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DETAILED MAPPING OF THE EAST AND WEST CACHE FAULT ZONES, UTAH —USING NEW HIGH-RESOLUTION LIDAR DATA TO REDUCE EARTHQUAKE RISK

Adam I. Hiscock, Emily J. Kleber, Greg N. McDonald, and Steve D. Bowman

Utah Geological Survey
1594 W. North Temple
P.O. Box 146100
Salt Lake City, Utah 84114-6100
(801) 537-3300, fax (801) 537-3400
adamhiscock@utah.gov
ekleber@utah.gov
gregmcdonald@utah.gov
stevebowman@utah.gov
https://geology.utah.gov/

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ABSTRACT

The Cache Valley region in northern Utah and southern Idaho contains and is surrounded by several large, hazardous fault zones which pose a significant earthquake risk. The 62-km-long East Cache fault zone (ECFZ) and the 80-km-long West Cache fault zone (WCFZ) bound the Cache Valley graben and both show evidence of large surface-faulting earthquakes in late Quaternary time. Other hazardous faults in the Cache Valley region include the intrabasin Dayton fault, which runs along the east side of Little Mountain and Bergeson Hill in northern Cache Valley, and the James Peak fault at the very southern end of the ECFZ. Additionally, the Wasatch fault zone (WFZ) to the west is also capable of generating large surface-rupturing earthquakes. This region is a rapidly growing area of northern Utah, with development spreading along the margins of the valley and encroaching on these hazardous fault zones. As part of this project, airborne light detection and ranging (lidar) elevation data was collected in the Cache Valley area to supplement existing data. High-resolution topographic data derived from this newly acquired lidar data has allowed for detailed mapping of surface traces of the ECFZ and WCFZ. Previously, the surface location and extent of fault traces associated with these fault zones were not well understood in many areas, owing to limited aerial photography coverage, heavy vegetation near range fronts, and the difficulty in recognizing moderate (<1 m) displacements in the field or on aerial photographs. Previous geologic mapping, paleoseismic investigations, historical aerial photography, and field investigations were also used to identify and map surface fault traces and infer fault locations. Special-study areas were delineated around fault traces to facilitate understanding of the surface-rupturing hazard and associated risk. Defining these special-study zones encourages the creation and implementation of municipal and county geologic-hazard ordinances dealing with hazardous faults. We identified potential paleoseismic investigation sites where fault scarps appear relatively pristine, are located in geologically favorable settings, and where additional earthquake timing data would be beneficial to earthquake research of the ECFZ and WCFZ. This work is critical to raise awareness of earthquake hazards in areas of Utah experiencing rapid growth. In addition, our investigation makes high-resolution lidar data available for use by researchers, local governments, and others.

INTRODUCTION

Cache Valley in northern Utah and southern Idaho is bounded on the east and west by the East Cache fault zone (ECFZ) and the West Cache fault zone (WCFZ), respectively. The region also includes the intrabasin Dayton fault, and the James Peak fault at the southern end of the ECFZ (figure 1). Cache Valley has experienced a population growth rate of 23.3% between 2000 and 2010, and contains the county's principal population centers, including Logan, Utah (pop. 51,542 [2019 U.S. census estimated data]), and Utah State University (2016 enrollment 28,118) as well as other technology and specialty manufacturing companies. Additionally, recreational visitation in the county has continued to substantially increase each year. Estimates of future growth predict that the county's population will exceed 232,000 by 2050 (Utah Foundation, 2014), with rapid growth spreading outward from existing communities and encroaching even further on these two already partially urbanized and potentially hazardous fault zones. The immediate proximity of this rapidly growing region to the ECFZ, WCFZ, Dayton fault and James Peak fault represents a substantial risk to the population and regional economy. This new, highly detailed fault mapping will facilitate a better understanding of the regional faults, leading to more responsible development as the region grows.

The ECFZ and WCFZ are composed of Holocene- and late Quaternary-active normal faults that bound Cache Valley on the valley's east and west sides, forming the Cache Valley graben (figure 1). The Cache Valley graben is part of the structural transition zone between the extending Basin and Range Province to the west and the uplifting Middle Rocky Mountains Province to the east and north (Stokes, 1977, 1986). Additionally, another major active fault, the Wasatch fault zone (WFZ), lies just to the west of Cache Valley (figure 1).

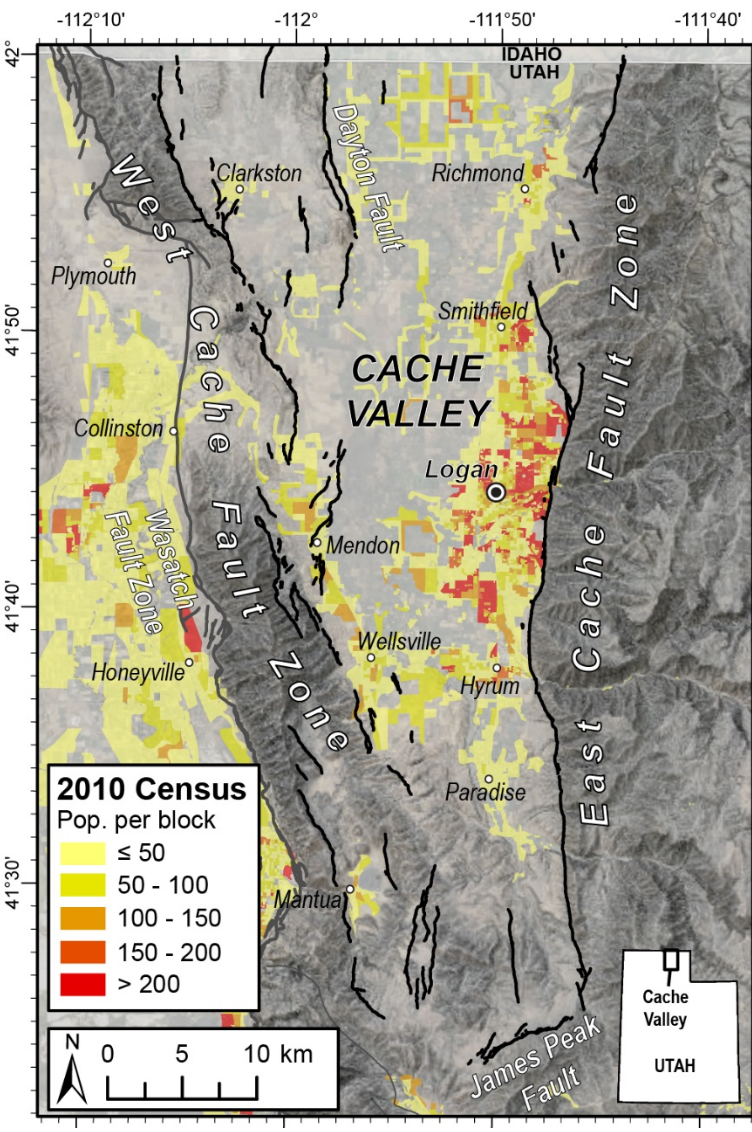

Figure 1. *East and West Cache fault zones, Dayton fault, and James Peak fault shown as heavy black lines and Wasatch fault zone shown as heavy gray lines (from the Utah Geological Survey Utah Geologic Hazards Portal, 2020). 2010 U.S. Census data are approximate population density per census block (AGRC, 2010). White circles indicate communities in the Cache Valley region.*

The ECFZ is separated into the Northern (24 km long), Central (18 km long), and Southern (20 km long) sections (McCalpin, 1989, 1994). South of the ECFZ, the northeast-southwest-trending James Peak fault has an 8-km-long surficial expression. Previous paleoseismic work has shown that the James Peak fault and the Southern section of the ECFZ do not rupture simultaneously and have low Quaternary slip rates relative to the WFZ and other faults in the Northern Wasatch-Teton Corridor (McCalpin and Forman, 1991). The WCFZ is separated into three sections, from north to south, the Clarkston (35 km long), Junction Hills (25 km long), and Wellsville (20 km long) faults. All three sections show evidence of Holocene rupture and previous paleoseismology investigations suggest that these three segments rupture independently of each other (Cluff and others, 1974; Black and others, 2000). East of the Clarkston and Junction Hills sections of the WCFZ, the north-south-trending Dayton fault has a 16-km-long surficial expression. No paleoseismic data exist for the Dayton fault. Most of the previous mapping of the ECFZ and WCFZ was completed prior to the availability of lidar data. Most of this mapping was performed at a coarse scale of 1:50,000 (McCalpin, 1989; Solomon, 1999), or on 1:24,000-scale geologic quadrangles (Mullens and Izett, 1963; Oviatt, 1986; Barker and Barker, 1993; Lowe and Galloway, 1993; Brummer and McCalpin, 1995; Evans and others, 1996).

For this U.S. Geological Survey (USGS)- and Utah Geological Survey (UGS)-funded project, we have produced fourteen 7.5-minute quadrangle maps (plates 1–14) showing updated surface fault trace mapping of the ECFZ, WCFZ, and James Peak fault principally using airborne lidar-derived imagery as well as available aerial photographs, previous geologic mapping, and field investigations. Each map displays the surface fault geometries mapped at 1:10,000 scale or greater, approximate age categories determined from previous geologic mapping and geomorphic relationships, and special-study areas (Lund and others, in press). Fault activity classifications are based on Lund and others (in press) and Western States Seismic Policy Council (WSSPC, 2018) Policy Recommendation 18-3. These fault activity classes are consistent with hazardous faults in the UGS *Utah Geologic Hazards Portal* (https://geology.utah.gov/apps/hazards/) and will ensure a seamless integration of fault geometries and attributes into the Utah database as well as the USGS *Quaternary Fault and Fold Database of the United States*. Additionally, these surface-fault-rupture hazard maps will be available through the *Utah Geologic Hazards Portal*. Surface-fault-rupture special-study areas defined in this report can be implemented in geologic hazard ordinances (building setbacks, critical infrastructure avoidance, etc.) by local governments to reduce risk from surface faulting hazard (Bowman and Lund, in press). In addition to the maps, potential paleoseismic trenching sites were identified (table 1). This mapping is timely as Utah's population and urban footprint continue to grow into undeveloped and geologically hazardous areas.

DATA SOURCES

Lidar Elevation Data

High-resolution (0.5-meter) USGS Quality Level 1 lidar elevation data of parts of the Cache Valley were acquired by the State of Utah and its partners in 2013–2014 for fault mapping, urban planning, and other purposes. This initial lidar dataset covered most of the Cache Valley floor but was missing crucial areas along valley margins where the WCFZ and ECFZ have surficial fault escarpments. In 2018, as part of this project, an additional 196.3 km^2 of high-resolution 0.5-meter, USGS Quality Level 1 (Heidemann, 2018) lidar data were collected by the State of Utah and its partners, with additional funding coming from this project (Utah Automated Geographic Reference Center, 2016 and 2018). Lidar derivative products that were useful for identifying and refining surficial fault traces include slope-shade images, various hill-shade images with different light directions and altitudes (figure 2), and contour lines. GlobalMapper (v.18) software was used to generate these images, as well as to generate topographic profiles perpendicular to scarps to investigate fault-scarp morphologies.

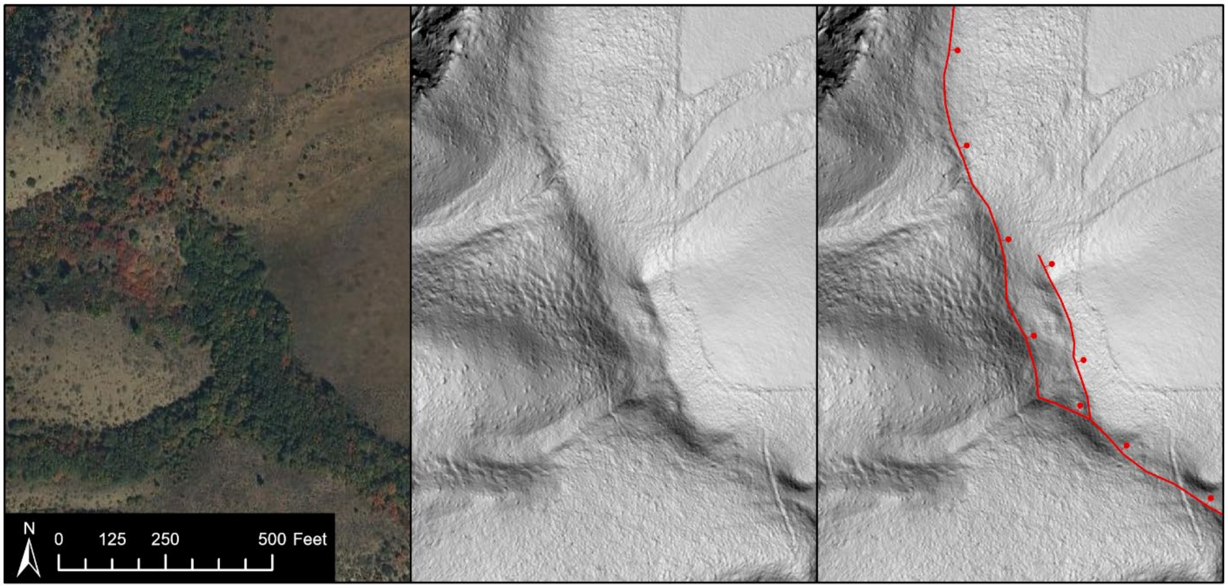

Figure 2. *Comparison between aerial photography and lidar slope-shade images at Raglanite Canyon on the Clarkston fault, West Cache fault zone. The fault trace is faintly visible in the aerial photo on the left, but far more visible on the slope-shade images. The far-right image shows the mapped trace of the fault based on the slope-shade image.*

Aerial Photography

Historical aerial photography from the UGS *Aerial Imagery Collection* (https://geodata.geology.utah.gov/imagery/) was used to map in urban areas where surface fault traces have been obscured by modern development. This collection includes low-sun-angle photographs of the fault zone, taken in the early 1970s, that predate much of the development along these fault zones (Cluff and others, 1970, compiled in Bowman and others, 2015b).

Previous Geologic Mapping

Previous UGS surficial and bedrock geologic mapping was useful for this project and includes surficial geologic strip maps of the WCFZ (Solomon, 1999) and ECFZ (McCalpin, 1989). Additionally, geologic 30' x 60' and 7.5-minute scale quadrangle mapping from Utah and Idaho were used as a check on our fault-trace mapping (Mullens and Izett, 1963; Crittenden and Sorensen, 1985; Oviatt, 1986; Barker and Barker, 1993; Lowe and Galloway, 1993; Brummer and McCalpin, 1995; Evans and others, 1996; Biek and others, 2003; Coogan and King, 2016; King and others, 2018). Unpublished mapping from Dr. Susanne Janecke at Utah State University was also used as a guide and reference for our surficial fault mapping (Oaks and others, 2005).

FAULT MAPPING

Fault Traces

Fault traces were mapped according to the standards and experience of the UGS mappers and authors of each map. Each mapper employed several different techniques to best represent fault scarps indicative of previous surface-fault rupture or deformation over time. The lidar imagery proved to be the most useful tool when mapping the faults in the Cache Valley region (Bowman and others, 2015a); however, it was not exclusively used. In areas of urban development, pre-development stereo-paired aerial images were used to identify and map fault traces. These photos were particularly useful in identifying fault traces that have been obscured by development, among other uses. Additionally, derivative lidar products such as slope-angle maps, slope-aspect maps, and topographic contours were used to discern fault scarps. Topographic contours were particularly useful when trying to discern a fault scarp from a paleo-shoreline, which are very prevalent on both the WCFZ and ECFZ.

Each mapped fault trace was assigned a fault activity classification based on Lund and others (in press) and Western States Seismic Policy Council (WSSPC, 2018) Policy Recommendation 18-3. Mappers use lidar data, previous geologic mapping, and geomorphic relationships to determine these classifications. These definitions are as follows:

- Latest Pleistocene–Holocene fault – a fault whose movement in the past 15,000 years has been large enough to break the ground surface.
- Late Quaternary fault – a fault whose movement in the past 130,000 years has been large enough to break the ground surface.
- Quaternary fault – a fault whose movement in the past 2.6 million years has been large enough to break the ground surface.

Special-Study Area Delineation

Special-study areas were delineated along the WCFZ, ECFZ, Dayton fault, and James Peak fault that define areas where additional investigation is recommended to evaluate the risk from surface faulting prior to development. Together with the fault traces, these delineated areas are critical to the creation and success of municipal and county geologic-hazard ordinances dealing with hazardous faults (Lund and others, in press) and understanding surface-faulting hazard and associated risk.

We categorized Quaternary faults along the WCFZ, ECFZ, Dayton fault, and James Peak fault as “well defined,” “moderately defined,” or “buried or inferred” fault traces. We considered a fault well defined if its trace is clearly detectable by a trained geologist as a physical feature on the ground surface (Bryant and Hart, 2007). Additionally, lineaments that we were unable to conclusively determine were fault-related were mapped as “lineaments.” For well-defined faults, the special-study areas extend 500 feet (152 m) on the downthrown side and 250 feet (76 m) on

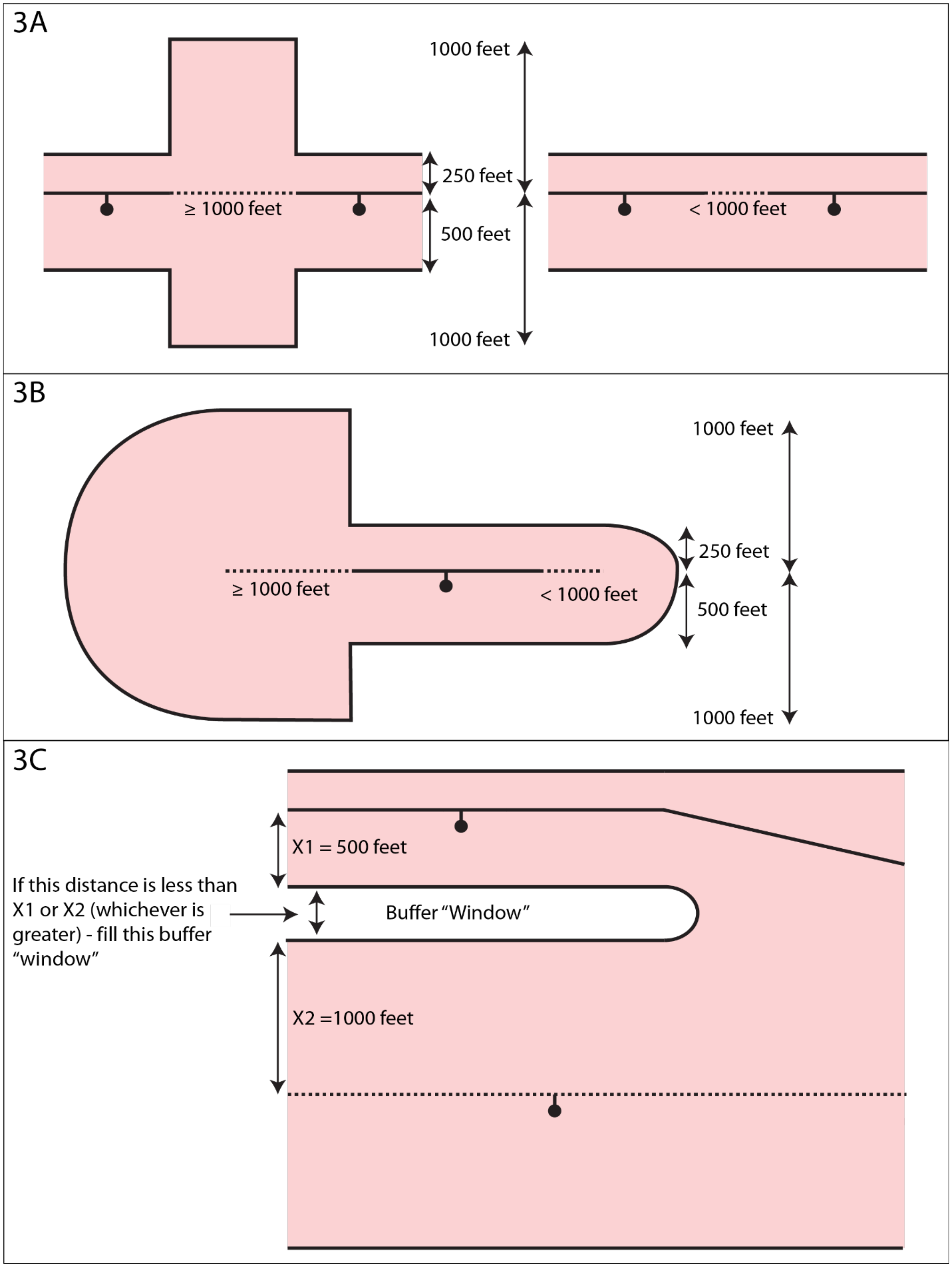

Figure 3. *Examples of special circumstances used when creating surface-fault-rupture special-study zones.*

the upthrown side of each fault. For moderately defined and buried or inferred faults, the special-study areas extend 1000 feet (305 m) on each side of the suspected trace of the fault. The special-study area dimensions are based on the *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, in press).

Several criteria were established for distinct circumstances pertaining to fault-related special-study areas. For traces of buried/inferred or moderately constrained faults less than 1000 feet (305 m) long that lie between and on-trend with well constrained faults, the well constrained fault special-study-area criteria were used (figure 3A). For buried/inferred or moderately constrained faults greater than 1000 feet (305 m) long, the special-study area includes 1000 feet (305 m) on both sides of the fault. For inferred faults at the end of a mapped fault trace that are longer than 1000 feet (305 m), we used an inferred fault special-study area (figure 3B). In areas where a buffer "window" exists (a space between the buffer zones of two sub-parallel fault traces), we include the window in the buffer zone if its width is less than the greater of the two surrounding buffers (figure 3C).

POTENTIAL PALEOSEISMIC INVESTIGATION SITES

We analyzed each fault section of the WCFZ and ECFZ, as well as the Dayton and James Peak faults, for potential paleoseismic investigation sites as part of our fault-trace mapping (figure 4). Sites were selected based on: (1) presence of a normal fault scarp, (2) scarp height that is reasonable for paleoseismic investigation (roughly 2–30 ft [0.5–10 m]), (3) scarp cutting young deposits (late Pleistocene to Holocene), and (4) mostly undisturbed. We identified 22 potential paleoseismic site locations (table 1, figure 4). Below are descriptions of specific paleoseismic site selection considerations for the WCFZ, Dayton fault, ECFZ, and James Peak fault.

The UGS works to maintain a relationship with local geotechnical engineering firms and consultants who conduct trenching investigations for clients along hazardous faults. These investigations are conducted for geotechnical considerations and are not full research-level paleoseismic investigations. The UGS is often invited to visit consultant trenches for a few hours to observe and document faulting. While not as useful as a full paleoseismic research investigation, these site visits still provide useful information in areas where we will most likely never be able to conduct a full research-level investigation.

West Cache Fault Zone

The Clarkston fault section of the WCFZ is defined by a steep, linear range front escarpment with predominantly well-located fault scarps along the east side of Clarkston Mountain. Several decent scarps crossing mid- to late Pleistocene-age fan surfaces may be suitable for paleoseismic trenching, although these fan ages are not well constrained. We identified at least four potential paleoseismic sites on the Clarkston fault (table 1, figure 4). Black and others (2000) conducted a paleoseismic trench investigation at the mouth of Winter Canyon on the Clarkston fault and determined timing of the most recent surface-faulting earthquake (MRE), but no timing for a potential penultimate surface-faulting earthquake (PE).

More data for the Clarkston fault is needed to determine recurrence intervals and slip-rate estimates.

The Junction Hills fault section is poorly defined and mostly expressed as a series of moderately located to inferred fault scarps from its northern boundary east of Short Divide, to its southern terminus near the town of Mendon. We identified two potential paleoseismic investigation sites on the Junction Hills fault (table 1, figure 4). The southernmost identified site is just north of the Roundy Farm stream-cut fault exposure, which was logged and dated by Black and others (2000). An MRE age was determined from this exposure, but no well-constrained PE age, and therefore no recurrence intervals and slip rate estimates are available for the Junction Hills fault.

The Wellsville fault section consists of two subparallel traces. The western trace follows the steep range front of the Wellsville Mountains, consisting of well-located faults in the Maple Bench area. We identified several sites along the western trace, including one site just north of the previous Deep Canyon trench site (table 1, figure 4). At Deep Canyon, Black and others (2000) identified both the MRE and PE events, and determined broadly constrained recurrence intervals and slip rate estimates for the Wellsville fault.

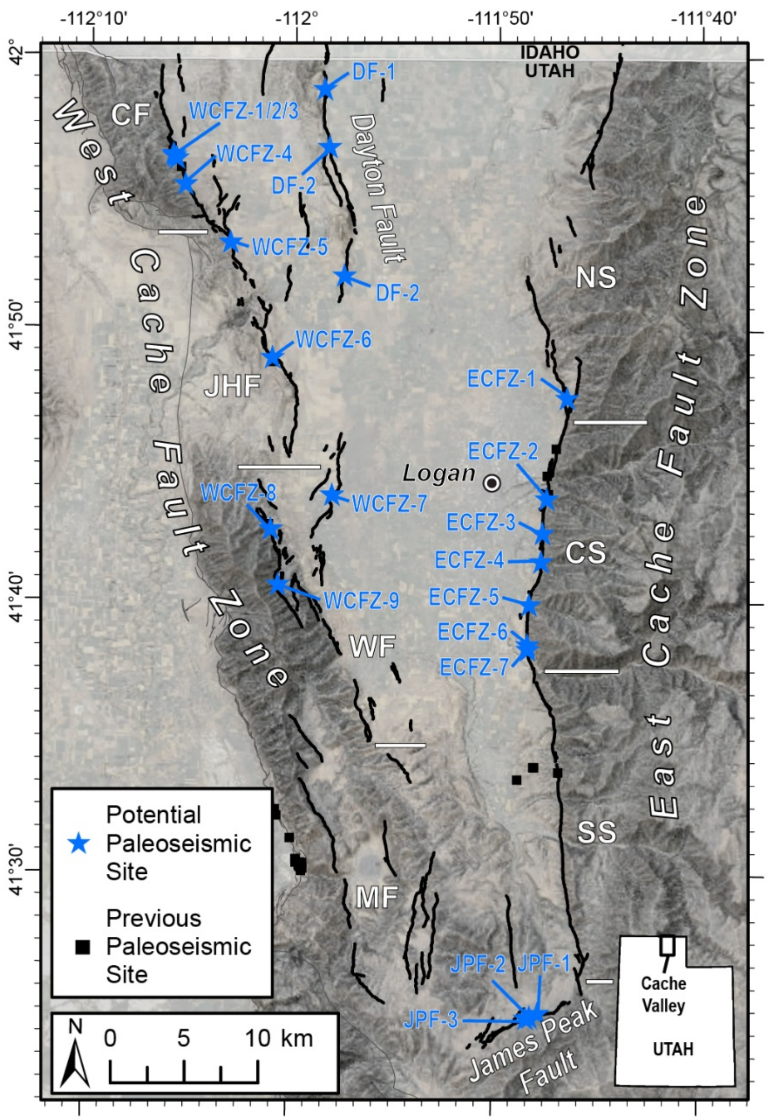

Figure 4. Potential paleoseismic trenching sites identified in this investigation (blue stars with labels) along the West Cache fault zone (WCFZ), East Cache fault zone (ECFZ), Dayton fault, and James Peak fault. Fault sections for the WCFZ labeled: CF – Clarkston fault, JHF – Junction Hills fault, WF – Wellsville fault, MF – Mantua area faults. Fault sections for the ECFZ labeled: NS – North section, CS – Central section, SS – Southern section. Previous investigations from the UGS Paleoseismology of Utah series are highlighted as black boxes. East and West Cache fault zones shown as heavy black lines, other regional faults shown as gray lines from the Utah Geological Survey Utah Geologic Hazards Portal (2020).

The eastern trace consists of mostly moderately located faults in the valley near the town of Wellsville, and north along the valley floor. We identified one potential site on the eastern trace along the valley floor, but the very small size of the scarp and potential high groundwater levels in the area could make the site very difficult to trench.

The southernmost part of the WCFZ consists of numerous older faults around Hyrum and Mantua. Most of these scarps are on older Quaternary fan surfaces that are difficult to access and have widespread shallow bedrock, making them challenging for paleoseismic trench investigations. We did not identify any potential paleoseismic sites in this area; however, no paleoseismic data exists for these faults, making them a good candidate for other (scarp profiling, etc.), non-trenching, paleoseismic investigations.

Dayton Fault

The north-south-trending Dayton fault runs along the eastern base of an unnamed low-lying intrabasin range, and runs from Bergeson Hill near the Idaho-Utah border to the southern end of Little Mountain near Newton, Utah. Several decent scarps crossing Holocene to late Pleistocene-age fan surfaces may be suitable for paleoseismic trenching, although these fan ages are not well constrained. We identified at least three potential paleoseismic sites on the Dayton Fault (table 1, figure 4). A natural exposure of the fault is present in a gravel pit near the southern end of the Dayton fault near Little Mountain. Dr. Susanne Janecke and Utah State University students have performed reconnaissance on this natural exposure, but no data has been published from it. One of our identified paleoseismic sites lies just to the south of this natural exposure and may present a good opportunity for a trench investigation in combination with a study of the exposure in the gravel pit.

East Cache Fault Zone

The ECFZ is defined by strong triangular facets of the Bear River Range indicative of a west-dipping normal fault. The Central section of the ECFZ consists of Holocene-age fault scarps, while the Northern and Southern sections consist of Quaternary-age scarps. Compared to the WCFZ, there are fewer possible trenching sites because of older aged fan surfaces. Each one of these sites should be scrutinized for local geologic relationships that make for suitable paleoseismic trenching sites. We identified seven potential paleoseismic sites on the ECFZ. Two trenching projects were previously performed on the Central section of the ECFZ. The first trenching project was performed ~1/2 mile (1 km) south of Logan Canyon and used thermoluminescence and accelerator mass spectrometry radiocarbon dating to provide limiting age constraints on the PE and poorly constrained MRE timing (McCalpin, 1994). The second trenching project was conducted north of the mouth of Logan Canyon at the Logan Country Club golf course, where excavation yielded better constraints for the MRE (McCalpin, 1994). Additionally, an unpublished investigation by Evans and McCalpin (2012) was conducted on the Southern section of the ECFZ.

James Peak Fault

The James Peak fault is a northeast-trending normal fault at the northern base of James Peak. Fault scarps define this range front, separating Neoproterozoic bedrock of James Peak from Tertiary Salt Lake Formation and Quaternary deposits. Several scarps exist away from the range front within Quaternary-age alluvial fans. We identified three potential paleoseismic sites on the James Peak fault, primarily within Quaternary fan or potentially mass-movement related deposits. These are not ideal sites, but there may be local geologic relationships that would make for suitable trenching sites.

CONCLUSIONS

This report presents the motivation, process, and products funded by USGS External Grant, Award G17AP00071, conducted by the UGS. We present fourteen 7.5-minute quadrangle plates with detailed mapping of the ECFZ, WCFZ, Dayton fault, and James Peak fault in northern Utah created using high-resolution airborne lidar-derived products, historical aerial photos, previous geologic mapping, and field investigations. The motivation for this work was timely due to the availability of the high-resolution lidar data, and the increasing population growth and development in Cache Valley.

Special-study areas were delineated based on the certainty of the fault-trace mapping and fault geometry. The special-study area dimensions are based on the *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, in press). These special-study areas were delineated to assist in land-use planning and regulation for local governments. Paleoseismic sites were identified along the ECFZ and WCFZ in Utah, as well as the Dayton and James Peak faults, to foster future paleoseismic research in areas that are being rapidly developed or lacking good earthquake timing and recurrence information, which is the case for most of the Cache Valley faults. We identified 22 potential sites with varying geologic conditions deemed potentially suitable for paleoseismic investigation (table 1). The 22 potential paleoseismic sites should not be considered a complete list of all sites on the ECFZ, WCFZ, Dayton fault, and James Peak fault, as additional sites may exist. We focused on identifying sites where fault scarps are sparse, given the nature of the fault, and in areas where development and ongoing disturbance have obscured fault scarps. This dataset was designed to assist the UGS and other paleoseismic investigators in determining future sites for paleoseismic investigation.

The results of this work will be implemented in the form of a peer reviewed UGS Report of Investigation publication and final publication of fault mapping in the *Utah Geologic Hazards Portal* (https://geology.utah.gov/apps/hazards/). Once the final publication is complete, the UGS will contact local governments to present them with the fault mapping and offer assistance in developing local ordinances, based on the delineated special-study areas. These maps will serve as a critical tool to helping communities assess their earthquake risk and become more resilient to earthquake effects and geologic hazards.

Table 1. *Potential paleoseismic sites along the West Cache fault zone (WCFZ), East Cache fault zone (ECFZ), Dayton fault (DF), and the James Peak fault (JPF). The table shows 22 sites and includes the potential site location. as well as a cursory comment regarding the potential qualities of the site for paleoseismic investigation.*

Site Number	Fault Zone, Section	Comments	UTM Zone 12N	
			Easting	Northing
WCFZ-1	WCFZ, Clarkston Fault	Decent scarp cutting younger alluvium, could make a good trench site on either the north or south side of the youngest channel cut. Possibly shallow bedrock to north and south.	408839	4643666
WCFZ-2	WCFZ, Clarkston Fault	Decent scarp cutting young looking alluvium, possibility of shallow bedrock close by.	408920	4643519
WCFZ-3	WCFZ, Clarkston Fault	In Winter Canyon, possible very young alluvium cut by scarp; need to field check, could be a good trench site if access is alright.	409088	4643372
WCFZ-4	WCFZ, Clarkston Fault	Young scarp, young fan, potential site.	409658	4641617
WCFZ-5	WCFZ, Junction Hills Fault	Degraded scarp, might be decent last-resort site.	412712	4637661
WCFZ-6	WCFZ, Junction Hills Fault	Decent scarp cutting Provo shoreline bench, hard to tell age, but looks Holocene.	415541	4629814
WCFZ-7	WCFZ, Wellsville Fault	Subtle scarp in flats.	419565	4620478
WCFZ-8	WCFZ, Wellsville Fault	Potential site, could be some landsliding/slumping going on around here.	415397	4618178
WCFZ-9	WCFZ, Wellsville Fault	Potential, could have shallow bedrock.	415880	4614403
DF-1	Dayton Fault	Subtle scarp looks like it cuts a young fan surface, in the middle of farm field.	419131	4648023
DF-2	Dayton Fault	Scarp crossing younger looking fan.	419443	4644089
DF-3	Dayton Fault	Young scarp, south of gravel pits, potential site.	420437	4635355
ECFZ-1	ECFZ, Northern Section	Older scarp (<130,000) but possible candidate. Perform more detailed mapping before trenching.	435542	4626967
ECFZ-2	ECFZ, Central Section	Scarp separating Bonneville gravels and sands, similar to setting of previous successful trenches by McCalpin to the north.	434148	4620138
ECFZ-3	ECFZ, Central Section	Scarp in young fan (Qaf2), needs further scrutiny before excavation.	433856	4617806
ECFZ-4	ECFZ, Central Section	Nice west-facing scarp in Bonneville gravels with east-facing graben at the mouth of Providence Canyon.	433757	4615871
ECFZ-5	ECFZ, Central Section	West-facing scarp in Bonneville deltaic deposits coming out of Millville Canyon.	432944	4612956
ECFZ-6	ECFZ, Central Section	Very small scarp in young fan (Qaf1). Not an ideal location, but worth consideration.	432820	4610230

Site Number	Fault Zone, Section	Comments	UTM Zone 12N	
			Easting	Northing
ECFZ-7	ECFZ, Central Section	Small scarp in young fan (Qaf1). Not an ideal location, but worth consideration.	432841	4609914
JPF-1	James Peak Fault	Strong scarp in Lake Bonneville aged fan. Potentially mass movement related deposits and should be scrutinized.	433481	4585189
JPF-2	James Peak Fault	Large scarp in Bonneville aged fan away from range front. This area should be searched for ideal trenching site.	432936	4584963
JPF-3	James Peak Fault	Large scarp in Bonneville aged fan away from range front. This area should be searched for ideal trenching site.	432662	4584873

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