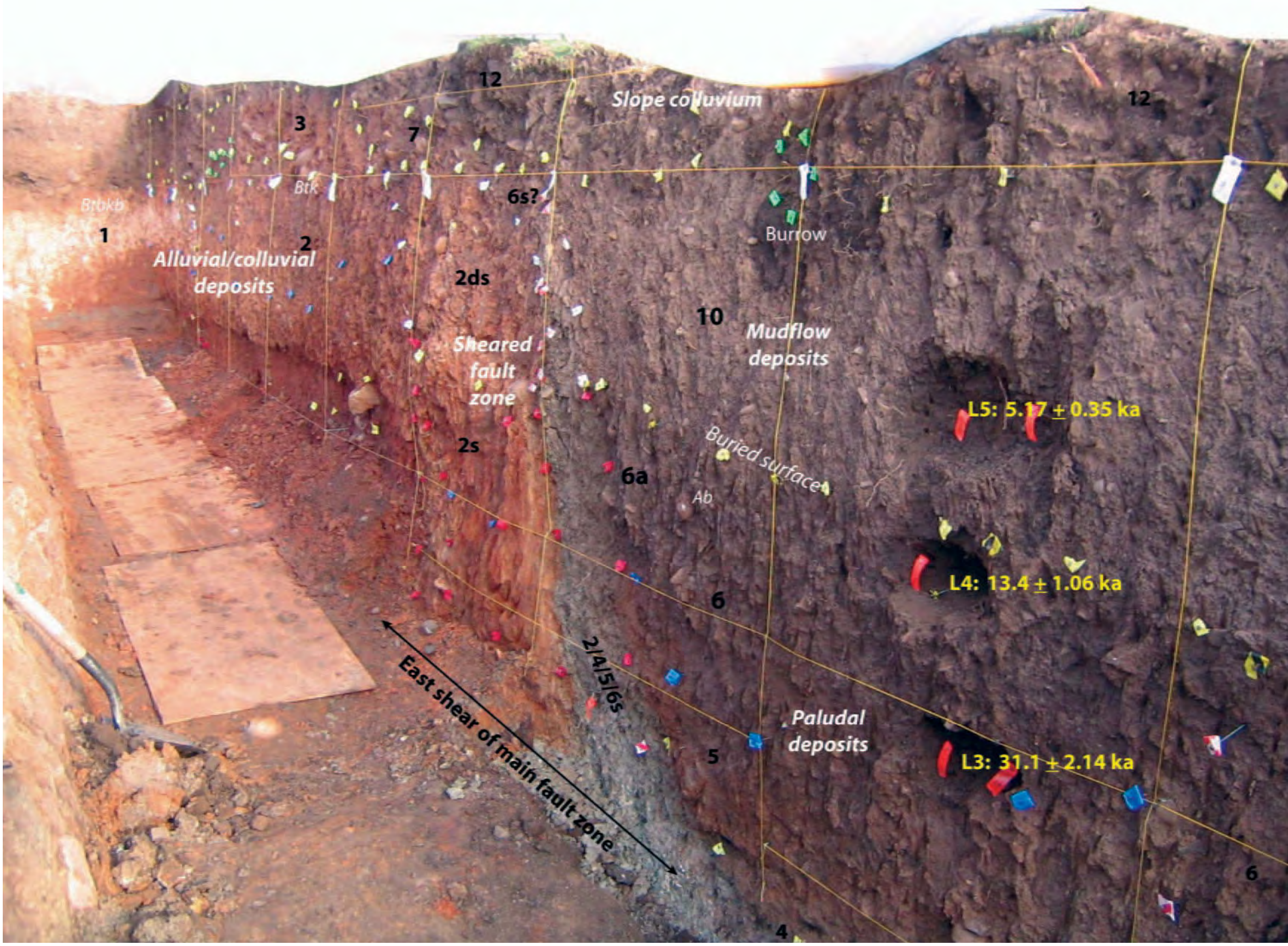
Paleoseismology of Utah, Volume 19

Late Quaternary Faulting in East Canyon Valley, Northern Utah

by Lucille A. Piety, Larry W. Anderson, and Dean A. Ostenaa



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Late Quaternary Faulting in East Canyon Valley, Northern Utah

by Lucille A. Piety[1], Larry W. Anderson[1], and Dean A. Ostenaa[2]

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Cover photo: *South wall of trench near the northern end of Main Canyon fault on the east side of East Canyon valley in northern Utah.*

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FOREWORD

This Utah Geological Survey Miscellaneous Publication, *Late Quaternary Faulting in East Canyon Valley, Northern Utah*, is the nineteenth report in the Paleoseismology of Utah series. This series makes the results of paleoseismic investigations in Utah available to geoscientists, engineers, planners, public officials, and the general public. These studies provide critical information regarding paleoearthquake parameters such as earthquake timing, recurrence, displacement, slip rate, fault geometry, and segmentation, which can be used to characterize potential seismic sources and evaluate the long-term seismic hazard of Utah's Quaternary faults.

This report, originally released as U.S. Bureau of Reclamation Seismotectonic Report 2008-1, presents new paleoseismic information for two "back-valley" faults on the eastern flank of the Wasatch Range. The Main Canyon (formerly "East of East Canyon" or "East Canyon – East Side") fault and the East Canyon fault are on the east and west sides, respectively, of the East Canyon valley area in Morgan and Summit Counties, Utah. The purpose of the study was to evaluate the Quaternary activity of the two faults as part of a seismic safety assessment of East Canyon Dam. To address this issue, the Bureau of Reclamation made a geomorphic evaluation of both faults, and excavated a trench across the northern part of the Main Canyon fault. The geomorphic evaluation revealed little or no evidence of Quaternary surface faulting on the East Canyon fault, but strong evidence of late Quaternary activity (scarps formed on geologically young deposits, faceted mountain spurs, disrupted drainages) on the Main Canyon fault. Using stratigraphic and structural relations, and radiocarbon and luminescence ages, it was determined that the trench exposed evidence for two surface-faulting earthquakes during the past 30,000 to 38,000 years, with the most recent event possibly as young as shortly before 5000 to 6000 years ago. There was also limited evidence for an unknown number of surface-faulting earthquakes older than 38,000 years. Differences in stratigraphic units on opposite sides of the fault in the trench prevented the determination of either the amount of offset or slip rate of the fault.

Determining well-constrained paleoseismic parameters for Utah's Quaternary faults is important because the new data will help refine fault activity and hazard models and improve earthquake-hazard evaluations for the region, all of which help reduce Utah's earthquake-related risk.

William R. Lund, Editor
Paleoseismology of Utah Series

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Late Quaternary Faulting in East Canyon Valley, Northern Utah

by Lucille A. Piety, Larry W. Anderson, and Dean A. Ostenaa

ABSTRACT

East Canyon valley, a 25-km-long by 5-km-wide "back-valley," is on the eastern flank of the Wasatch Range about 25 km northeast of Salt Lake City and the Wasatch Front. Previous geologic mapping and the geomorphic expression of this north-northeast-trending valley suggest that East Canyon valley is a middle to late Cenozoic half-graben bounded on the west by the East Canyon fault. The Main Canyon fault, previously referred to as the "East of East Canyon" or "East Canyon – East Side" fault, is a down-to-the-west normal fault that partly coincides with the drainage divides that bound the east side of East Canyon valley. The Main Canyon fault cuts across existing topography, but has nearly continuous expression in the landscape for about 26 km. Previous interpretations have suggested that the Main Canyon fault is a minor structural feature, antithetic to the East Canyon fault.

A trench excavated across a 0.4-m-high, west-facing scarp on unconsolidated sediments near the northern end of the Main Canyon fault exposed a 5-m-wide fault zone that juxtaposes alluvium/colluvium on the footwall against paludal (marsh) deposits on the hanging wall. Recurrent surface ruptures formed upslope-facing scarps that interrupted the east-flowing drainages, which were ponded temporarily along the fault. The trench exposed a record of two faulting events during the past 30,000 to 38,000 years, but the difference in the stratigraphic units on opposite sides of the fault did not allow for an estimate of the amount of displacement. Age estimates based on luminescence and radiocarbon analyses, supported by an assessment of soil development, indicate that the most recent surface-rupturing earthquake likely occurred shortly before 5000 to 6000 years ago, but could be as old as 10,000 to 12,000 years ago.

Recurrent late Pleistocene and Holocene displacement on the Main Canyon fault is consistent with faulting histories determined for other northerly trending, mostly down-to-the-west normal faults east of the Wasatch Range in north-central Utah. Although the overall geomorphology and the trenching results indicate recurrent late Quaternary surface rupturing earthquakes associated with the Main Canyon fault, the East Canyon fault lacks evidence for late Quaternary or Quaternary surface faulting, which suggests that such activity has not occurred or has occurred at a very low rate. Finally, geology and geomorphology suggest that the Main Canyon fault has not had recurrent displacement throughout the late Cenozoic, but instead became active only during the past few million years.

INTRODUCTION

The East Canyon area (hereafter referred to as East Canyon valley) is on the eastern flank of the Wasatch Range about 25 km east of the range-bounding Wasatch fault (Figure 1). Paleoseismic studies in the northern and central mountains east of the main Wasatch Range indicate that late Quaternary faulting is associated with several northerly trending valleys (e.g., Morgan Valley, Strawberry Valley) east of the range-bounding Wasatch fault (Nelson and VanArsdale, 1986; Sullivan and others, 1988; Figure 1). Although Sullivan and others (1988) discussed the East Canyon area in their assessment of faulting in the central Utah region, they conducted only a brief reconnaissance of the faults in the valley, and this reconnaissance focused on the East Canyon fault. While they failed to identify any late Quaternary fault scarps associated with the East Canyon fault, they concluded that the southern portion of the fault shared some of the characteristics of recognized late Quaternary faults in north-central Utah and hence was a potential seismic source. This assessment of the faults in East Canyon valley was undertaken as part of a reevaluation of fault seismic sources for the probabilistic seismic hazard analyses (PSHA) conducted by the Bureau of Reclamation (BOR) for East Canyon Dam.

A consultant review board that convened in 2006 to review BOR work assessing the safety of East Canyon Dam recommended that “Additional geology and paleoseismic investigations of the East Canyon and East Canyon East Side faults should be undertaken to try to better constrain the slip rates on these faults, the ages of their most recent surface faulting earthquakes, and the surrounding geologic structure.” In previous studies, the East Canyon fault was considered the primary seismic source, despite little detailed work. In response to the Consultant Review Board recommendation in 2006, Dean Ostenaa (formerly in the BOR Seismotectonics and Geophysics Group) began an assessment of the East Canyon area by examining previous reports, published and unpublished literature and geologic maps, and aerial photographs. In August 2006 he conducted a ground reconnaissance of the East Canyon area and noted a possible late Quaternary fault scarp along the northern portion of what we now refer to as the Main Canyon fault. Trench investigations were initiated in the fall of 2006 to try to determine the origin and history of the scarp where it crosses the northern end of East Canyon valley. A trench was excavated, described, sampled, and reviewed in October 2006. The trench exposed evidence for recurrent late Pleistocene and Holocene tectonic surface ruptures on the Main Canyon fault. Interpretations of fault history from the trench exposure are consistent with the geomorphic expression of the fault, which suggests geologically recent displacements on the Main Canyon fault, but no long-term record of movement throughout the late Cenozoic.

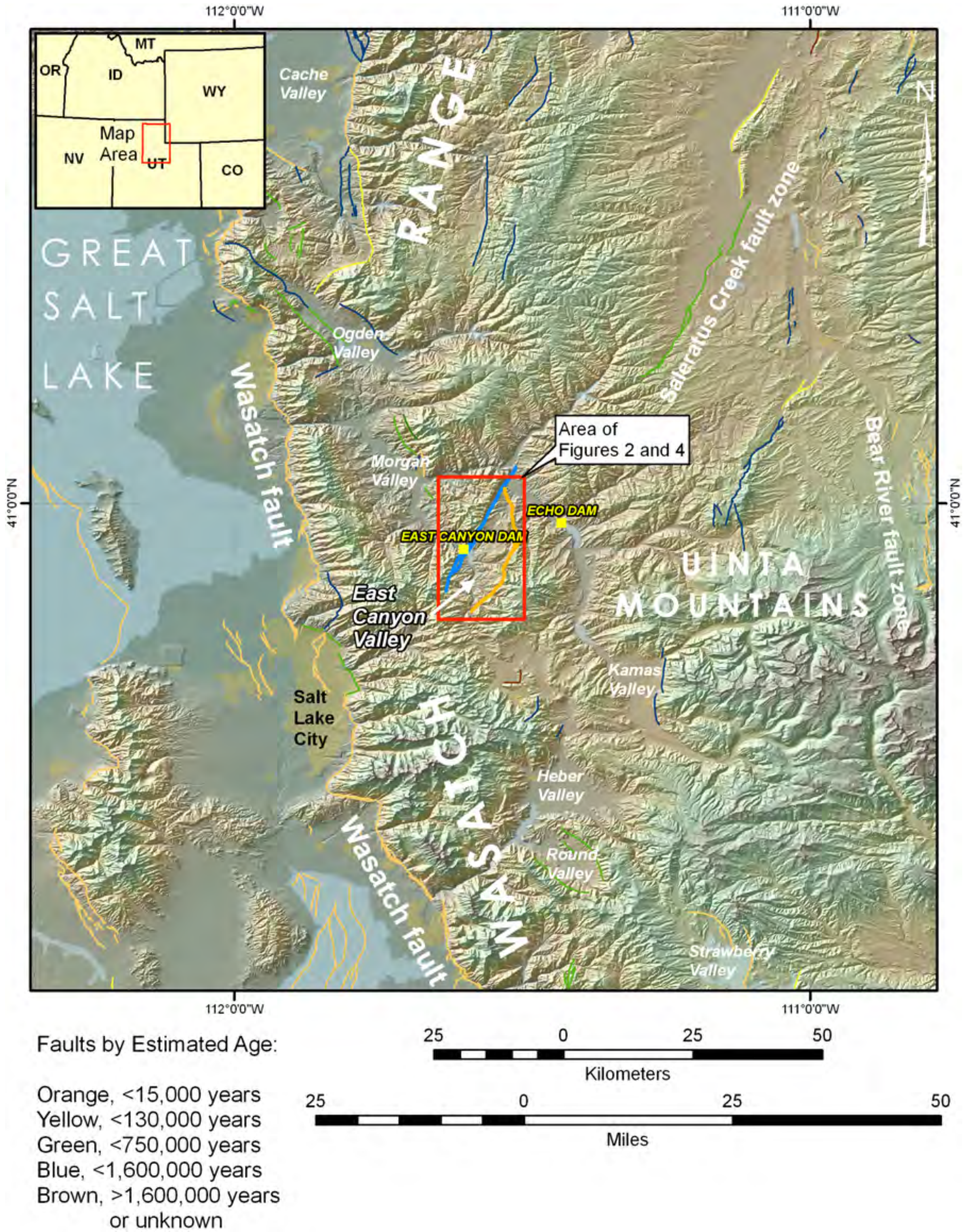

Figure 1. *East Canyon valley and Quaternary faults in northeastern Utah. Faults and their ages are from the database of Quaternary faults and folds by the U.S. Geological Survey (2010), except for the ages of the Main Canyon and East Canyon faults. The ages for these faults have been modified on the basis of the conclusions of this study.*

Additional assessment of the possible tectonic features in East Canyon valley was done in 2007 using existing mapping, black-and-white 1:40,000-scale aerial photographs, additional field reconnaissance, and an aerial overflight. The geologic evidence suggests that displacement on the East Canyon fault, which bounds the west side of East Canyon valley, was primarily responsible for the initial formation of the valley probably late in the middle Cenozoic. However, displacements on the East Canyon fault do not appear to have continued into the late Quaternary.

GEOLOGY AND TECTONIC GEOMORPHOLOGY OF EAST CANYON VALLEY

East Canyon valley formed through a combination of fault displacement, sedimentation, and erosion, similar to other valleys east of the main Wasatch Range (Sullivan and others, 1988). East Canyon valley is defined geologically by the extent of the Norwood Tuff (Tn) and older underlying conglomerate deposited within a Cenozoic basin (Toc or Tc; Bryant, 1990; Figure 2 and Figure 3). Because of the deposition of these units, a valley or basin must have been present in this area during the late Eocene and early Oligocene (about 30 to 40 million years ago). In addition, a linear north-northeast-striking faulted contact between these units and older rocks and increasing backtilting of these units toward the fault with depth indicate that displacement on the East Canyon fault continued during and after deposition of the two units (Figure 2). Surfaces or pediments cut on the erodible Norwood Tuff along the west side of East Canyon valley further suggest that drainages from the west side of the valley dominated, probably because of the topographic escarpment created by displacements on the East Canyon fault and the presence of the resistant Echo Canyon Conglomerate on the footwall. The pediments also suggest that the valley was a closed basin, or nearly so, for a time during the early Pleistocene (about 2 million years ago to several hundred thousand years ago). Subsequently, the present drainages of East Canyon Creek and the Weber River were established (Sullivan and others, 1988). Headward erosion on tributaries to these two main drainages removed sediment from East Canyon valley and left a drainage divide at Hogback Summit (elevation 6250 feet) between East Canyon Creek and the Weber River (Figure 2 and Figure 4). East Canyon Creek enters East Canyon valley from the south, flows across the East Canyon fault at East Canyon Dam, and continues northwest to join the Weber River in Morgan Valley. Thus, the outlet for flow and the lowest point along the drainage in East Canyon valley south of Hogback Summit crosses the East Canyon fault.

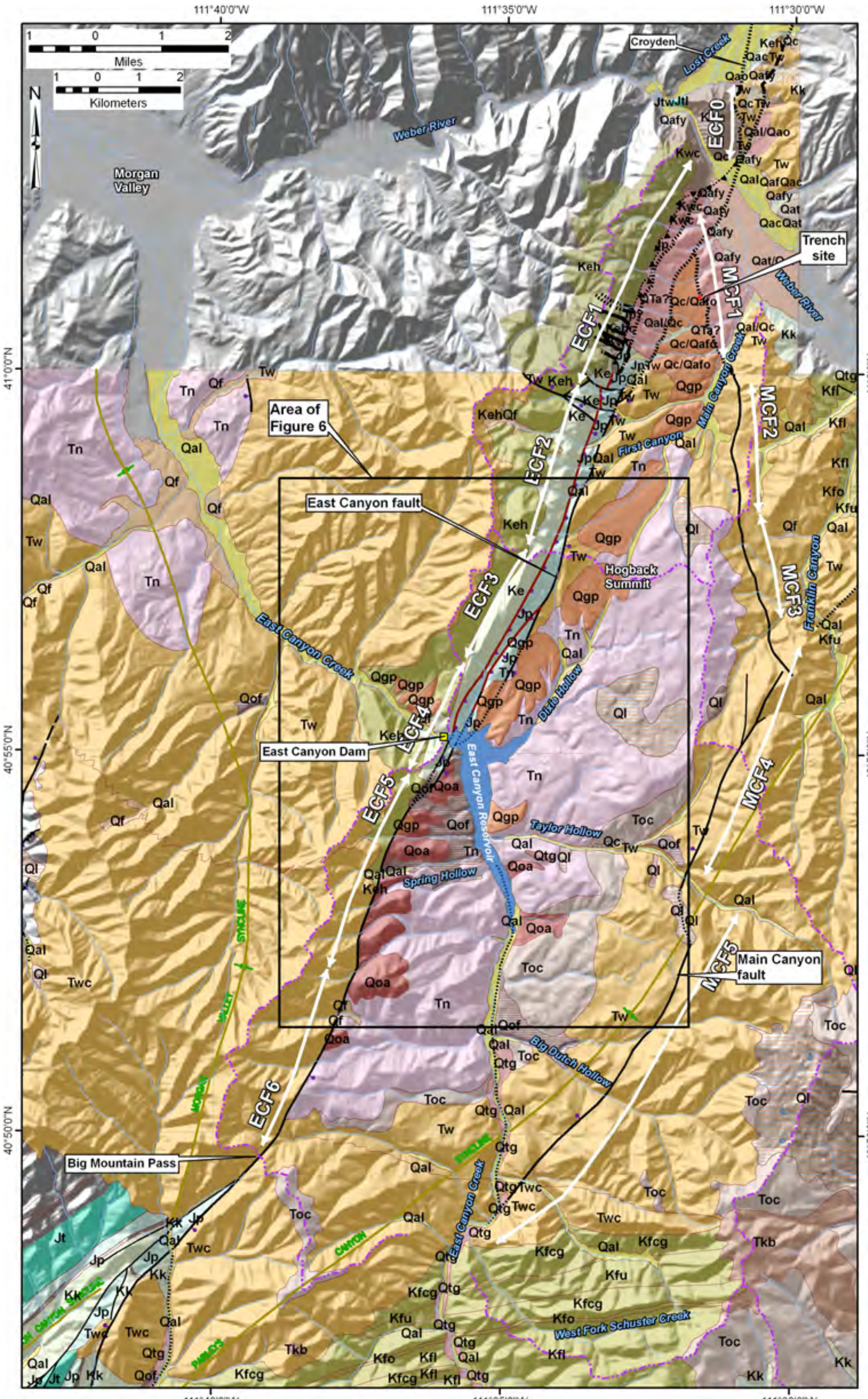

Figure 2. *Generalized geology of East Canyon valley. Geology south of latitude 41 degrees is from Bryant (1990). Geology north of latitude 41 degrees is from Coogan (2002). See Figure 3 for an explanation of geologic units and symbols.*

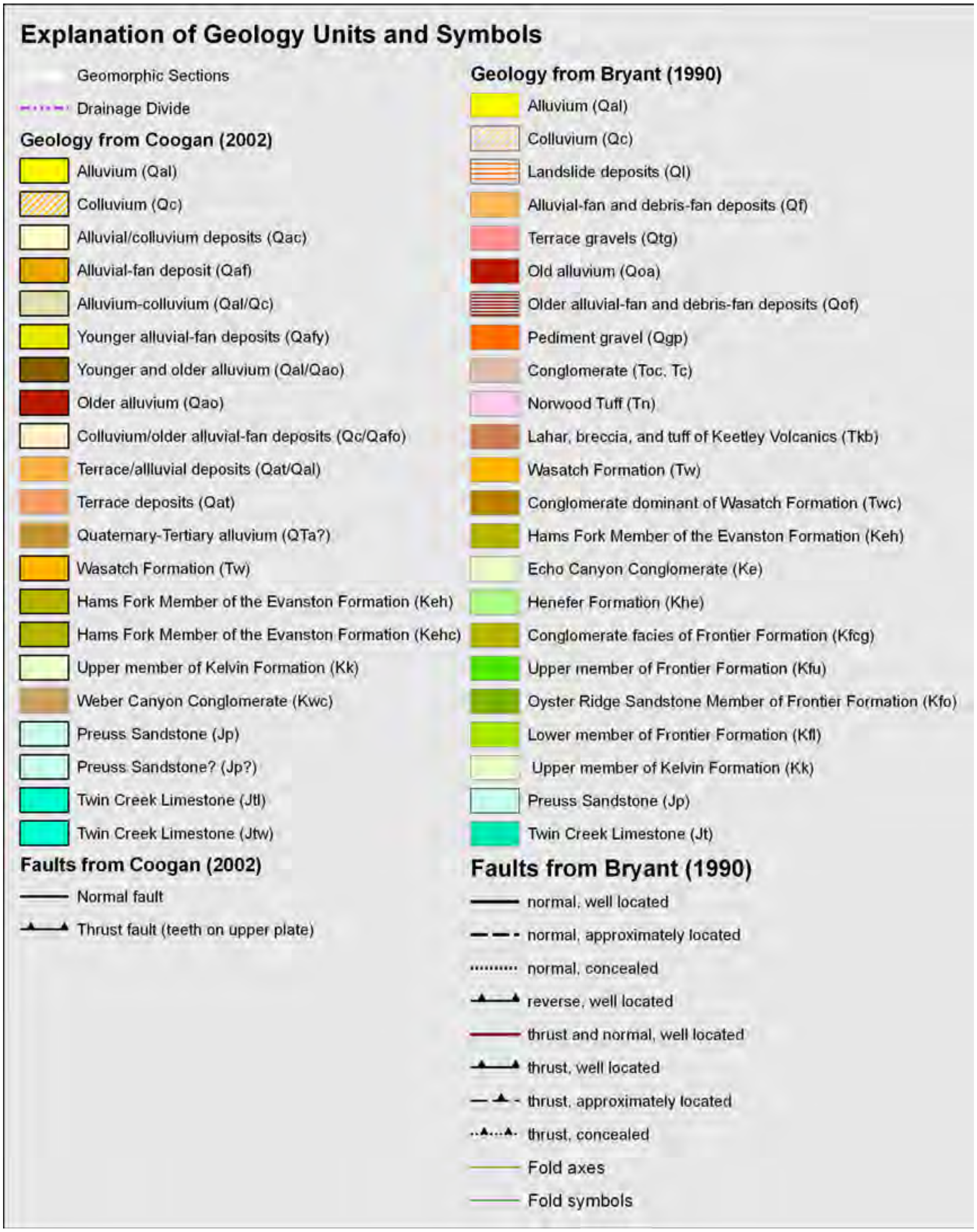

Figure 3. *Explanation of geologic units mapped in East Canyon valley (see Figure 2).*

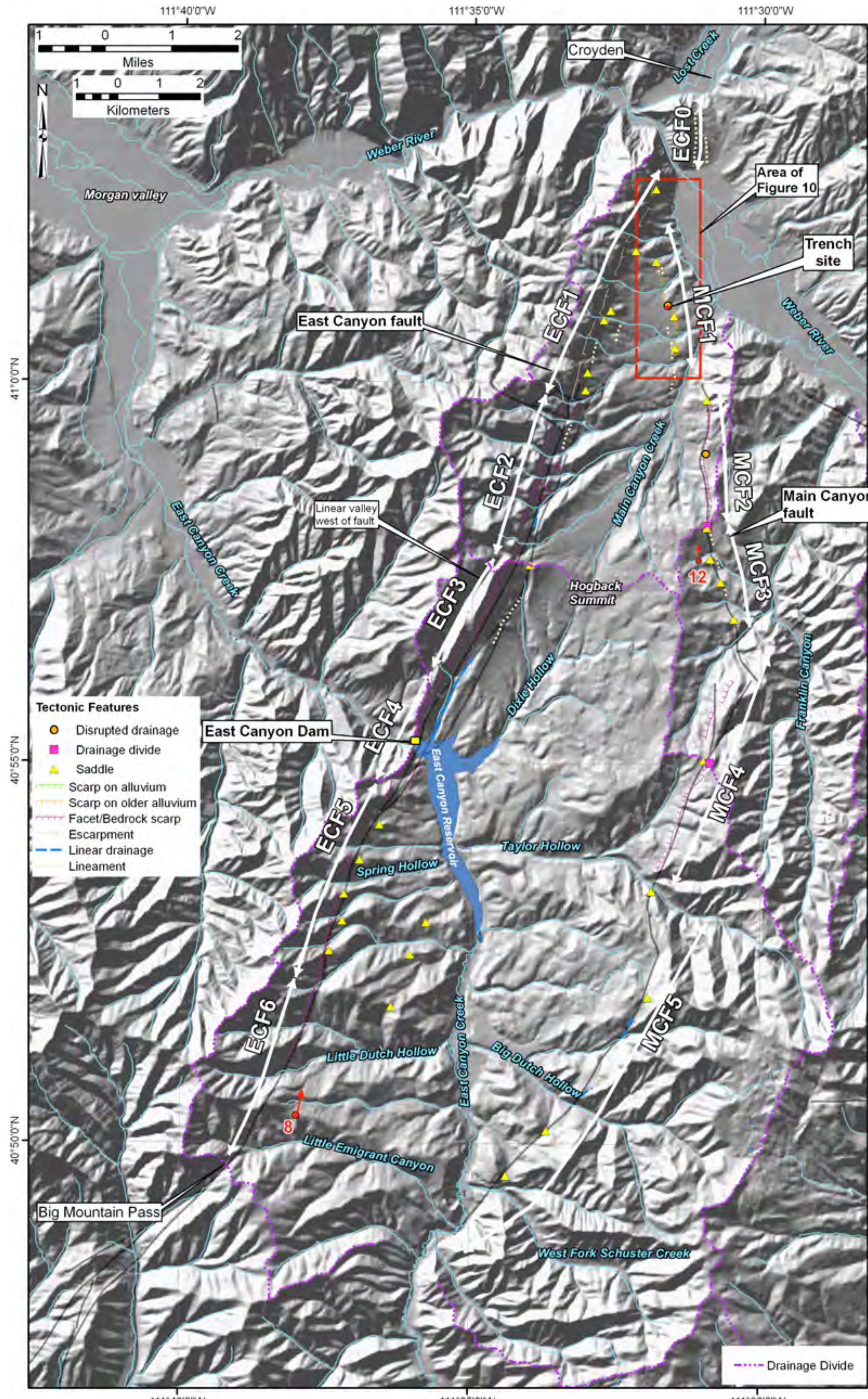

Figure 4. *Geomorphic sections and tectonic geomorphic features along the East Canyon and Main Canyon faults in East Canyon valley. Gray lines show mapped fault traces (Figure 2). Red numbers and arrows indicate the locations of Figure 8 and Figure 12.*

Presently, the best topographic expression of East Canyon valley is north of about Spring Hollow (Figure 2). South of this point, older deposits mapped as Norwood Tuff (Tn) by Bryant (1990) are preserved in the west half of the valley, and Wasatch Formation (Tw) and an older conglomerate (Toc) are preserved in the east half (Figure 2). North of Spring Hollow, early Quaternary (younger than about 2 million years) alluvial fans are preserved near East Canyon Reservoir and along Taylor Hollow. North of Taylor Hollow, Pleistocene pediment gravels (Qgp) are present along both Dixie Hollow, which flows southward into East Canyon Reservoir, and Main Canyon Creek, which flows northward into the Weber River. North of First Canyon, younger Pleistocene and Holocene alluvial fans are present in the northern (about 3 km) of the valley.

East Canyon Fault

The Cenozoic East Canyon fault has a length of at least 26 km, extending from near the town of Croyden north of the Weber River to near Big Mountain Pass on the south-southwest (Figure 2). Southwest of Big Mountain Pass, the fault loses its geomorphic expression as it crosses the crest of the Wasatch Range, where the fault then splays into a series of fault strands that apparently die out within the Emigration Canyon syncline (Bryant, 1990). Previous seismotectonic studies subdivided the East Canyon fault into two sections or segments that overlap immediately east of East Canyon Dam. The northern section begins near the Weber River and terminates east of East Canyon Dam. The southern section begins near the dam and ends near Big Mountain Pass.

The primary sources of bedrock mapping for the East Canyon fault are Bryant (1990), Coogan and King (2001), and Coogan (2002). Basically, the East Canyon fault was originally interpreted to be an east-dipping, west-verging thrust fault that was later re-activated as a down-to-the-east normal fault. Typically, this multi-stranded fault juxtaposes resistant west-dipping Cretaceous and early Tertiary rocks against either erodible, steeply east-dipping Jurassic rocks (Preuss Formation; Jp) or early Tertiary sedimentary rocks (Wasatch Formation; Tw) and/or the Norwood Tuff (Tn). In some areas, however, particularly where there are multiple strands of the fault, the Preuss Formation is also faulted (up-on-the-west) against the west-dipping Wasatch Formation or Norwood Tuff. The East Canyon fault is structurally complex due to earlier thrusting and later normal faulting.

The geomorphic expression of the East Canyon fault varies significantly, and for ease of discussion the fault has been subdivided into seven sections (ECF0 through ECF6), which are based on the differences in the geology and geomorphic expression of the fault (Figure 2 and Figure 4). Landscape features that might have a tectonic origin were mapped using aerial photographs and are portrayed on Figure 4.

The northernmost section (**ECF0**), which is about 1.8 km long, is north of the Weber River and juxtaposes Weber Canyon Conglomerate (Kwc) on the west against younger Wasatch Formation (Tw; Figure 2). The Weber Canyon Conglomerate forms a large unnamed hill north of the Weber River. North-trending lineaments along the east side of the hill might be related to the fault, and are the northernmost surficial expression of the East Canyon fault (Figure 4).

In the next section (**ECF1**), about 6 km long, the fault is composed of up to three traces, one of which is the mapped trace of the East Canyon thrust (Figure 2). The western trace of the East Canyon fault south of the Weber River forms an escarpment about 350 m high in resistant Evanston Formation (Keh) and Weber Canyon Conglomerate (Kwc) along the west margin of East Canyon valley. The drainage divide for Main Canyon Creek on the west side of the valley is nearly parallel to and is less than 1 km west of this trace of the fault. East-flowing drainages from the divide have eroded the escarpment, which is embayed (Figure 5). Alluvial fans have been deposited along the base of the escarpment. The eastern trace (or the middle trace of Coogan [2002]) is expressed as lineaments and saddles that are 0.3 to 0.4 km east of the western trace. All three traces are shown as concealed by Coogan (2002). The western and middle traces are concealed by Quaternary-Tertiary alluvium (QTa?). The eastern trace is shown as a concealed contact between Quaternary-Tertiary alluvium and Quaternary colluvium/older alluvial-fan deposits (Qc/Qafo). A few saddles (notches) are present along the middle trace, where hills mapped as Quaternary-Tertiary alluvium are separated from the bedrock escarpment to the west.

Figure 5. *East-facing escarpment along section ECF1 of the East Canyon fault. Escarpment is formed by resistant Evanston Formation and Weber Canyon Conglomerate. Approximate fault location is shown by arrows. Note the embayed character of the escarpment and the alluvial-fan deposits at the foot of the escarpment.*

In the next section to the south (**ECF2**), which is about 5 km long, two fault traces were mapped by Bryant (1990). The western and central traces of Coogan (2002) in section ECF1 merge into the western trace of Bryant (1990). The western trace is expressed as discontinuous, low, east-facing facets or bedrock scarps in very resistant, late Cretaceous (about 95 to 65 million years ago) Echo Canyon Conglomerate (Ke; Figure 2). The drainage divide for Main Canyon Creek is between 2 and 3 km west of the fault trace, and the facets/bedrock scarps are preserved only on ridges between the incised east-flowing drainages that head at the divide (Figure 4). The eastern trace, mapped by Bryant (1990) between Preuss Formation (Jp) and Wasatch Formation (Tw), is expressed as discontinuous east-facing facets or bedrock scarps, lineaments, and a linear drainage. The area between the two fault traces is topographically low, and is underlain by erodible Preuss Formation. The topographic low is bounded by higher surfaces cut into the Wasatch Formation on the east and into Echo Canyon Conglomerate on the west.

The next section to the south (**ECF3**), which is about 3 km long, has two or three traces (figure 6). The western trace is expressed as nearly continuous linear facets or bedrock scarps in Late Cretaceous Echo Canyon Conglomerate (Ke). The drainage divide for Main Canyon Creek is about 1 km west of the western trace or is coincident with the top of the facet/bedrock scarp along this trace. The facet is only slightly eroded because little drainage reaches it. West-flowing drainage collects in a linear valley immediately west of the facet and east-flowing drainages begin at the top of the facet/bedrock scarp and have little drainage area at the facet (Figure 4). The eastern trace juxtaposes Preuss Formation (Jp) against Wasatch Formation (Tw) or Norwood Tuff (Tn). Bryant (1990) shows this trace as mostly concealed by Quaternary pediment gravels (Qgp). He portrays an additional central fault trace within Preuss Formation (Jp). This trace bounds the west side of a linear ridge; the eastern trace bounds the east side of this ridge. A south-flowing drainage has developed along the central trace.

The next section to the south (**ECF4**) is about 3 km long and just east of East Canyon Dam (Figure 6). Bryant (1990) continues the three traces of ECF3 to East Canyon Creek, but shows only two fault traces south of the creek. This is the area where the north and south sections or segments of Sullivan and others (1988) overlap. North of the reservoir, the west trace juxtaposes Echo Canyon Conglomerate (Ke) and Preuss Formation (Jp), and is expressed as a facet or bedrock scarp. The drainage divide coincides with the top of the facet, so that there is little drainage to erode the facet. The middle trace north of East Canyon Creek is shown within the Preuss Formation. The east trace north of East Canyon Creek is portrayed as concealed by Quaternary pediment gravel (Qgp) and as curving to the west to join the central trace under East Canyon Reservoir.

South of East Canyon Creek, Bryant (1990) shows the East Canyon fault as two traces. The west trace juxtaposes Echo Canyon Conglomerate (Ke) and Preuss Formation (Jp), and is expressed as a facet or bedrock scarp. A portion of this trace is shown as concealed by older (Pleistocene) debris-fan deposits (Qof). Bryant (1990) portrays the east trace as a fault contact between Preuss Formation (Jp) on the footwall and older (Pleistocene) alluvium and debris-fan deposits (Qoa and Qof) on the hanging wall. He

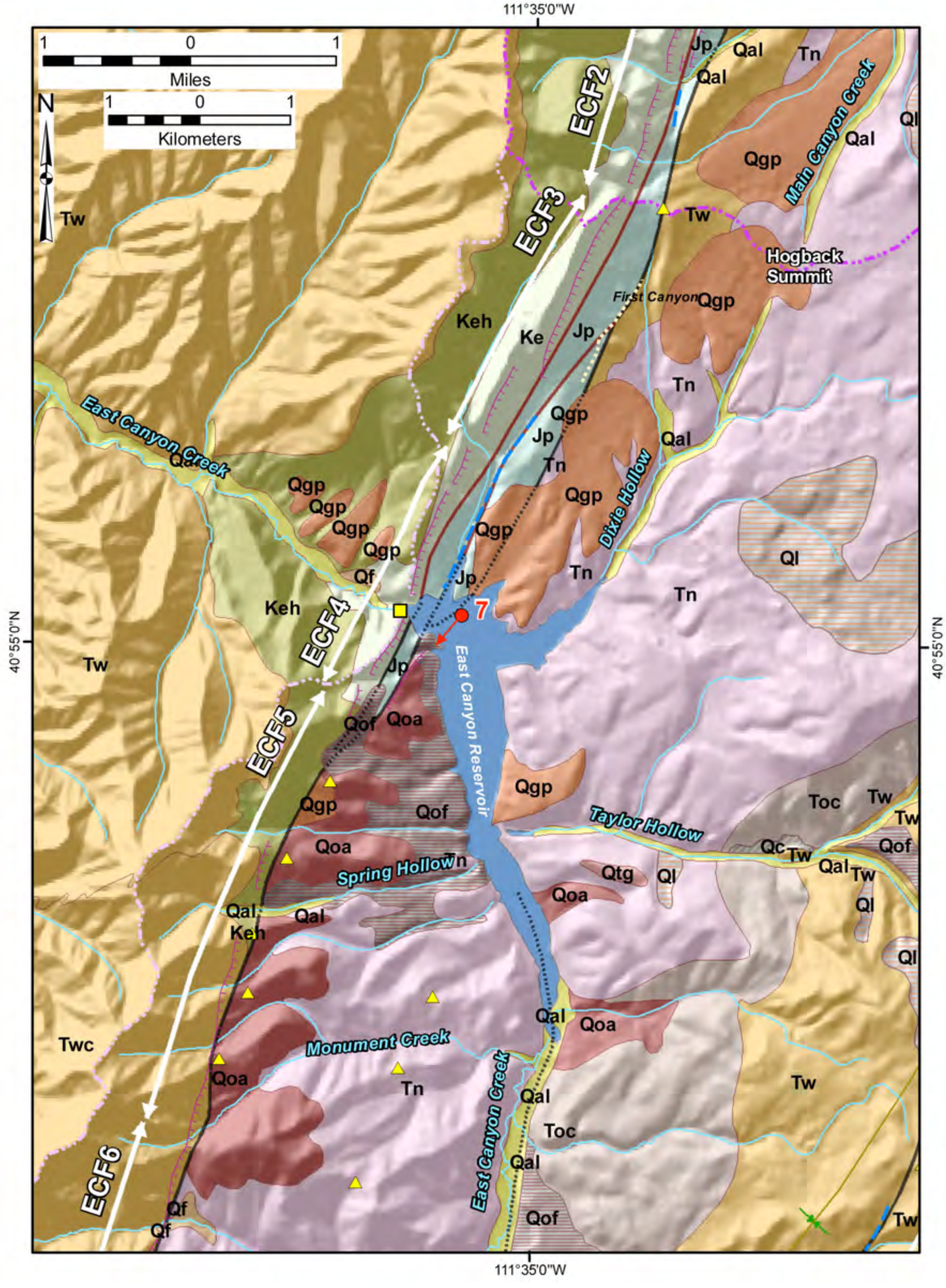

Figure 6. *Enlargement of geology and geomorphic features along the East Canyon fault near East Canyon Dam (yellow square). Geology is from Bryant (1990). Red arrow shows location of Figure 7. See Figure 3 and Figure 4 for explanation of units and symbols.*

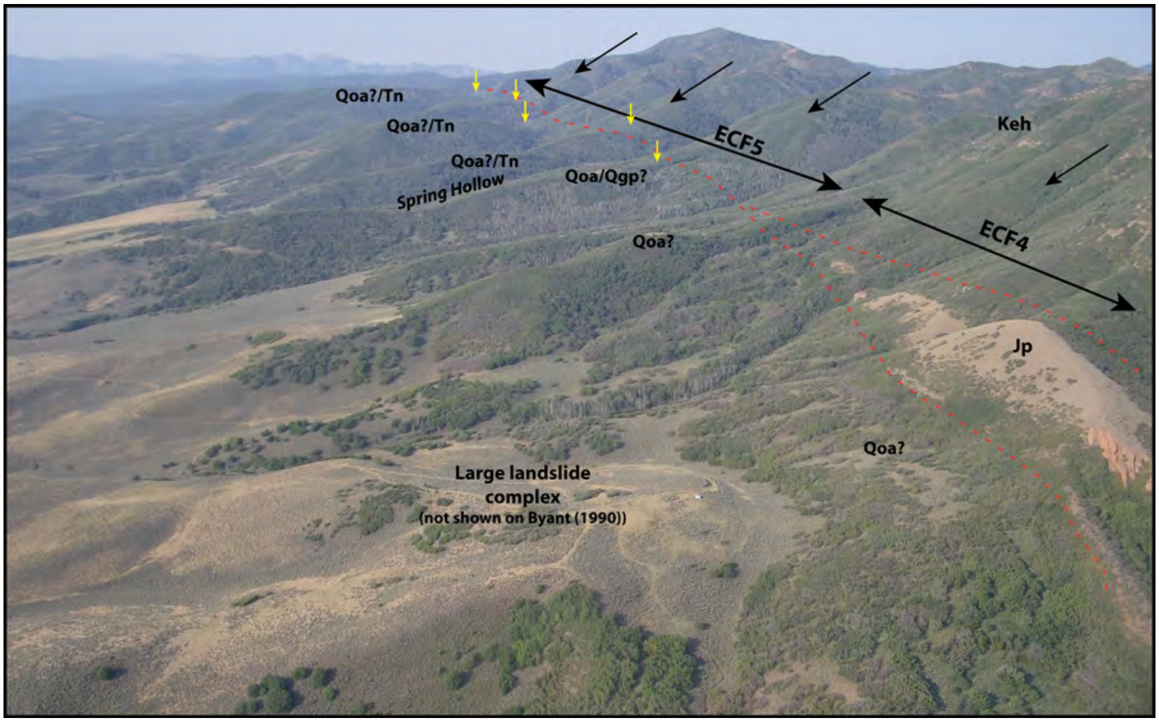

Figure 7. *Sections ECF4 and ECF5 along the East Canyon fault immediately south of East Canyon Dam (Figure 6). Photograph taken looking southwest. Approximate location of the East Canyon fault is shown by the dotted red lines. Facets in bedrock on the footwall are indicated by black arrows. Saddles or notches at the uphill extent of high surfaces mapped by Bryant (1990) as Pleistocene alluvium or debris-fan deposits are indicated by yellow arrows. Photograph by L.W. Anderson in 2007.*

also shows a portion of this trace as concealed by Pleistocene debris-fan deposits. A large unmapped landslide is present just east of the eastern trace (Figure 7).

In the next section to the south (**ECF5**), about 5 km long, Bryant (1990) portrays the East Canyon fault as a single trace (Figure 6) with older (Pleistocene) alluvium (Qoa) and pediment gravel (Qgp) on the hanging wall in fault contact with the Evanston Formation (Keh) or conglomerate within the Wasatch Formation (Twc) on the footwall. Facets or bedrock scarps are present on the footwall (Figure 7). The older alluvium and pediment gravel are preserved on high dissected hills that are disconnected from the bedrock by saddles or notches (Figure 6 and Figure 7)

In sections ECF4 and ECF5, the East Canyon fault is expressed as discontinuous, east-facing facets or bedrock scarps on the footwall and as saddles (Figure 7 and Figure 8). These saddles are topographically low areas between the bedrock and the mapped Quaternary deposits. Although these low areas align with the mapped trace of the East Canyon fault, their origin is unclear. Aerial reconnaissance and limited field studies conducted as part of this investigation did not reveal direct evidence for fault displacement of the Quaternary units as implied by Bryant's mapping. It is possible that the topographic expression is the result of erosion. In addition, the ages of the mapped Quaternary units are unknown.

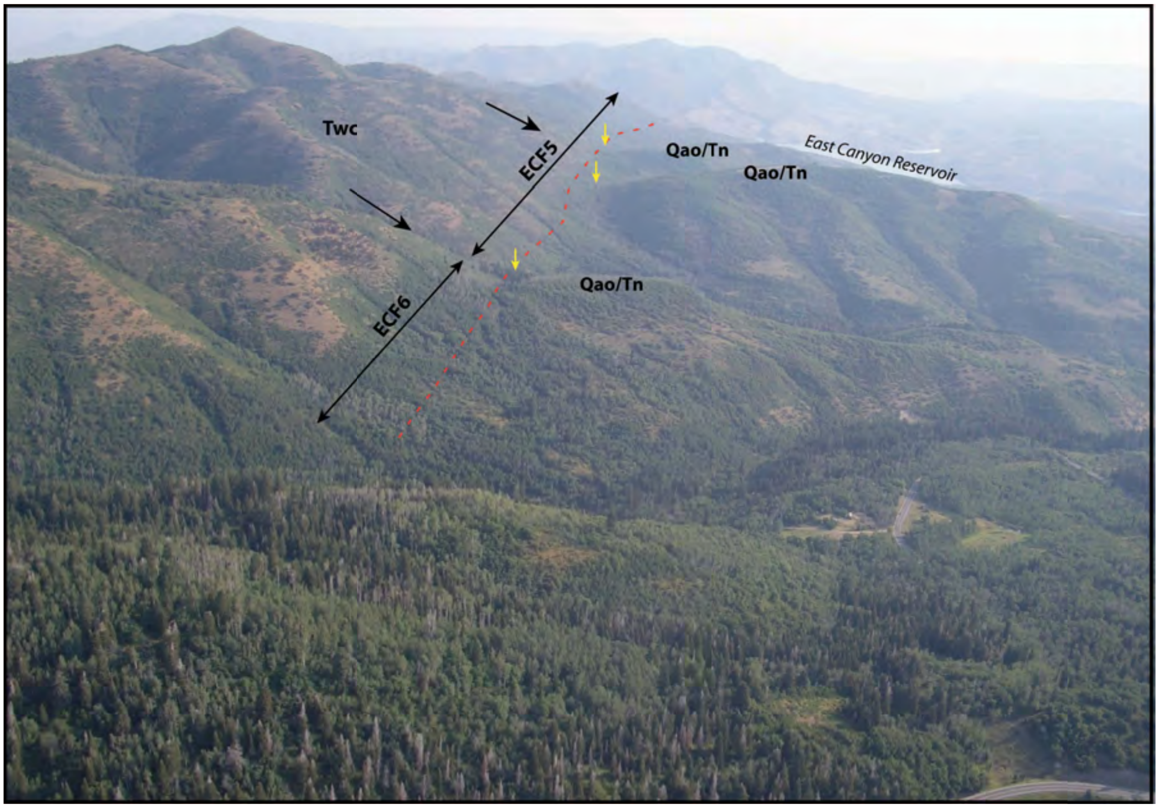

Figure 8. *Sections ECF5 and ECF6 of the East Canyon fault south of East Canyon Dam (Figure 4). Photograph taken looking north. Approximate location of the East Canyon fault is shown by the red dotted line. Bedrock facets formed in bedrock on the footwall are shown by black arrows. Saddles or notches at the uphill extent of high surfaces mapped by Bryant (1990) as Quaternary alluvium or debris-fan deposits on the hanging wall are indicated by yellow arrows. Photograph by L.W. Anderson in 2007.*

The final section at the south end of the fault (**ECF6**), about 4 km long, is shown by Bryant (1990) as a single trace (Figure 2). The fault is expressed as nearly continuous facets or bedrock scarps eroded by east-flowing drainages that head on a divide about 1 km west of the fault trace. High, dissected remnants, shown as Norwood Tuff by Bryant (1990), are preserved on the hanging wall. These remnants decrease in elevation to the south. Geomorphic expression of the East Canyon fault as a normal fault ends near Big Mountain Pass.

The map pattern of the Norwood Tuff and underlying conglomerate suggests that East Canyon valley was present as a topographic depression when these units were deposited during the middle Cenozoic. Rotation of the Norwood Tuff to the west further suggests that displacements continued on the East Canyon fault after deposition of the Norwood Tuff. Quaternary displacement on the East Canyon fault has not been demonstrated. Bryant's mapping implies that Pleistocene alluvium and debris-fan deposits are offset in sections ECF4, ECF5, and ECF6 (the portion of the fault south of East Canyon Dam). However, the nature and ages of any deposits related to these high, dissected surfaces are unknown. The presence of high surfaces of Tertiary Norwood Tuff and possible Quaternary gravels on the hanging wall immediately east of the fault suggests that any Quaternary displacement has been very limited. The notches or saddles along these sections could have an erosional origin. The East Canyon fault in these three sections is still visible in the landscape in large part because of the presence of the resistant Wasatch Formation conglomerate on the footwall. In contrast, the East Canyon fault north of East

Canyon Dam, especially sections ECF1 and ECF2, is expressed as a high escarpment that lacks high surfaces on the hanging wall, although the escarpment is embayed and eroded. North of East Canyon Dam, the fault is shown by Bryant (1990), Coogan and King (2001), and Coogan (2002) as concealed by Quaternary deposits where they are present.

Sullivan and others (1988) concluded that the portion of the East Canyon fault south of East Canyon Reservoir may have been active during the late Quaternary. While our studies have been limited, like Sullivan and others (1988) we have not observed any scarps on what may be late Quaternary or Quaternary deposits or surfaces. Consequently, because direct evidence for or against late Quaternary displacements has not been recognized, we do not know whether or not displacements on the East Canyon fault continued into the Quaternary. Because such displacements cannot be entirely discounted, early Quaternary activity on the East Canyon fault is considered to be possible.

Main Canyon Fault

The Main Canyon fault was mapped by Bryant (1990) as two separate traces: a northern one, about 10 km long that strikes nearly north and extends north into the Ogden quadrangle (Coogan and King, 2001), and a southern one, about 16 km long that strikes northeast (Figure 2). On Bryant's map, both faults are west dipping and located entirely within the Tertiary Wasatch Formation (Tw), except for a 2-km-long section of the fault just south of the Right Fork of Taylor Hollow, where the fault is covered by a landslide (Figure 2). Coogan's (2002) map continues the Main Canyon fault north of latitude 41° N as a concealed trace between Quaternary-Tertiary alluvium on the footwall and Quaternary colluvium over older alluvial-fan deposits on the hanging wall (Figure 2). Coogan's map shows the Main Canyon fault terminating at the eastern trace of the East Canyon fault about 1 km southwest of the Weber River valley.

There is no geologic evidence that the Main Canyon fault existed late in the middle Cenozoic. The extent of the Norwood Tuff can be explained by displacements on the East Canyon fault alone. Displacements on the Main Canyon fault have affected topography, but not in the sense that a middle or late Cenozoic basin had developed. Regardless, the geomorphic expression of the fault is nearly continuous north of Taylor Hollow as bedrock scarps or as lineaments and scarps on alluvium (Figure 4 and Figure 9). The fault cuts across existing topography indicating that displacements on the fault are geologically young, perhaps occurring only during the past few million years. In addition to scarps, the principle geomorphic features produced by the Main Canyon fault are disrupted (abandoned) drainages and differences in the degree of incision along drainages that cross the fault. Because the fault cuts across topography and drainage divides, the geomorphic expression of the fault is highly variable and depends in part on the direction of fault displacements relative to existing drainages.

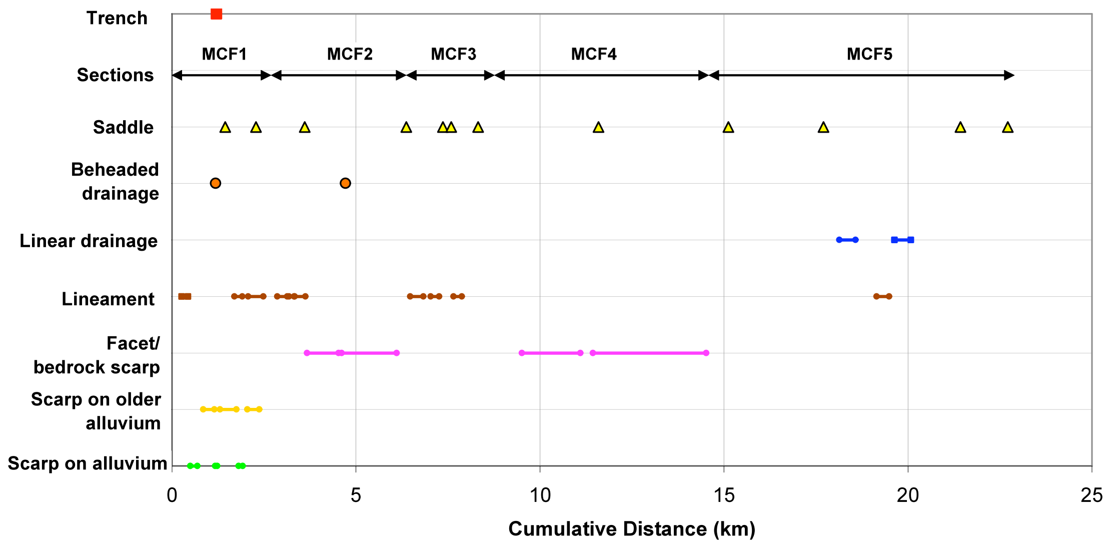

Figure 9. *Distribution of possible tectonic geomorphic features along the Main Canyon fault. The features are plotted by distance from the north end of the fault. Taylor Hollow is at the boundary between sections MCF4 and MCF5.*

For ease of discussion, the Main Canyon fault has been subdivided into five sections (MC1 through MC5) on the basis of differences in geomorphic expression of the fault (Figure 4 and Figure 9). Bryant (1990) shows nearly the entire fault as a single trace. The northernmost section (**MCF1**), which is about 3.5 km long, is that portion of the fault north of Main Canyon Creek. The fault cuts across early Quaternary (less than about 2 million years old) alluvial fans on eastward slopes and has formed upslope-facing (west-facing) scarps (Figure 10). East-flowing drainages from the escarpment along the East Canyon fault are barely incised on the hanging wall, but are markedly incised into older deposits downstream on the footwall (Figure 11; Appendix A). Displacements on the Main Canyon fault flattened gradients of the drainages on the hanging wall, which resulted in ponding adjacent to the fault. Topographic profiles along the smaller drainages flatten at the fault. The fault crosses Main Canyon Creek seemingly without a change in gradient or incision, but this is a much larger drainage that heads at a divide (Hogback Summit) within East Canyon valley. Because of its larger size, Main Canyon Creek may have been able to maintain its gradient after faulting events. The fault also may step to the east at Main Canyon Creek, so that displacements may not have been continuous across the drainage.

In this northern section (MCF1), fault scarps are present on surfaces of two broad age groups: younger alluvial fans and older alluvial fans or gravel deposits. The younger alluvial fans, which form the main part of the valley floor, are now graded to a level below the fault scarps. At least one drainage has been disrupted (cut off from its downstream continuation) because of reversal of gradient caused by fault displacements along this section of the fault (Figure 10). Other small drainages may be disrupted but have not been identified at the scale of the existing mapping.

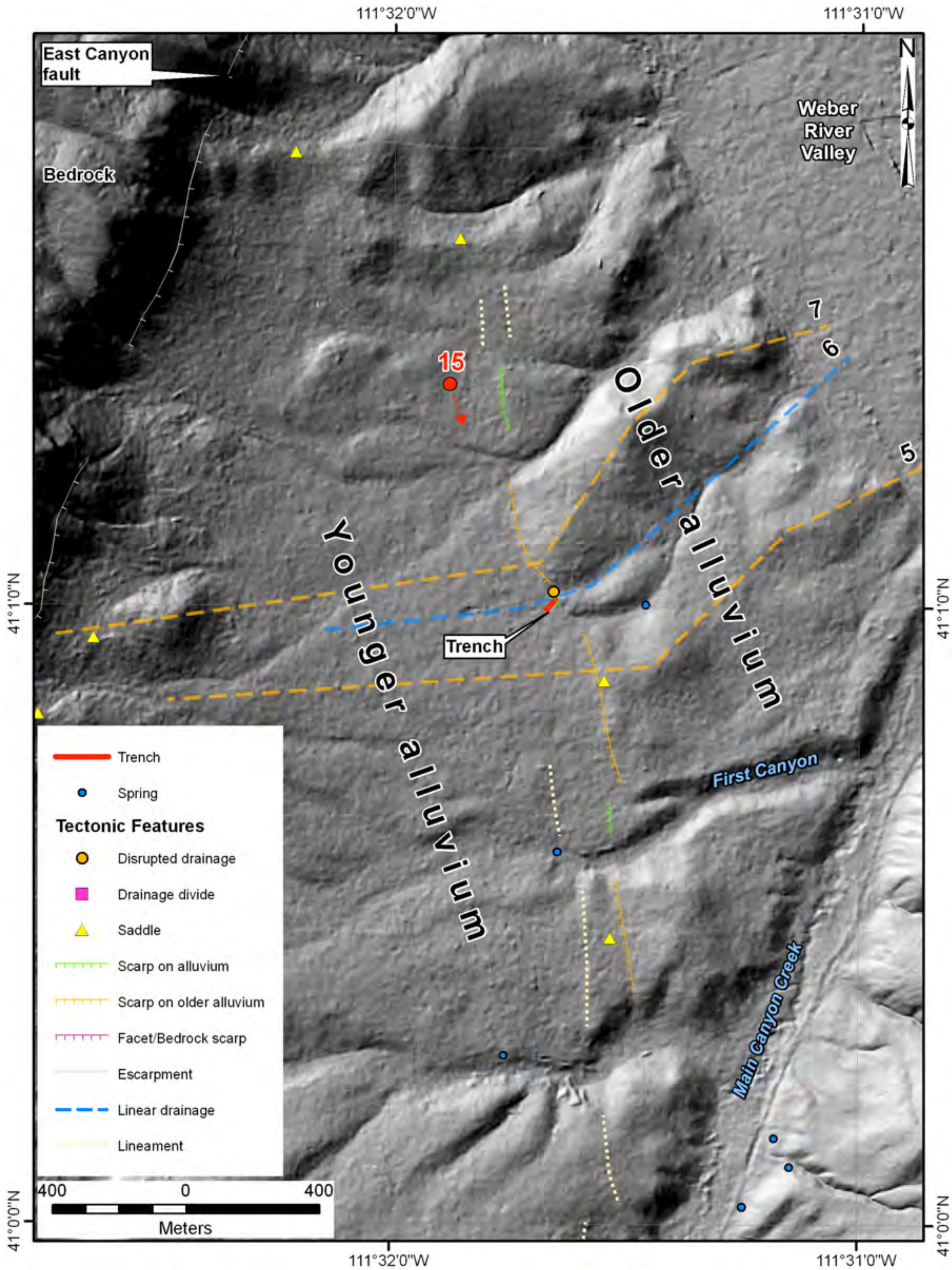

Figure 10. *Possible tectonic geomorphic features in the vicinity of the trench excavated near the north end of the Main Canyon fault. Older alluvium is preserved east of the fault; younger alluvium is west of the fault. Red arrow shows location of Figure 15. Drainage profile 6 (blue dashed line) and ridge profiles 5 and 7 (orange dashed lines) shown on Figure 11. Background is a hillshade created from 1997 aerial photographs, ground control, and a generated grid.*

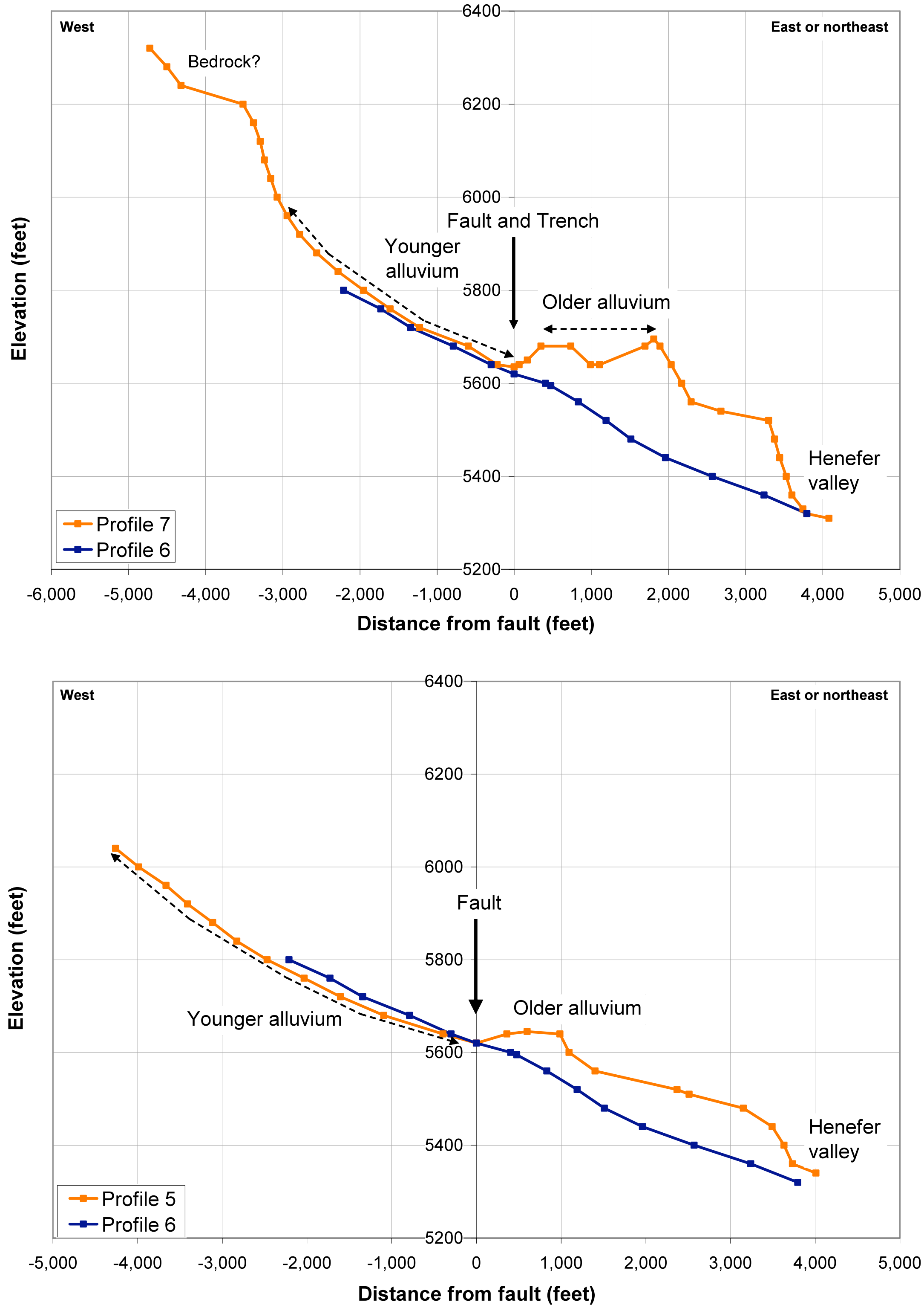

Figure 11. *Topographic profiles in the vicinity of the trench excavated near the north end of the Main Canyon fault. Differences in incision across the fault are shown by the drainage profile (blue) and the ridge profiles (orange). See Figure 10 for locations of the profiles.*

The location of the northern end of the Main Canyon fault is not known with any certainty. Coogan and King (2001) and Coogan (2002) map the north-northwest-striking Main Canyon fault as intersecting the north-northeast-striking East Canyon fault at an oblique angle about 2 km south of the Weber River (Figure 2). However, both fault traces are shown as concealed, and bedrock outcrops in this area are scarce even though the area is fairly well dissected. Possible west-facing scarps and lineaments that were observed by L.W. Anderson on an aerial overflight in July 2007 suggest that the Main Canyon fault could continue with a more northerly trend than that shown by Coogan and King (2001) and Coogan (2002). If the surficial expression of the Main Canyon fault continues north of the Weber River, then the fault could be 1 to 2 km longer than it is presently portrayed, and the structural relation between the Main Canyon fault and the East Canyon fault would be even more uncertain.

In the next section to the south (**MCF2**), about 3 km long between Main Canyon Creek and a drainage divide, displacements on the Main Canyon fault are downslope facing and have produced steep facets or bedrock scarps (Figure 12 and Figure 13). At least one drainage (a tributary to Bachelor Canyon) has been disrupted by fault displacements along this section of the fault (Figure 4 and Figure 14), and a saddle is present where the fault crosses the drainage divide at the south end of this section.

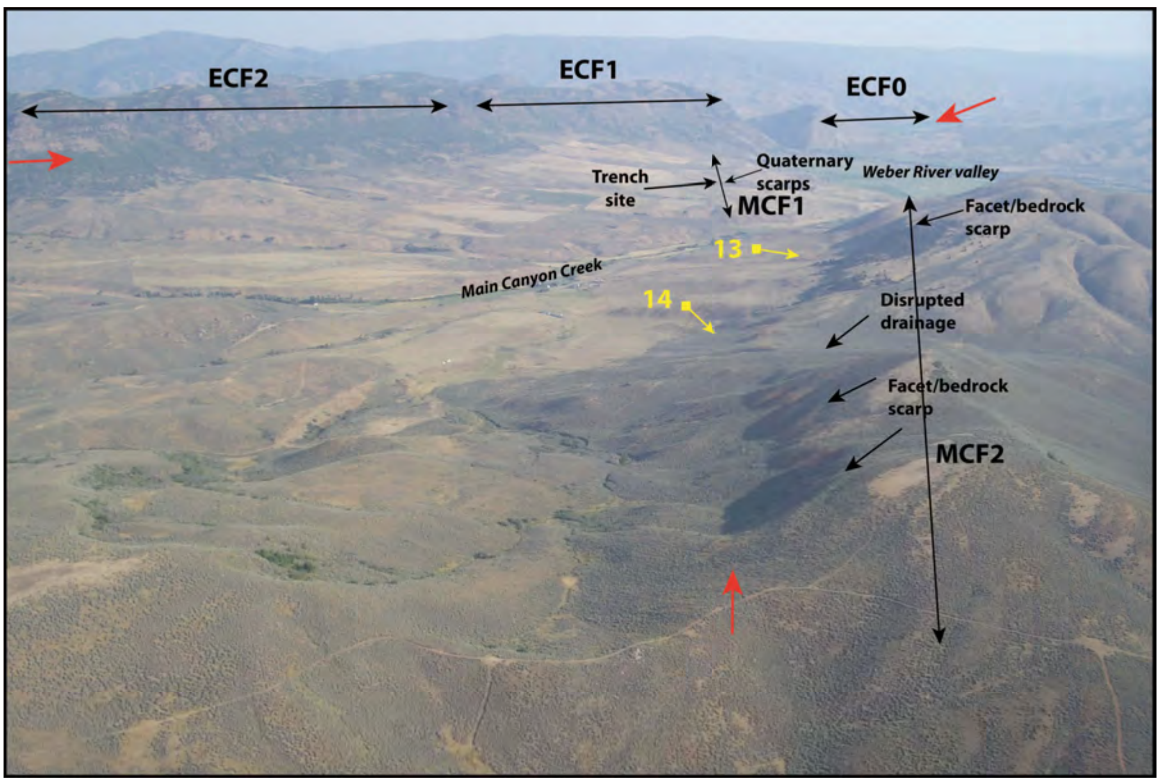

Figure 12. *Oblique aerial photograph of sections MCF1 and MCF2 of the Main Canyon fault and sections ECFO, ECF1, and ECF2 of the East Canyon fault (Figure 4). Photograph taken looking north. Approximate locations of faults shown by red arrows. Locations of Figure 13 and Figure 14 are shown by the yellow arrows. Photograph taken by L.W. Anderson in 2007.*

Figure 13. Facets and bedrock scarp (between red arrows) along section MCF2 of the Main Canyon fault (Figure 12). The facets and scarps are on Tertiary Wasatch Formation on the footwall. Quaternary surfaces are preserved on the hanging wall (middle ground). View is to the east. Photograph taken by D.A. Ostenaa in 2006.

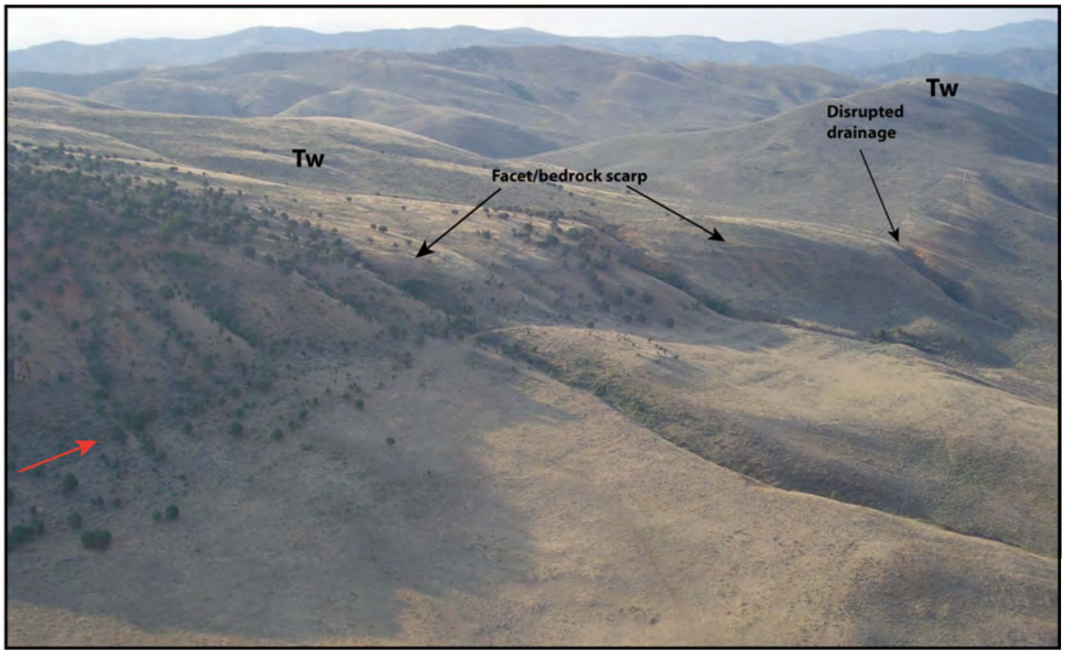

Figure 14. Lineaments, facets, bedrock scarps, and disrupted drainage along section MCF2 of the Main Canyon fault (red arrow) (Figure 12). Facets are in Tertiary Wasatch Formation (Tw) on the footwall. Wasatch Formation is also on the hanging wall. View is to the southeast. Photograph by L.W. Anderson in 2007.

In the next section to the south (**MCF3**), about 3 km long between the drainage divide and the Right Fork of Franklin Canyon, displacements on the fault are upslope facing. The fault is expressed as discontinuous lineaments and saddles across ridges (Figure 4 and Figure 9).

In the next section to the south (**MCF4**), 6 km long between the Right Fork of Franklin Canyon and Taylor Hollow, displacements on the fault are downslope facing. The fault in this section is expressed nearly continuously as west-facing facets or bedrock scarps (Figure 4). The facets/bedrock scarps continue to Taylor Hollow, where the fault appears to bound the east side of a higher alluvial surface preserved along the north side of Taylor

Hollow (Figure 2). However, the alluvial surface does not cross the fault, so it cannot be used to evaluate age of displacement.

In the southernmost section (**MCF5**), about 8.5 km long between Taylor Hollow and near West Fork Schuster Creek, the Main Canyon fault is expressed as discontinuous saddles, lineaments, and linear drainages (Figure 4 and Figure 9). Landslides along and near the fault (most not mapped on Figure 2) complicate an assessment of the geomorphic expression of this section of the fault. The trace of the fault curves to the southwest and intersects the canyon of East Canyon Creek, where a short section of that drainage coincides with the fault. Bryant (1990) does not map the fault south of this point, and no geomorphic expression of the fault was noted to the south.

In summary, definite evidence for late Quaternary surface rupture is present only along the northern about 3.5 km of the fault, where it forms west-facing scarps on alluvial fans that are likely late Quaternary. However, geomorphic expression of the Main Canyon fault is nearly continuous from the Weber River valley to Taylor Hollow, and discontinuous south of this point to near West Fork Schuster Creek.

LATE QUATERNARY SURFACE RUPTURES

As noted above, the only potential fault scarps identified on late Quaternary surfaces in East Canyon valley are along the northern 3.5 km of the Main Canyon fault (section MCF1; Figure 4 and Figure 10). A trench was excavated across one of these scarps to determine if the scarp has a tectonic origin and to estimate the age of any fault displacements. A backhoe trench was excavated across a 70-m-long, 0.4-m-high, west-facing scarp on an alluvial fan that is inset into higher surfaces to the north and south (Figure 10 and Figure 15). The scarp is part of a higher, broader, west-facing slope from one of the remnants of uplifted older alluvium.

Alluvial fans from the escarpment along the East Canyon fault to the west are graded to an elevation below the west-facing scarps along the Main Canyon fault (Figure 10 and Figure 16). Drainages on active alluvial fans are only slightly incised on the hanging wall of the Main Canyon fault (Figure 11). The drainages become markedly more incised on the footwall, which has been uplifted relative to the alluvial fans on the hanging wall. The highest (oldest) remnants preserved between the incised drainages on the footwall are capped by subrounded to rounded, quartzite cobbles and boulders and may be remnants of older Pleistocene alluvial-fan deposits or possibly weathered Tertiary Wasatch Formation.

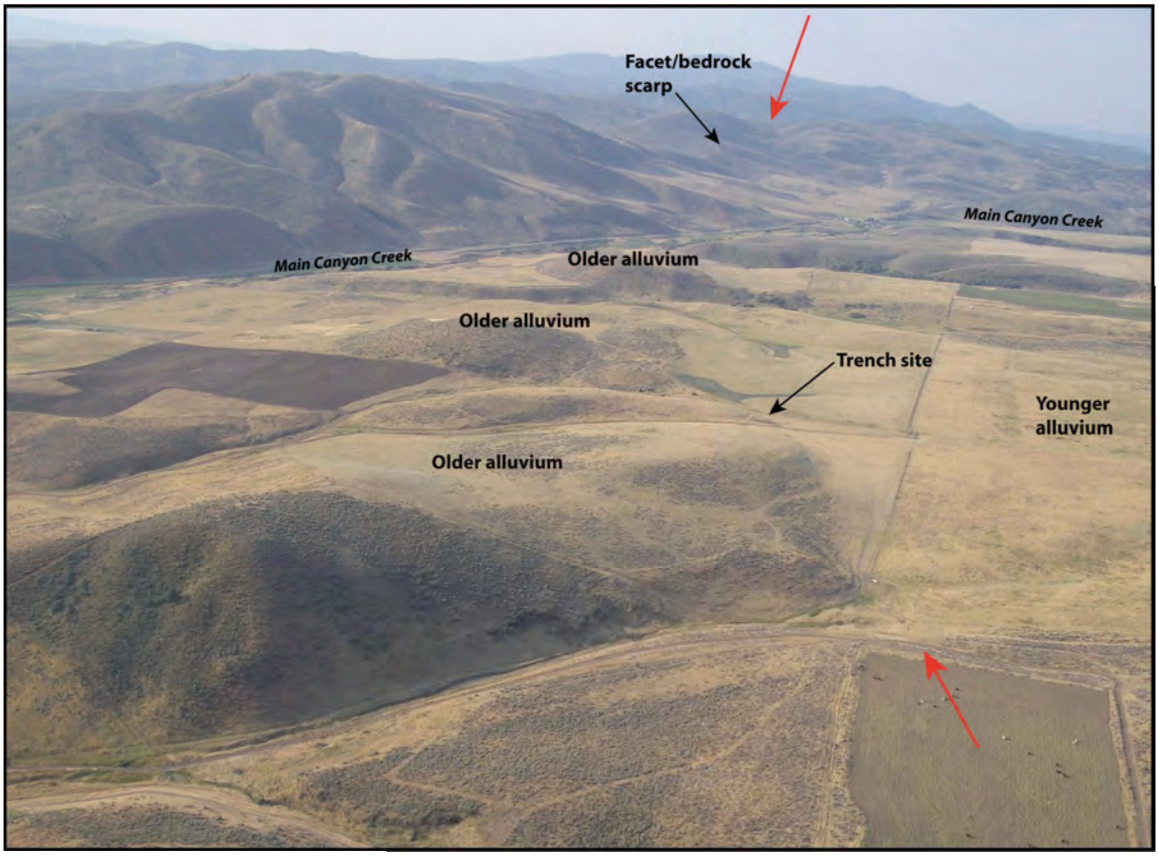

Figure 15. *Oblique aerial photograph looking south along sections MCF1 (foreground) and MCF2 (background) of the Main Canyon fault (Figure 10). Approximate location of the Main Canyon fault indicated by red arrows. West-facing scarps and trench site are along section MCF1. Photograph taken by L.W. Anderson in 2007.*

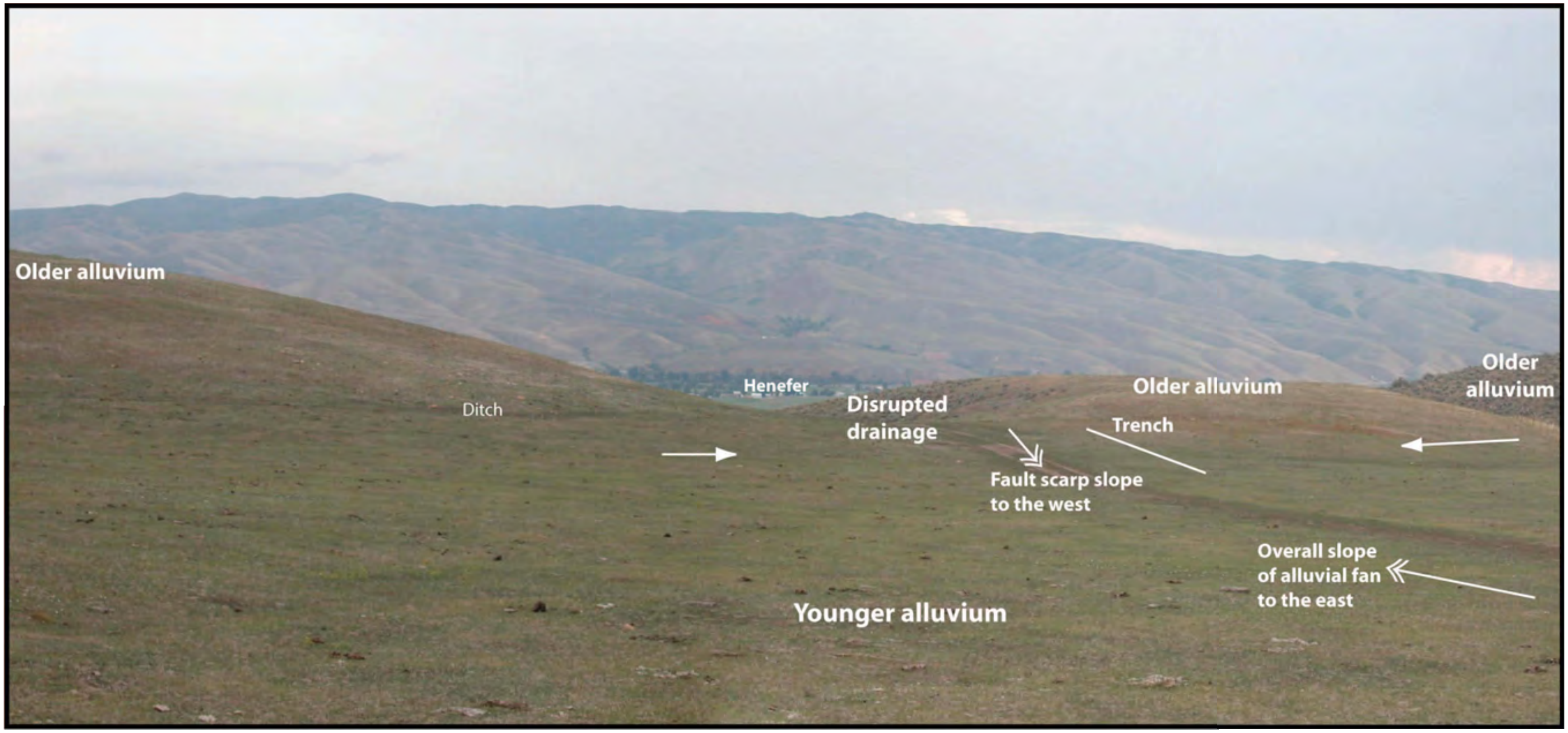

Figure 16. *Geomorphic features in the vicinity of the trench excavated near the north end of the Main Canyon fault. West-facing fault scarp is indicated by solid-headed arrows. Slope of the scarp is shown by the double-headed arrow. The scarp opposes the overall fan slope to the east as shown by the other double-headed arrow. View is to the east.*

The older remnants are shown by Coogan (2002) to be possibly Pleistocene and/or Pliocene alluvium (QTa?; Figure 2). These hills, which are shown as older alluvium on Figure 10, Figure 15, and Figure 16 are about 90 to 120 m above the Weber River valley, and are higher than pre-Bull Lake surfaces reported by Sullivan and others (1988). Their pre-Bull Lake surfaces are between 45 and 70 m above the central Weber River valley and have estimated ages of >200 ka to <500 ka (thousand years), 350 ka to 370 ka, and 440 ka to 470 ka. However, the remnants of older alluvium near the trench site have been uplifted along the Main Canyon fault, and so it is difficult to estimate their original height above the Weber River valley. If late Quaternary displacements on the Main Canyon fault had not occurred, then the alluvial fans should slope more or less evenly to the Weber River to the northeast. The remnants of older alluvium at the trench site are likely at least as old as the pre-Bull Lake surfaces reported by Sullivan and others (1988). It also is possible that the remnants are much older, perhaps on the order of a million years.

West-facing scarps also are present on lower surfaces that appear to be on the order of 30 to 60 m above the valley. The lower elevations of these surfaces relative to the older remnants suggest that the lower surfaces may be remnants of Pleistocene alluvial fans. These remnants are small, and projecting them to the Weber River valley is difficult; however, they may be correlative to the pre-Bull Lake surfaces reported in Sullivan and others (1988). The scarp where the trench was excavated is on one of these surfaces.

Displacements on the Main Canyon fault have flattened the gradients of the east-flowing drainages and small drainages are particularly affected (Appendix A). The drainage immediately north of the trench site has been uplifted to the point that the drainage ponds at the fault and no longer flows to the east through the footwall. Larger drainages appear to be able to adjust to displacements on the fault, and may be affected only temporarily by gradient changes caused by fault displacements.

Although the overall drainage direction is to the east, displacements on the Main Canyon fault form west-facing scarps that create local slopes to the west (Figure 16). At the trench site, colluvium has moved downslope to the west across the scarp. The scarp at the trench site also receives colluvium from the higher scarp preserved to the north of the disrupted drainage. Colluvium has likely filled in the drainage that at one time separated this hill to the north from the trench site after the drainage was disrupted by uplift on the Main Canyon fault. Sediment shed from the slope was no longer removed by the drainage (Figure 16).

Trench Across the Main Canyon Fault

The trench site is on a southwest-facing scarp on a Pleistocene alluvial fan. Younger paludal sediments and alluvium are preserved west of the scarp. The scarp, which is about 0.4 m high and trends about N70°W, aligns with higher scarps to the north and south (Figure 10). The higher scarps are between about 6 and 20 m high. The scarp where the trench was excavated is separated from the higher scarps by drainages.

The maximum slope of the scarp at the trench is about 6° to the southwest. The general slope of the ground surface northeast of the trench is about 2° to the southwest. The ground surface between stations 8 and 13 m is flat or nearly flat. The ground surface southwest of the trench slopes a few degrees to the northeast. Because the scarp faces upslope, overall scarp angle would not vary systematically with scarp age.

A trench about 13 m long and about 2 m wide was excavated across the scarp. The low scarp height and the low scarp angle made it difficult to excavate the trench perpendicular to the trend of the scarp. In addition, the location and strike of the fault associated with the scarp were not well constrained. As a result, the trench as excavated was not perpendicular to the scarp, which trends about N70°W at the trench site (Figure 17). The fault strands that were exposed by the trench strike between N65°W and N85°W.

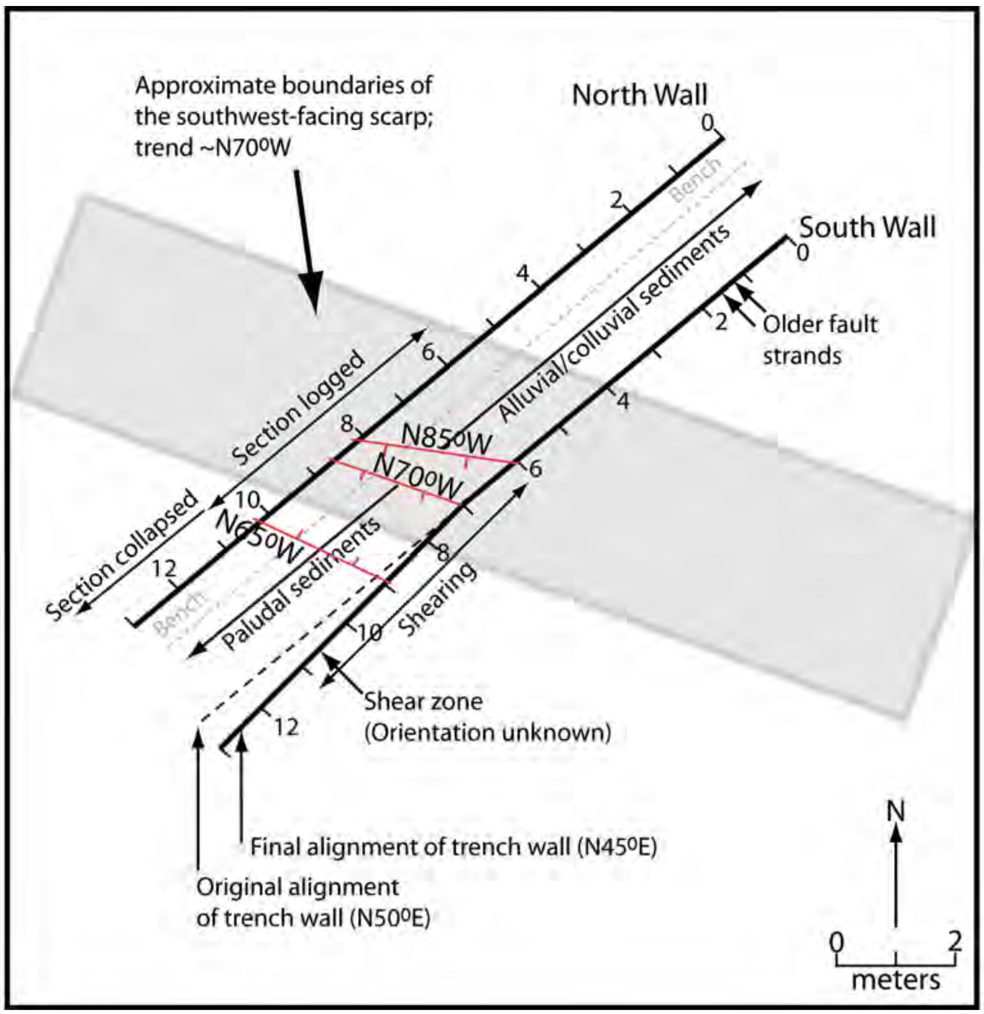

Figure 17. *Sketch map showing the orientation of the trench relative to the west-facing fault scarp (gray box) and the main shears (shown in orange) exposed in the walls of the trench.*

Methods

The south wall of the trench was excavated vertical for logging, and a bench was dug along the north wall for safety.

Once the trench was excavated, the walls were cleaned with picks, small shovels, and trowels. Horizontal and vertical string lines were set to form a meter grid; secondary lines were established in some areas at 0.5 m and 0.25 m intervals in places to make mapping easier. Color digital photographs were taken of each 1-m square. A photo mosaic of each trench wall was constructed in *Adobe PhotoShop*. These photo mosaics were used to map stratigraphic boundaries and fault-related features (Appendix B).

The trench was initially dug with a trend of N50°E (Figure 17). However, before the trench could be logged, an intense storm filled the trench with water to a depth of about 1.5 m, and portions of both walls at the lower end of the trench collapsed. The water was pumped from the trench, and the south wall between stations 7 and 13 m was re-excavated with a backhoe. The trend of the new section of the south wall was N45°E (Figure 17). The new section was cleaned, and the string grid was resurrected and replaced, where necessary. The lower about 1 m of the south wall that was not re-excavated and the north wall between stations 6 and 11 m were re-cleaned to remove the silty deposits that coated the lower walls. The collapsed section of the north wall, between stations 11 and 13 m, was not re-excavated. A preliminary log of the north wall had been made before the collapse, and this was used (Appendix B).

Because the trench intersects the scarp and fault zone at angles less than perpendicular, the fault zone is exposed in the south wall between stations 6 and 9 m, but is exposed in the north wall between stations 8 and 10 m (Figure 17). The strike of the main shear zone is N70°W near the base of the trench exposure, and has an average dip of 81°W. Other distinct shear zones strike N85°W and N65°W, and have average dips between 70°W and 75°W (Figure 17).

Characteristics, Ages, and Tectonic Interpretation of the Stratigraphic Units Exposed in the Trench

Twelve stratigraphic units were identified and mapped in the trench (Figure 18; Appendices B and C). Units are generally labeled oldest to youngest in ascending numerical order. The main fault zone is clearly expressed as a steep southwest-dipping shear zone that juxtaposes alluvial/colluvial units on the footwall and paludal (marsh) deposits on the hanging wall (cover photograph). The units on the hanging wall and footwall were subdivided on the basis of depositional unconformities between the units as indicated by erosion surfaces and/or soil development. The only unit that can be traced across the main fault zone is slope colluvium (unit 12) from the higher slope west of the trench. Because the surface ruptures that created the scarp disrupted small drainages on the alluvial fans and caused local ponding along the scarp for some time after surface rupture occurred, correlative stratigraphic units are not present on opposite sides of the fault. Units on the footwall are primarily slope colluvium and/or alluvium. Units on the hanging wall are primarily paludal deposits, which were deposited in ponded areas that collected loess and fine alluvial sediment from the adjacent low-gradient slopes. At least two mudflow deposits that originated from the adjacent steeper slopes, probably from the hill north of the trench site, are exposed in the trench. One mudflow deposit fills a channel on the footwall (unit 8); the other is on the hanging wall and fills the graben along the scarp (unit 10). The relation between these two deposits cannot be determined directly from the trench exposures. Better soil development on unit 8 suggests that it is older than unit 10.

Ages for the units exposed in the trench were determined from luminescence analyses on nine samples and radiocarbon analysis on one sample (Appendix D). Ages obtained from these methods are supported by the degree of soil development observed in the trench exposure. Soil development was used to estimate the ages of the oldest units, which yielded maximum values from luminescence analyses. Soil development was generally compared to descriptions by Sullivan and others (1988) for dated Quaternary deposits in other valleys in the northern Wasatch Range. The nine samples collected for luminescence analyses were submitted to the Luminescence Dating Laboratory at the U.S. Geological Survey, Denver, Colorado, for analyses (Appendix E). Eight bulk sediment samples were collected and submitted to Paleo Research Institute, Golden, Colorado, for cleaning, examination, and analyses (Appendix F). Only one sample (ECT-C8) yielded enough charcoal for an accelerator mass spectrometry (AMS) age. This sample was sent to the Keck Carbon Cycle AMS Facility at the University of California, Irvine, for analysis (Appendix F).

Dark, rounded pellets with diameters of about 1 mm are common to abundant in most of the paludal deposits exposed on the hanging wall. The pellets were extracted from the bulk sediment samples collected for possible radiocarbon dating and were examined by Paleo Research. They concluded that the pellets are asphaltum and the results from a Fourier Transform infrared spectrometry analysis matched most closely those of man-made asphalt (Appendix G). Additional analyses were recommended. Asphaltum pellets from one sample (ECT-C7) from unit 6 were submitted to Humble Instruments & Services for additional analyses (Appendix G). Results from chromatography and spectrometry indicate that the asphaltum from the trench is not from processed (man-made) hydrocarbons, but is probably from some type of natural oil seep associated with Cretaceous marine or lacustrine rocks and could be from the Wasatch Formation, which is a known oil reservoir. The asphaltum from the trench does not appear to be from gilsonite deposits that are present in northeastern Utah, which would indicate a significant transport distance for the deposits.

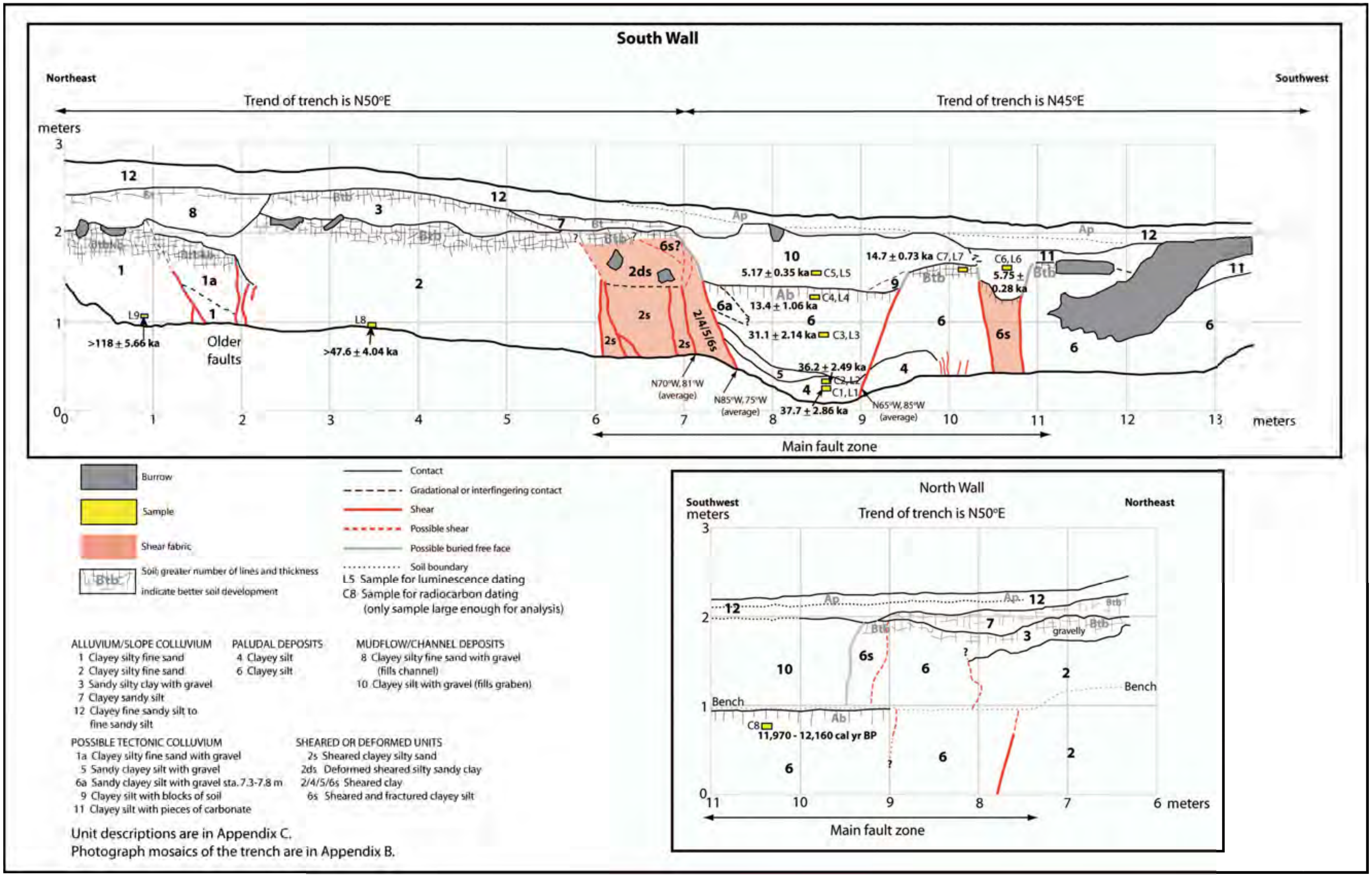

Figure 18. *Interpreted log of the trench excavated near the north end of the Main Canyon fault.*

Units 1, 1a, and 2

The oldest unit in the trench (unit 1) is alluvium and/or colluvium (Figure 18; Appendices B and C). Distal sediment in this unit may have come from two different directions: either deposited as alluvial fans from the escarpment to the west or as colluvium from the higher fan remnant to the east. The unit is clayey, silty fine sand with a few percent of gravel, either scattered through the deposit or in lenses. The deposit was probably clay-rich initially. Regardless, thick clay films, strong prismatic structure, and stage III carbonate on which the clay films are overprinted suggest that the deposit is quite old, and has undergone several cycles of soil formation and disintegration. A luminescence date for sample L9 of greater than 118,000 $\pm$ 5660 years is likely a minimum age (Table 1; Appendix E), because of the problems in applying optically stimulated luminescence (OSL) dating to sediment with strong soil development. The soil development suggests that the deposit is at least several hundred thousand years old (Sullivan and others, 1988), and may be as old as 1 to 2 million years. Carbonate-filled shear zones between stations 1 and 2 m indicate faulting event(s) older than the ones associated with the main fault zone between stations 6 and 11 m.

Unit 1 is displaced near station 2 m against the next oldest unit (unit 2), which has characteristics similar to those of unit 1, and probably has a similar origin. The degree of soil development in unit 2 is much less than that in unit 1 (Appendices B and C). The soil on unit 2 has prominent clay films and is red, but it lacks carbonate and evidence for polycyclic formation that are present in unit 1. A luminescence date from unit 2 near the base of the trench (sample L8) yielded an age of greater than 47,600 $\pm$ 4040 years (Table 1; Appendix E), which is likely a minimum because of the problems in applying OSL dating to sediment with strong soil development. Thick red argillic horizons with strongly developed soil structure were interpreted by Sullivan and others (1988) to be correlative with the Bull Lake glaciation, and date from about 60 ka-70 ka to about 130 ka-140 ka. This age range is consistent with the luminescence date.

Unit 1a may be a tectonic colluvial wedge derived from unit 1 due to a faulting event that displaced units 1 and 2. Unit 1a is similar to unit 1, but has slightly more gravel (Appendix C). We interpret unit 1a to be a colluvial wedge on the basis of the gravel content, its limited extent and wedge shape, and its position just downslope of a carbonate-filled shear zone (Figure 18; Appendices B and C).

Table 1. *Quartz blue-light OSL ages from trench across Main Canyon fault (Mahan, 2007 [Appendix E]).*

Sample information expected age: stratum	% Water content[a]	K (%)[b]	Th (ppm)[b]	U (ppm)[b]	Cosmic dose[c] additions (Gy/ka)	Total Dose Rate (Gy/ka)	Equivalent Dose (Gy)	n[d]	Age (ka)
ECT-L5	5 (48)	2.27 ± 0.11	12.5 ± 0.33	3.58 ± 0.13	0.26 ± 0.02	3.59 ± 0.07	18.6 ± 1.22	22 (30)	5.17 ± 0.35[e]
post MRE sediments (youngest?)									
ECT-L6	13 (57)	3.23 ± 0.06	12.1 ± 0.33	3.30 ± 0.12	0.27 ± 0.02	4.28 ± 0.07	24.6 ± 1.15	29 (35)	5.75 ± 0.28[e]
ECT-L4	9 (74)	2.15 ± 0.07	12.5 ± 0.32	3.47 ± 0.12	0.26 ± 0.02	3.31 ± 0.06	44.3 ± 1.94	24 (28)	13.4 ± 1.06[e]
sediment buried by MRE									
ECT-L7	10 (54)	1.62 ± 0.14	11.3 ± 0.27	2.54 ± 0.11	0.26 ± 0.02	2.78 ± 0.06	40.9 ± 3.11	27 (35)	14.7 ± 0.73[e]
ECT-L3	9 (68)	1.82 ± 0.12	12.0 ± 0.27	3.23 ± 0.12	0.25 ± 0.02	2.98 ± 0.05	92.6 ± 2.18	30 (37)	31.1 ± 2.14[e]
"Event 1" sediment wedge									
ECT-L2	13 (58)	1.50 ± 0.05	11.3 ± 0.29	3.16 ± 0.11	0.23 ± 0.02	2.65 ± 0.05	96.0 ± 6.21	8 (20)	36.2 ± 2.49[f]
pre-Event 1 sed/soil									
ECT-L1	15 (51)	1.36 ± 0.06	10.8 ± 0.27	2.55 ± 0.10	0.21 ± 0.02	2.50 ± 0.04	94.2 ± 2.36	15 (15)	37.7 ± 2.86[f]
pre-Event 1 sed									
ECT-L8	7 (51)	1.56 ± 0.14	11.1 ± 0.23	2.38 ± 0.11	0.24 ± 0.02	2.67 ± 0.05	>127 ± 5.02	16 (29)	>47.6 ± 4.04[e]
older, weathered, Bt soil development									
ECT-L9	7 (34)	1.68 ± 0.09	11.0 ± 0.24	2.80 ± 0.10	0.24 ± 0.02	2.84 ± 0.05	>334 ± 8.34	21 (24)	>118 ± 5.66[e]
oldest, stage III carbonate soil, reddened									

[a]Moisture value used in calculation of age (usually 45% of total saturation, except ECT-9 which was 60%). Figures in parentheses indicate the complete sample saturation %.

[b]Analyses obtained using laboratory Gamma Spectrometry (low resolution NaI).

[c] Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Stephans (1982) and Prescott and Hutton (1994). See Appendix E for details and references.

[d]Number of replicated equivalent dose (De) estimates used to calculate the mean. Figures in parentheses indicate total number of measurements made including failed runs with unusable data.

[e]Dose rate and age for fine-grained 90-125 µm quartz sand. Linear and exponential fit used on age, errors to one sigma.

[f]Dose rate and age for fine-grained 90-250 µm quartz sand. Exponential fit used on age, errors to one sigma.

Unit 3

Unit 3 was deposited on unit 2 after a period of erosion. Unit 3 is gravelly slope colluvium and contains more gravel than the older, underlying units. The gravel is likely from the gravel deposit upslope because of its high percentage of quartzite stones that are also present in the gravel deposit upslope. Soil development, while still relatively strong, is much less than the soils developed in units 1 and 2. The soil in unit 3 has thick, dark clay films, and strong blocky structure. Pedogenic carbonate is absent. This soil is similar to those described by Sullivan and others (1988) for deposits from about 60 ka-70 ka to about 130 ka-140 ka. Unit 3 does not intersect any tectonic features.

Unit 4

Unit 4, which is preserved within the main fault zone, is the oldest paludal (or marsh) deposit exposed in the trench. The unit is massive, brown clayey silt with about 1 percent gravel. The unit has stage II+ carbonate, which includes irregularly shaped, elongated nodules that are oriented horizontally or subhorizontally. Two luminescence dates (samples L1 and L2) from this unit yielded ages of 37,700 $\pm$ 2860 years and 36,200 $\pm$ 2490 years (Table 1; Figure 18; Appendix E). Because the marsh was likely present due to ponding against a fault scarp, displacement on the fault zone would have occurred before this time. The base of unit 4 was not exposed in the trench, so its total thickness is not known. The presence of a marsh along the scarp suggests that the drainages from the escarpment to the west were not through going at this location at the time. This implies that displacement on the Main Canyon fault had uplifted the drainages enough so that flow to the northeast was disrupted on the smaller drainages.

Unit 5

Unit 5 is a reddish, 0.1-m-thick bed with about 5 percent gravel just below unit 6 between stations 7.5 and 8.5 m on the south wall. On the basis of its position adjacent to the fault zone, gravel content, and wedge shape, unit 5 is interpreted to be scarp-derived colluvium. Unit 5 would have been deposited just after the earthquake that created the topographic low that became the marsh into which unit 6 was deposited.

Units 6 and 6a

Unit 6 includes paludal deposits, which are up to 0.7 meters thick in the trench, but their base is not exposed so their total thickness is not known. The unit is massive, brown clayey silt with about 1 percent gravel. The unit is present both within the fault zone between stations 7 and 11 m, and west of the fault zone (stations 11 to 13 m). A higher gravel content (5 to 10 percent), gravel clasts oriented with a slope to the southwest, and wedge shape suggest that some of unit 6 near the fault zone may be scarp-derived colluvium. This sediment is designated unit 6a. A luminescence date (sample L3) from a depth of about 1 m in unit 6 yielded an age of 31,100 $\pm$ 2140 years, slightly younger than the dates from underlying unit 4 (Table 1; Appendix E). The scarp-derived colluvium (unit 5) just below unit 6 suggests that an unconformity is present between units 4 and 6, although the time represented may be only a few thousand years. The faulting event that resulted in deposition of scarp colluvium (unit 5) and created the marsh into which unit 6 was deposited occurred between 36,200 ± 2490 years and 31,100 ± 2140 years, the bracketing ages from units 4 and 6.

Two luminescence samples (L4 and L7) near the top of unit 6, one near station 8.5 m and one near station 10.2 m, yielded ages of 13,400 ± 1060 years (L4) and 14,700 ± 730 years (L7). A radiocarbon age of 11,970 to 12,160 cal years BP (L8; Appendix F) from the north wall is consistent with the luminescence ages. The difference in the ages from samples separated by about 0.3 m vertically on the south wall suggests that it took several tens of thousands of years for the fine sediment (alluvial and eolian) to accumulate in the marsh created by displacement on the fault about 30 ka to 38 ka. Unit 6 within the graben has an A horizon developed in it. Unit 6 outside of the graben has a Bt horizon. The difference in soil development may be the result of different landscape positions once a portion of unit 6 was downdropped into the graben. This area would have been wetter and received a greater influx of finer sediment than the portion of unit 6 outside of the graben. Unit 6 is displaced along several shears within the broad shear zone between stations 7 and 11 m.

Unit 7

Unit 7 is slope colluvium that has a stone line with about 30 percent gravel at its base. The rest of the unit has about 15 percent gravel. The unit has characteristics similar to those of unit 3, and likely has a similar source. The stratigraphic relation, the stronger soil developed in unit 3, and the stone line at the base of unit 7 suggest an unconformity between units 3 and 7. Unit 7 overlies sheared blocks of unit 2 between stations 6 and 7 m, and does not appear to be displaced. On the north wall, slope colluvium with similar characteristics (e.g., 25 percent gravel, Bt soil horizon) is present between stations 6 and 9 m. The slope colluvium on the north wall also overlies the east end of the main fault zone, as does unit 7 exposed on the south wall. For these reasons, the slope colluvium on the north wall is tentatively correlated with unit 7.

Unit 8

Unit 8 is on the footwall only, between stations 0 and 2 m on the south wall. (The area where this unit would be present on the north wall was destroyed during the initial excavation.) This unit is a mudflow deposit of clayey, silty fine sand with up to 5 percent gravel. It appears to fill a channel. An argillic (Bt) horizon has formed in the unit and has moderately thick clay films and strong, medium blocky structure. The soil is less developed than the soils in the older units on the footwall.

Unit 9

Unit 9 is a 0.3-m-thick, wedge-shaped unit between stations 9 and 9.5 m on the south wall. This unit contains blocks of soil that appear to be rotated. On the basis of its position adjacent to a fault zone, blocks of soil, and wedge shape, unit 9 is interpreted to be scarp-derived colluvium. Unit 9 would have been deposited just after the faulting event that downdropped unit 6 and created the graben into which unit 10 was deposited.

Unit 10

Unit 10 is a mudflow deposit that is visible in both trench walls. It is massive clayey silt with up to 5 percent gravel that is dispersed throughout the unit without stratification or bedding. The unit is thickest within the graben, where it is about 0.6 m thick. Soil on unit 10 has an A horizon only. Pedogenic carbonate is not present. A luminescence (L5) from near the base of the unit at a depth of 0.7 m yielded an age of 5170 $\pm$ 350 years (Table 1; Figure 18). Unit 10 buries unit 6 in the graben. The burial is likely the result of a tectonic event on the fault that created a new scarp or enhanced a preexisting one and downdropped unit 6. The soil developed on this part of unit 6 is a dark A horizon that contains more silt in its upper 30 cm than in the rest of the soil. Because unit 6 within the graben was buried by unit 10, the soil on this part of unit 6 is less developed than the soil developed on unit 6 between stations 9.5 and 10 m, an area outside of the graben (Figure 18). The luminescence age from unit 10 indicates that the earthquake that displaced unit 6 and created the graben in which unit 10 was deposited occurred before 5170 $\pm$ 350 years. The luminescence ages from the upper part of unit 6 suggest that this displacement occurred after 13,400 $\pm$ 1060 years and 14,700 $\pm$ 730 years, the ages from the upper part of unit 6.

Unit 11

Unit 11 is gray clayey silt with about 1 percent gravel that is visible on the south wall between stations 10.5 and 13 m. Between stations 10.5 and 11.75 m, the unit contains small pieces (<1 mm) of carbonate that appear to have been eroded from unit 6. Unit 11 was deposited above a 0.5-m-wide shear zone in which unit 6 had been downdropped. The pieces of carbonate indicate that erosion of free faces above the bounding faults in this small shear zone provided some of the material for unit 11. We interpret unit 11 to be fine-grained, scarp-derived colluvium on the basis of its geometry, relation to the adjacent free faces, and sedimentological properties. The unit has an A horizon only; no pedogenic carbonate was visible in the unit. A luminescence sample at a depth of about 0.6 ms within the unit near station 10.5 m yielded an age of 5750 $\pm$ 280 years (L6; Table 1; Figure 18). The relation between unit 11 and unit 10, the similar characteristics of the two units, their relations to the shear zones, the lack of a marked contact between the two units, and the luminescence ages suggest that the units are correlative in age.

Unit 12

Unit 12 is slope colluvium that is present along the length of the trench. Its texture varies from clayey, fine sandy silt between stations 0 and 7 m to fine sandy silt between stations 7 and 13 m. Gravel content is highest, up to 10 percent, between stations 0 and 7 m. Unit 12 is sediment that has eroded from the higher slope of the hill to the east of the trench since the last faulting event. The gravel content decreases near station 7 m at a point that coincides with a decrease in large boulders on the ground surface. The unit does not have any visible soil development other than an Ap (plow) horizon along most of the trench. The unit is present in both the south and north walls, and it overlies all of the other units in the trench. The unit is not visibly offset along the shear zone, and the unit does not markedly thicken across the shear zone.

Sequence of Faulting, Deposition, and Erosion

Figure 19 is a schematic drawing of the how the trench site may have looked at times during the sequence of events that deposited and displaced the exposed units. Brief descriptions of these events are given below.

Older than 38,000 years ago (could be as long ago as 1 million to 2 million years) (Figure 19A)
(Before the two most-recent surface-faulting earthquakes on the main fault zone)

Unit 1 is deposited, probably as alluvial-fan deposits from the escarpment along the East Canyon fault to the west of the trench site.

Recurrent fault ruptures likely occur, and eventually the toes of the alluvial fans are uplifted and older alluvial-fan deposits or Wasatch Formation is exposed on the footwall of the Main Canyon fault. The only direct evidence of fault displacement during this time is a zone of shears between stations 1 and 1.5 m and a possible tectonic colluvial wedge downslope of one shear (unit 1a).

Soil develops on unit 1 (and 1a) during several climatic cycles.

Fault displacement on a shear near station 2 m offsets the tectonic colluvial wedge (unit 1a) against unit 2, alluvial-fan deposits from the west or colluvium from the scarp or slope to the east.

Soil develops on unit 2.

If the tectonic ruptures formed marshy (or ponded) areas west of the fault scarp as they did in later events, there is no evidence for them in this part of the trench. The lack of ponded sediment may indicate that the uplift along the Main Canyon fault had not yet been enough to strand (reverse or disrupt) the drainages flowing to the northeast toward the Weber River from the escarpment along the East Canyon fault. This could imply that displacement on the Main Canyon fault was initiated during the late Quaternary, or possibly the middle Quaternary.

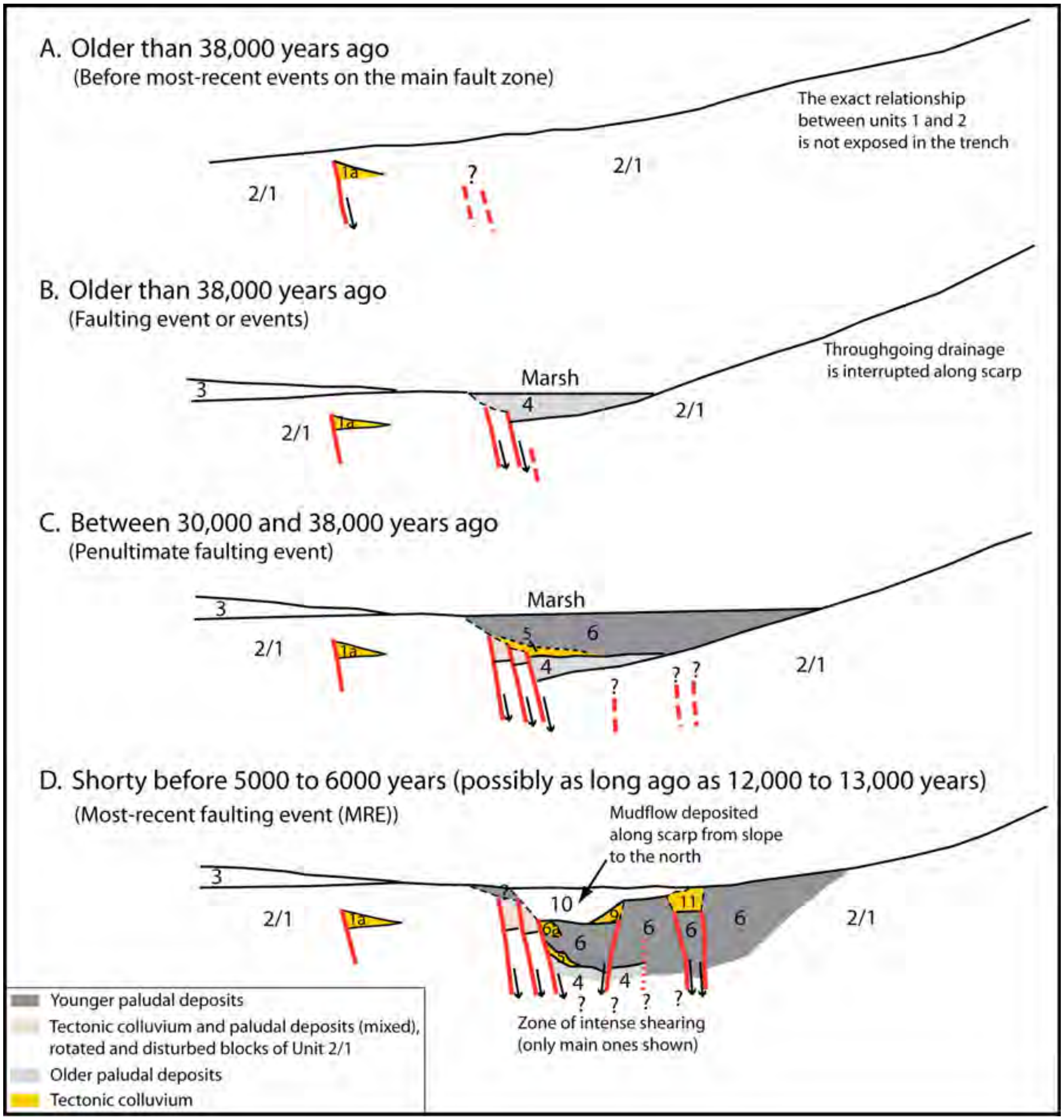

Figure 19. *Schematic drawing (looking south) of possible sequence of events interpreted from the trench exposure. Dashed red lines indicate the locations of fault strands with future displacements.*

Older than 38,000 years ago (Figure 19B)
(Faulting event or events)

At least one, and more likely several, fault displacements occur on shears between stations 6 and 7.5 m.

Displacements shear and disrupt unit 2.

The youngest of these ruptures blocks drainage from the west, and a marsh forms along the scarp. (Marshes may have formed during older faulting events, but we do not have direct evidence for this exposed in the trench.)

Unit 4 is deposited as fine sediment from the adjacent slopes washes into the marsh and as loess (eolian silt and fine sand) settles into the marsh.

As the marsh fills with sediment, it is repeatedly wetted and dried. The soil development suggests that this area on the hanging wall was not subaerial for any length of time. The soil consists primarily of carbonate that is concentrated into irregularly shaped nodules.

Unit 4 may have buried or nearly buried the scarp.

The upper part of unit 2 is eroded between stations 2 and 7 m. Unit 3 is deposited as slope colluvium from the higher remnant to the east on the footwall.

Between about 30,000 and 38,000 years ago (Figure 19C)
(Penultimate surface-faulting earthquake)

Fault displacement on at least one of the shears between stations 7 and 7.5 m.
Displacement also may have occurred on other shears.
Unit 4 is displaced.

Deposition and erosion after faulting event.

Unit 5 is deposited as tectonic colluvium through erosion of the west-facing scarp (primarily from unit 2) that formed during the faulting event.

The west-facing scarp that formed during the event blocks east-flowing drainage, and a marsh forms along the scarp.

Unit 6 is deposited in the marsh through a combination of alluvial and eolian processes. Based on the relative extent of the units exposed in the trench, the marsh when unit 6 was deposited may have been larger than the marsh when unit 4 was deposited. However, it may be that the shapes of the two marshes differed, but this cannot be resolved by the two-dimensional trench exposure.

As the marsh fills with sediment, a cumulic soil develops in unit 6.

The soil development suggests that the area was probably subaerial, but still wet at least at times.

Shortly before about 5000 to 6000 years ago, possibly 12,000 to 15,000 years ago (Figure 19D)
(Most-recent surface-faulting earthquake, MRE)

Fault displacement on the shears between stations 7 and 11 m.

Unit 6 is displaced in a graben between stations 7.5 and 9 m.
Graben is bounded by scarps that formed during the faulting event.

Shortly after the scarps formed, unit 9 is deposited at the base of a scarp near station 9 m as the scarp degrades. Soon afterwards, a mudflow (unit 10), possibly from the relatively steep slope to the north of the trench site, fills the graben and buries unit 9 and the downdropped portion of unit 6. Unstable slopes created by the surface faulting may have contributed to the occurrence and size of the mudflow. The mudflow may have occurred before scarp-derived colluvium was deposited along the scarp at station 7.5 m, or any scarp-derived colluvium at this location may have been incorporated into the mudflow deposit.

Soil development changes and slows on the portion of unit 6 within the graben once the unit is buried and in a different landscape position.

Soil development continues on the portion of unit 6 west of the graben (stations 9.5 to 13 m). This portion of unit 6 remains near the ground surface.

A fault zone between stations 10.5 and 11 m also has displacement, and unit 6 is also sheared and downdropped here.

Unit 11 is deposited between stations 10.5 and 12 m as scarp-derived colluvium. Pieces of carbonate that appear to be from the soil developed in unit 6 are incorporated into unit 11.

This faulting event, the MRE, likely occurred shortly before 5 ka to 6 ka, the ages from near the base of units 10 and 11 that fill the graben formed during this event. Unit 10 is interpreted to be a mudflow deposit that was deposited relatively quickly. The buried A horizon in the upper part of unit 6 in the graben and the sharp contact between units 6 and 10 support this interpretation. If unit 10 accumulated slowly, then a cumulic soil would have formed and incorporated any soil developed in unit 6. However, it is possible that the MRE could be closer to the maximum bracketing age (12,000 to 15,000 years).

At some point, a channel is cut into units 2 and 3 between stations 0 and 2 m. The channel fills with a mudflow deposit (unit 8). This mudflow likely originated on the higher slope north of the trench. The soil developed on unit 8 suggests that some time interval elapsed between the deposition of unit 8 and the deposition of unit 12.

Since about 5000 and 6000 years ago
(Not shown on Figure 19)

Once units 10 and 11 are deposited, soils begin to develop on them.

As part of the scarp degradation processes and continued slope processes, slope colluvium (unit 12) is deposited across the scarp. Unit 12 is likely the material that continuously moves down this slope.

Soil develops on unit 12.

Plowing has disturbed the upper few centimeters of unit 12.

CONCLUSIONS

Exposures in the trench confirm that the scarps along the northern Main Canyon fault have a tectonic origin, and were likely formed by recurrent surface-faulting earthquakes. Stratigraphic units, ages, and tectonic events interpreted from the trench are summarized in Figure 20. Dating of faulted and unfaulted deposits exposed in the trench suggests that two surface-rupturing earthquakes have occurred since about 30,000 to 38,000 years ago. The MRE likely occurred shortly before 5000 to 6000 years ago, but could be as old as 12,000 to 15,000 years. Characteristics of the sediment filling the graben and a distinct, buried A horizon preserved on unit 6 beneath the graben fill (unit 10) suggest that this earthquake occurred closer to the minimum bracketing age than to the maximum bracketing age. The orientation of the fault and its sense of displacement relative to the landscape resulted in fault scarps that face upslope. When scarps formed, the generally east-flowing drainages were blocked at least temporarily, and fine alluvial and eolian sediments were trapped in the resulting ponds and marshes. Consequently, the alluvial-fan and colluvial deposits that are preserved on the footwall were not exposed in the trench on the hanging wall, and neither the amount of offset nor a slip rate could be estimated. The penultimate faulting earthquake occurred between about 30,000 and 38,000 years ago, when a marsh also formed in response to scarp formation. Evidence for older surface-faulting earthquakes (older than 38,000 years ago) on the Main Canyon fault is present in the trench, but the timing of these events could not be estimated with any accuracy from the available exposures.

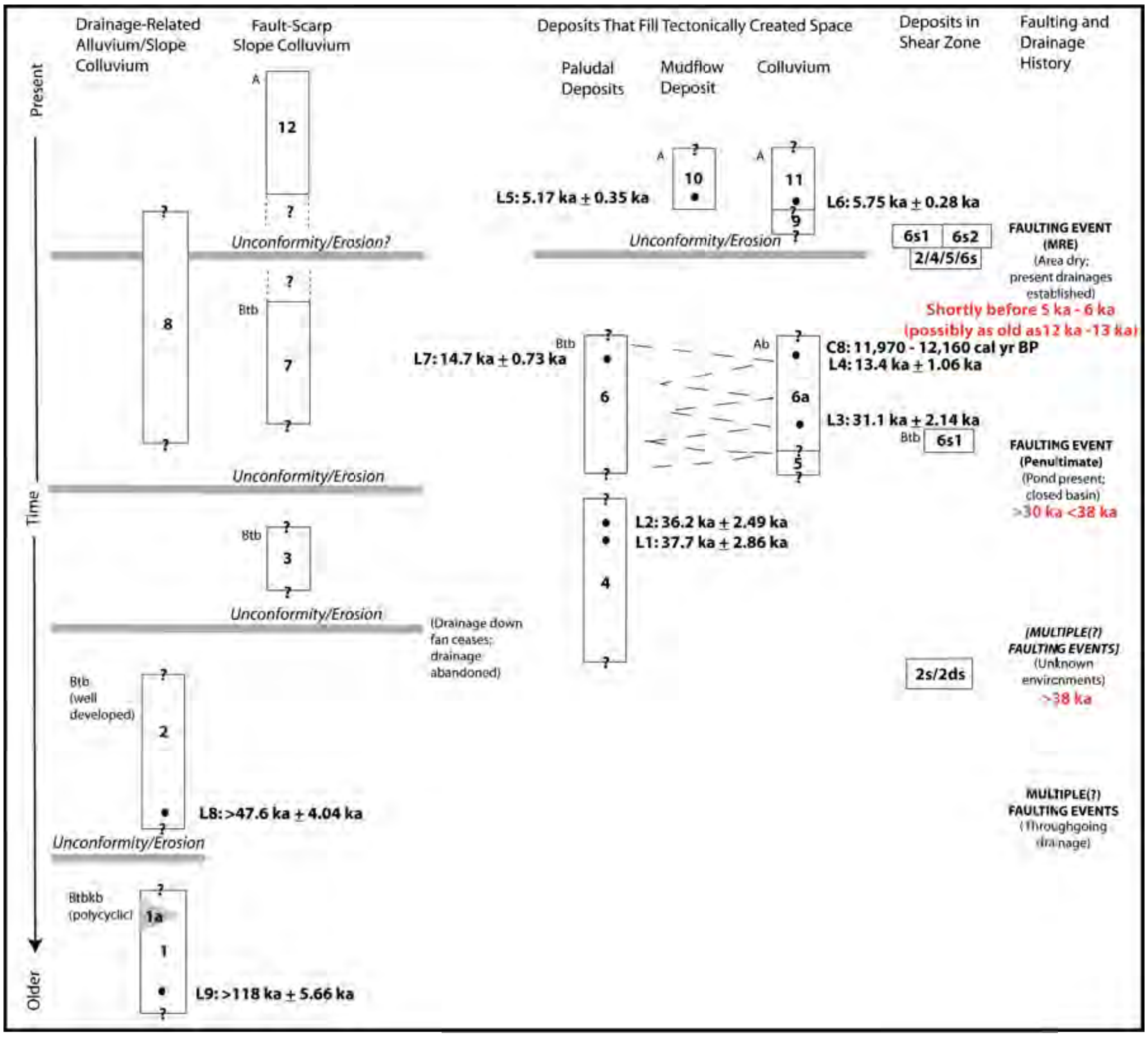

Figure 20. *Stratigraphic units, ages, and tectonic events interpreted from the trench excavated near the north end of the Main Canyon fault.*

The geomorphic expression of the Main Canyon fault is consistent with the faulting history interpreted from the trench exposure. Although late Quaternary tectonic scarps have been recognized only at the north end of the fault, between Main Canyon and the Weber River valley, facets or bedrock scarps, saddles, and lineaments are present nearly continuously to Taylor Hollow, a distance of at least 20 km. The fault cuts across topography, and its geomorphic expression varies depending upon whether the offsets face upslope or downslope. The geomorphic expression of the southern about 6 km of the Main Canyon fault (south of Taylor Hollow) is more discontinuous than it is to the north, but is still present. Thus, the total length of late Quaternary rupture could be as long as 26 km. The lack of an escarpment or a late Cenozoic basin along the fault suggests that the fault did not experience surface ruptures during the entire Cenozoic, but has only been recently active.

The geomorphic expression of the East Canyon fault is quite different than that of the Main Canyon fault. The East Canyon fault has produced an eroded escarpment in resistant rocks at its north end, and facets/bedrock scarps along about 26 km of the fault. No obvious scarps on late Quaternary or Quaternary deposits have been observed associated with the East Canyon fault, in contrast to the Main Canyon fault. This expression, along with the pattern of Tertiary rocks preserved in East Canyon valley, suggests that displacements occurred earlier on the East Canyon fault than on the Main Canyon fault, beginning some time before the Norwood Tuff was deposited during the Oligocene and continuing for some time thereafter. The lack of evidence for late Quaternary or Quaternary activity associated with the East Canyon fault suggests that such activity has not occurred or has occurred at only a very low rate.

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Matt Jones (BOR Seismotectonic and Geophysics Group) generated hillshades for the East Canyon valley study area by obtaining images from the U.S. Geological Survey (USGS) National Aerial Photography Program (NAPP) along with camera calibration files. He then obtained ground control by finding features visible on the aerial photographs, going to the area, and recording GPS coordinates of the control locations. With this information, he was then able to run an aerotriangulation solution in a photogrammetry system and generate a grid across the study region. The NAPP photographs provided a standardized set of cloud-free aerial photographs. The photographs for the East Canyon area were acquired from a flight at an altitude of 20,000 feet in September and October 1997.

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