavas. C) Devils Kitchen fault scarp looking east.

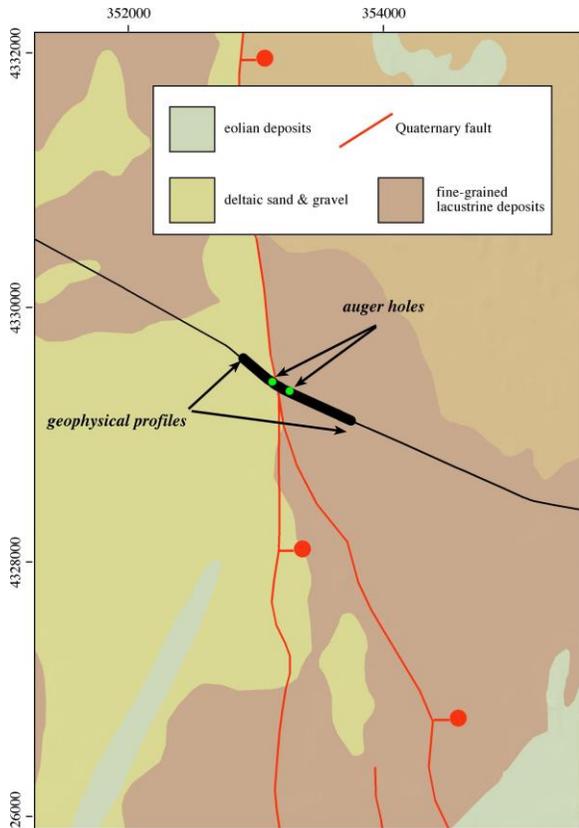


Figure 3. Geologic map (after Hintze and Davis, 2002) of the Clear Lake fault site with fault locations mapped for this study. The position of geophysical surveys, as well as auger hole locations, are also shown. UTM coordinates 12N, NAD83

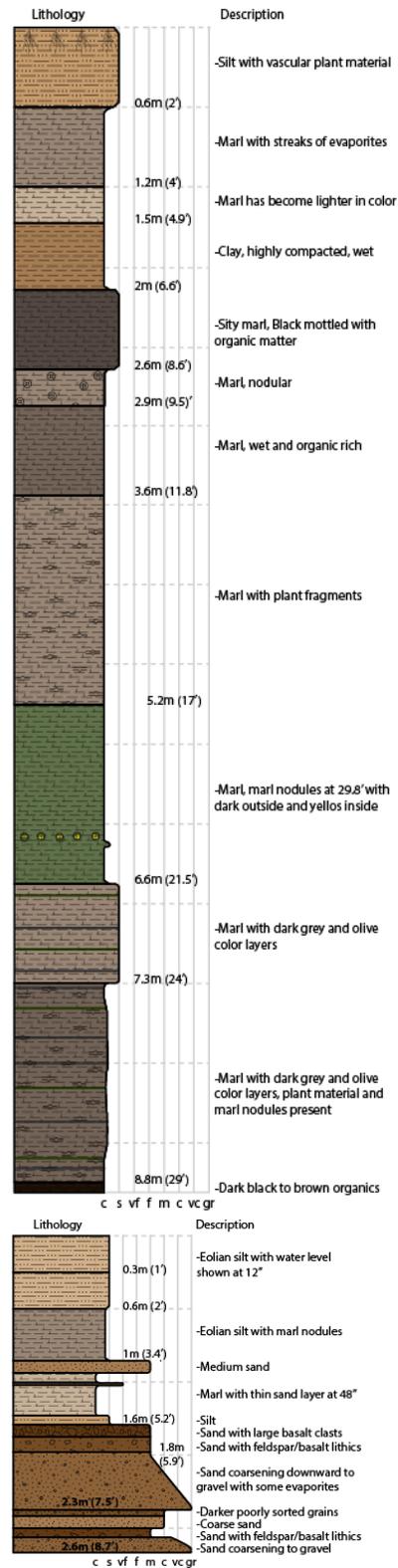


Figure 4. Details of hanging wall (upper) and footwall (lower) shallow stratigraphy of the Clear Lake Fault. Dotted grey lines indicate 0.61m intervals.

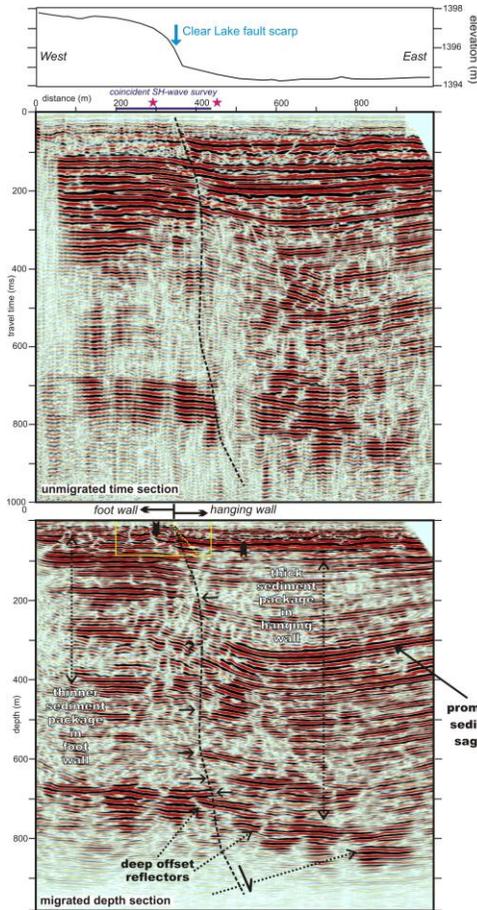


Figure 5. P-wave seismic sections of the Clear Lake fault with the CDP elevation profile. Top is an unmigrated P-wave stacked time section. Bottom is a migrated P-wave stacked section converted from time to depth using a simplified RMS velocity function (datum is 1400 m). Red stars indicate locations of hand augered holes. Black dashed lines indicate interpreted faults. Horizontal arrows indicate offset reflectors. Vertical arrows indicate shallow offset reflector.

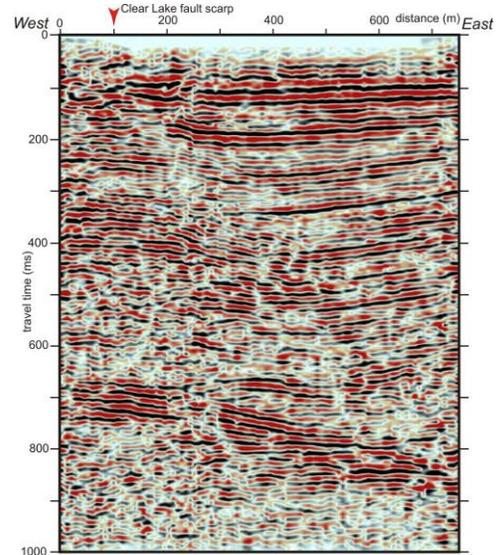


Figure 6. Vectorized P-wave seismic reflection profile collected by the USGS (Crone and Harding, 1984) over the Clear Lake fault (mostly over the hanging wall of the fault to the east of the scarp), displayed with the same travel-time to horizontal distance ratio as in Fig. 5

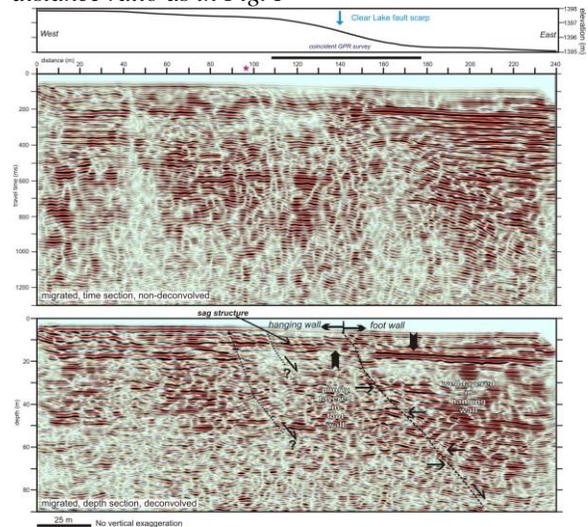


Figure 7. SH wave seismic profile over the Clear Lake fault scarp site, displayed with same format as Figure 5 (datum is 1400 m). Vertical arrows indicate offset of shallowest clear reflection.

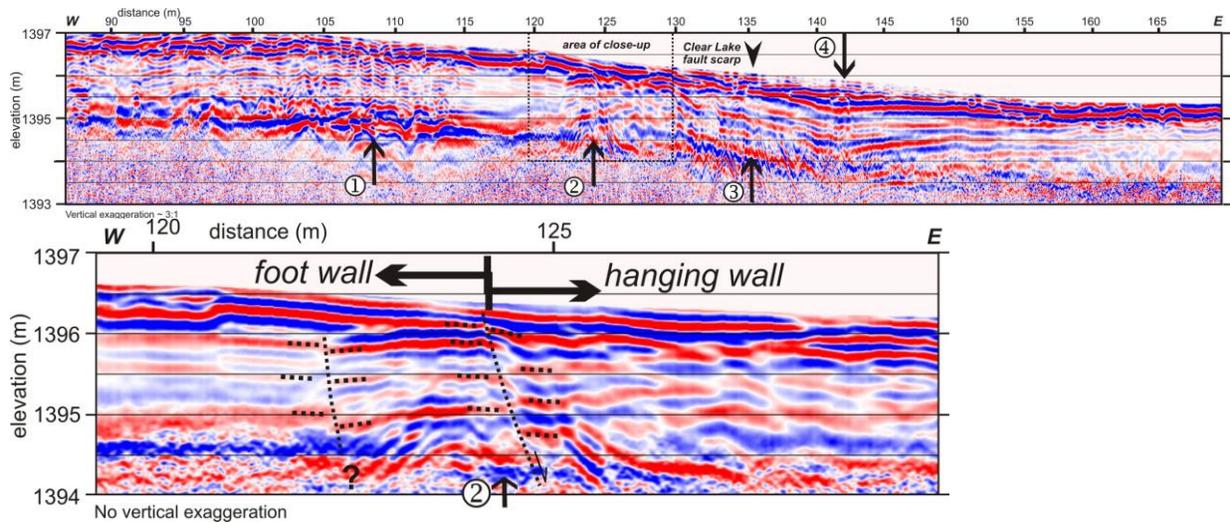


Figure 8. (TOP) GPR section for Clear Lake fault site. Box shows area expanded below. Numbers refer to areas discussed in the text. (BOTTOM) Excerpt from GPR section above. Dashed black lines indicate interpreted offset reflectors.

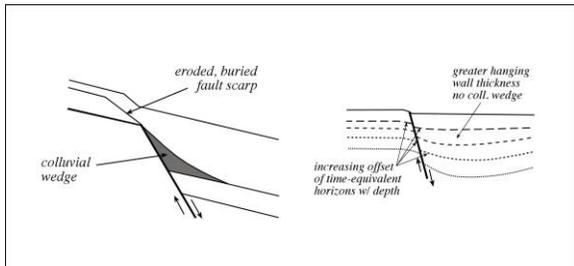


Figure 9. Comparative conceptual models of trench relationships for episodic slip (left, modified from Buddensiek et al, 2008) and continuous creep, similar to Ferrelly et al. (2002)

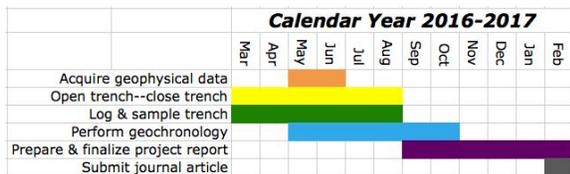


Figure 10. Schedule for completion of major project tasks.