PALEOSEISMOLOGY OF UTAH, VOLUME 10

POST-BONNEVILLE PALEOEARTHQUAKE CHRONOLOGY OF THE SALT LAKE CITY SEGMENT, WASATCH FAULT ZONE, FROM THE 1999 "MEGATRENCH" SITE

by

James P. McCalpin, GEO-HAZ Consulting, Inc., Crestone, Colorado

MISCELLANEOUS PUBLICATION 02-7
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources
2002

UTAH GEOLOGICAL SURVEY

J.P. McCalpin
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Cover: photograph by James McCalpin
of megatrench looking from toe to head

ISBN 1-55791-670-5
UTAH GEOLOGICAL SURVEY
Miscellaneous Publication 02-7
2002

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Paleoseismology of Utah, Volume 10

FOREWORD

This Utah Geological Survey Miscellaneous Publication, *Post-Bonneville Paleoearthquake Chronology of the Salt Lake City Segment, Wasatch Fault Zone, from the 1999 Megatrench Site*, is the tenth 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 on paleoearthquake parameters such as timing, recurrence, displacement, slip rate, and fault geometry, which can be used to characterize potential seismic sources and evaluate the long-term seismic hazard presented by Utah's Quaternary faults.

This report presents the results of a paleoseismic investigation designed to date a long series of consecutive earthquakes on the Wasatch fault zone and to measure the variability of recurrence times between the events. Geologists have long recognized that the comparatively short average recurrence interval (compared to most other basin-and-range normal faults) between large surface-faulting earthquakes on the Salt Lake City segment of the Wasatch fault zone during mid- to late-Holocene time is potentially anomalous, and possibly affected by the rise and fall of Lake Bonneville. This study extends the paleoearthquake record back to Bonneville time (approximately 15,000 years before present), nearly doubling the previous record, and provides new information on the timing and periodicity of surface faulting on the Salt Lake City segment from the latest Pleistocene through the Holocene. The trench and accompanying auger hole for this study exposed 26 meters of vertical section, roughly four times that of a typical paleoseismic trench on the Wasatch fault zone, hence the name "Megatrench."

Dr. James P. McCalpin, GEO-HAZ Consulting, Inc., conducted the megatrench study with funding received through the U.S. Geological Survey National Earthquake Hazard Reduction Program (NEHRP). Geologists from the Utah Geological Survey assisted with trench logging. This study was first released in 1999 as a NEHRP Final Technical Report. The Utah Geological Survey appreciates the opportunity to work with Dr. McCalpin to make the results of this important paleoseismic investigation more readily available to the user community.

William R. Lund, Editor
Paleoseismology of Utah Series

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POST-BONNEVILLE PALEOEARTHQUAKE CHRONOLOGY OF THE SALT LAKE CITY SEGMENT, WASATCH FAULT ZONE, FROM THE 1999 MEGATRENCH SITE

James P. McCalpin, GEO-HAZ Consulting, Inc., Crestone, CO 81131

ABSTRACT

The Wasatch fault "megatrench" was excavated in September 1999 across two fault scarps totaling 18 meters high on the Salt Lake City segment of the Wasatch fault zone (WFZ). The purpose of the megatrench was to date a long series of consecutive earthquakes (8-12 events?) on the WFZ and measure the variability of recurrence times between the events. This variability could then be used in calculating the future probability of large earthquakes on the WFZ.

The trench was located 1 kilometer north of the mouth of Little Cottonwood Canyon, at an elevation of 1,525 m, between the Bonneville highstand (ca. 17.5 ka) and Provo (ca. 16.5 ka) shorelines of the Bonneville lake cycle. The trench and accompanying auger hole exposed 26 meters of vertical section, roughly 4 times that of the typical trench on the WFZ.

Each fault scarp was underlain by a major normal fault with 7-9.5 meters of vertical displacement measured on the top of Bonneville-age lake beds (ca. 17- 20 ka). Two antithetic faults were also exposed which had no surface expression, having been buried by wash-facies colluvium shed from the larger scarps.

Deposits exposed in the trench are divisible into three packages, from oldest to youngest: (1) lake beds of Bonneville age, (2) early Holocene loess overlain by fan alluvium, and (3) scarp-derived colluvium. The lake beds contain two bouldery diamictons that may represent earthquake-induced landslides, but otherwise do not contain recognizable tectonic colluvium. The alluvial fan deposits contain one small colluvial wedge but not on a major fault. All the remaining 4 colluvial wedges and one underlying fissure fill overlie the early Holocene alluvium. Charcoal and organic soils were present throughout the stratigraphic section, and I obtained 25 radiocarbon age estimates.

The one surprise in the trench was the existence of a thick buried soil developed on the lake deposits and buried by the early Holocene fan. This soil suggests a long period of nondeposition adjacent to the faults (that is, fault inactivity) between ca. 9 ka and 17.2 ka. That time span is roughly 5 times as long as the typical recurrence interval (1,350 years) between the latest four major earthquakes on this segment of the WFZ. The quiescent interval could be either an irregularity typical of the long-term behavior of the WFZ, or a response to the drying up of Lake Bonneville between 17.2 ka and ca. 11 ka, which relieved a huge weight on the downthrown fault block of the WFZ. If it was an unloading effect, it died out by 5 ka, and it has not affected the regular 1,350 year recurrence cycle since that time.

The megatrench contained stratigraphic evidence for seven paleoearthquakes younger than the Bonneville Flood (ca. 17.2 ka), at ca. 1.3 ka (Event Z), 2.3 ka (Event Y), 3.5 ka (Event Z), 5.3 ka (Event W), 7.5 ka (Event V), 9 ka (Event U), and 17 ka (Event T). Event T occurred when the site was submerged in Lake Bonneville. An additional event (S?) may have been responsible for a landslide into the lake between ca. 17 and 20 ka.

I did not use the long recurrence times in the early Holocene and latest Pleistocene to recomputed future earthquake probabilities for the WFZ, because they may represent a response to lake desiccation and crustal rebound of the hanging wall of the WFZ. Instead, I assumed that the coefficient of variation (COV) of recurrence (standard deviation divided by mean) over the long term approaches 0.36, as suggested by the ergodic hypothesis of McCalpin and Slemmons (1998). This value falls halfway between COVs of 0.21 and 0.5 used by McCalpin and Nishenko (1996) to predict probabilities of 22 percent and 11 percent, respectively, for a large earthquake in the next 100 years on the Salt Lake City segment. If I assume that conditional probability varies linearly with COV over this relatively small range, then an assumed recurrence COV of 0.36 would imply a conditional probability of about 16 percent for M>7 earthquakes in the next 100 years.

INTRODUCTION

The goal of this study was to excavate a trench into the Wasatch fault zone deep enough to expose evidence of all (8-12?) paleoearthquakes that have occurred since abandonment of the Bonneville shoreline (ca. 17,200 calendar years before present, or 17.2 ka). Then, I would attempt to date these paleoearthquakes to define a series of 7-11 recurrence intervals at a single site. Finally, I would compare the mean recurrence and its variability of recurrence to the recurrence values deduced previously for the Salt Lake City fault segment, from shallower trenches and/or from ergodic substitution for the whole WFZ (McCalpin and Nishenko, 1996).

In order to capture the entire post-Bonneville record of paleoearthquakes on the Salt Lake City segment, I had to trench the Wasatch fault on a Bonneville-age (ca. 17.2 ka) geomorphic surface, rather than on a mid-Holocene alluvial fan, as commonly done in prior trench investigations. Fault scarps of the WFZ are typically 15-25 meters high when they displace Bonneville-age surfaces. Due to the height of these older fault scarps, the trench I finally excavated had to be abnormally wide, long, and deep, by Utah standards. I informally termed the trench a “megatrench,” a term that is used throughout this paper.

The megatrench was located about 1 km north of the mouth of Little Cottonwood Canyon, on the north flank of the latest glacial moraine (age ca. 20-25 ka). Woodward-Clyde Consultants had previously trenched this site in 1979 (Swan and others, 1981), with 4 trenches about 3 m deep. However, due to the shallowness of those trenches, the unstratified nature of graben fill, the lack of datable material, and fault strands that were not trenched, Swan and others (1981) made few firm conclusions about the chronology of Holocene faulting at the site. This site is unique in that it encompasses transition zones in both geomorphology and structure, as described later.

I excavated the megatrench from Sept. 13-17, 1999 across the two subparallel scarps that compose the main scarp of the WFZ (McCalpin and Nelson, 2000); together these scarps have 18 meters of vertical relief. The trench was benched, with 1.5 meter-high walls leading down to 1 meter-wide bench levels, in two sets, and then a 3-4 meter-deep inner slot 1 meter wide. Altogether the trench encompassed 23 meters of vertical exposure. An additional 3 meters of vertical "exposure" was gained by drilling a 3 meter-deep hollow-stem auger hole at the toe of the trench.

Acknowledgments

This study was made possible by funding from U.S. Geological Survey, under NEHRP Grant 99HQGR0056 to co-investigators James P. McCalpin (GEO-HAZ Consulting, Inc., Estes Park, CO) and Craig V. Nelson (Western GeoLogic, Salt Lake City, Utah). Landowner permission to trench was kindly granted by Mr. Robert Despain, Sandy, Utah. The Utah Geological Survey (UGS) provided hydraulic trench shoring and trench logging assistance, via the participation of Bill Black, Greg McDonald, and Barry Solomon. The trench was mainly logged by McCalpin, Nelson, Darlene Batatian (Salt Lake County Geologist) and L.C. Allen Jones (consulting geologist, Logan, UT). The auger drill rig was loaned to us by the Department of Geology, Utah State University. The Jones family (Leon L. Jones, Amelia C. Jones, and Ezra T. P. Jones, Salt Lake City and Ogden, Utah) assisted in auger drilling and sample collection. Alexandra Nelson assisted in wall cleaning. I thank Steve Forman (University of Illinois-Chicago) and Bill Lund (UGS) for reviewing this paper.

GEOLOGIC AND GEOMORPHIC SETTING OF THE MEGATRENCH SITE

Location and Local Geology

The Salt Lake City segment of the Wasatch fault zone (WFZ) extends for about 46 kilometers at the base of the Wasatch Range from the Traverse Mountains on the south to the Salt Lake salient on the north (figure 1). The Salt Lake City segment displays abundant geologic and geomorphic evidence for multiple surface-faulting earthquakes during Holocene time (Schwartz and Coppersmith, 1984). Fault scarps on Bonneville-age (ca. 14-17 ka) deposits tend to be 20-25 meters high, on Provo-age (ca. 13 ka) deposits 10-15 meters high, on early Holocene alluvial fans 5-8 meters high, and on late Holocene alluvial fans 2-5 meters high. Personius and Scott (1992) subdivide the Salt Lake City segment into a southern Cottonwood section, a shorter central East Bench fault, and an even shorter northern Warm Springs fault (figure 1).

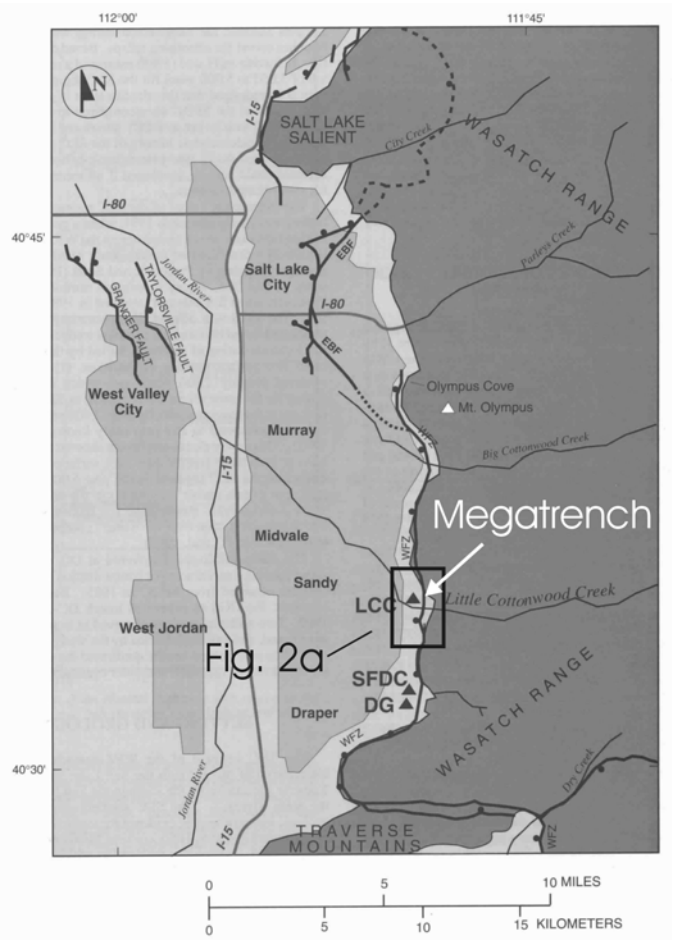


Figure 1. Location map of megatrench study area, showing the Salt Lake City segment of the WFZ. Fault traces are thick black lines, ball on downthrown side. EBF, East Bench fault; LCC, Woodward-Clyde Little Cottonwood Canyon trench site of 1979 (Swan and others, 1981); SFDC and DG, trench sites at South Fork Dry Creek and Dry Gulch (Black and others, 1996).

The megatrench was in the center of the Cottonwood section. Most of the fault scarps in the Cottonwood section displace geomorphic surfaces formed by shoreline processes in Lake Bonneville near its highstand (figure 2), while a smaller proportion displace alluvial fans of Holocene age.

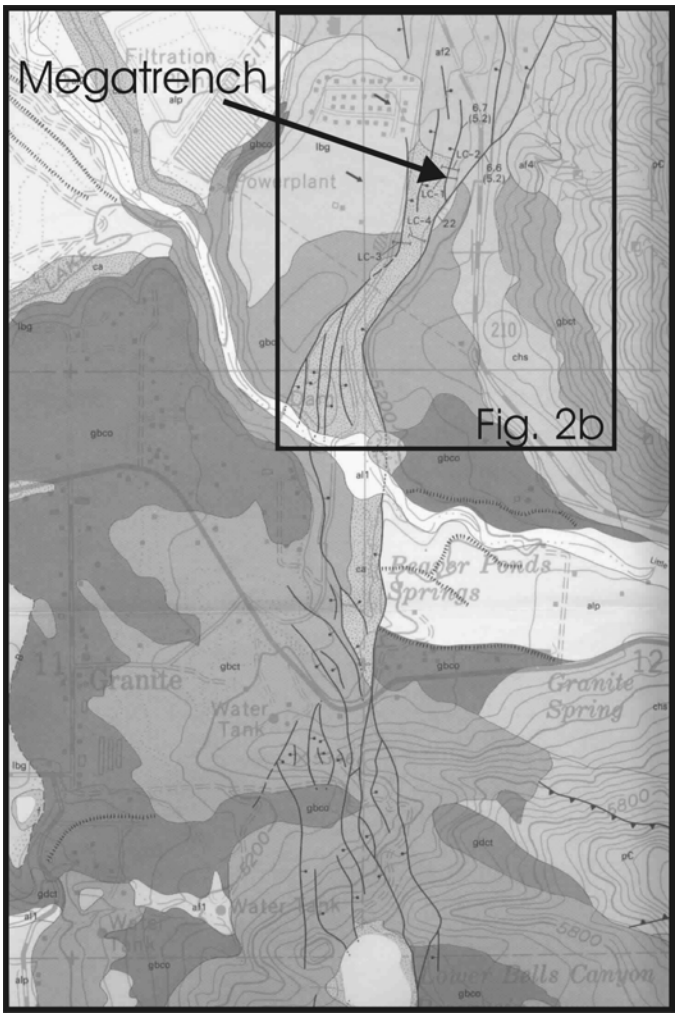


Figure 2a. Geologic map of the central Cottonwood section of the Salt Lake City segment, from Personius and Scott (1992). Map units of glacial origin begin with "g"; those of alluvial origin with "a"; those of colluvial origin with "c"; those of lacustrine origin with "l"; see table 1. Bells Canyon Reservoir (bottom center) lies in a graben of the WFZ developed in the terminal moraine of Bells Canyon (map unit gbct). On the south side of Little Cottonwood Creek, the WFZ truncates a broad alluvial terrace (map unit alp) graded to the Provo shoreline. North of Little Cottonwood Creek the WFZ is expressed as a graben in Bells Canyon till, with a central fill of colluvium and alluvium (map unit ca). Trenches excavated by Swan and others (1981) are labeled LC-1 through LC-4 at upper center in the graben. Small numbers near scarps indicate scarp height in meters, with numbers in parentheses showing vertical surface offset in meters.

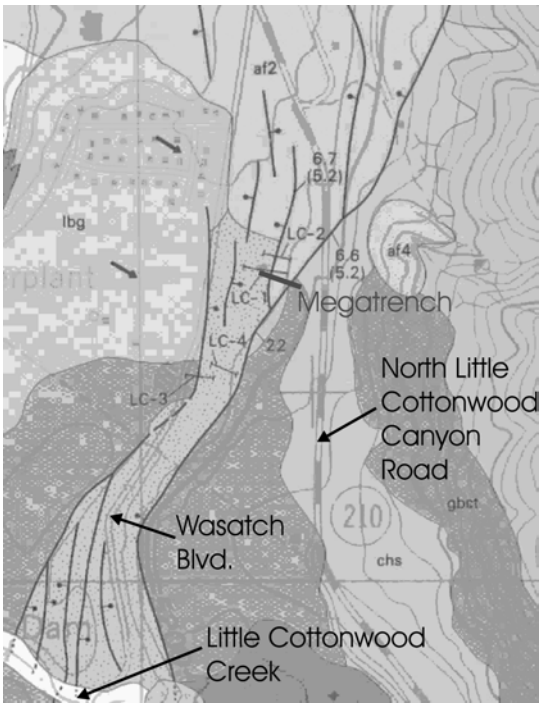


Figure 2(b). Enlargement showing location of the megatrench in relation to the four 1979 trenches of Swan and others (1981), which are labeled LC-1 through LC-4 at upper center. Map unit abbreviations are explained in table 1. South of the megatrench, the WFZ is expressed as a rather symmetrical graben with a single normal fault on each margin. In the area of the megatrench, the graben begins to widen and become more complex. For example, the eastern margin fault develops two splay faults that trend more northerly than the graben margin. The widening and complexity are coincident with the early Holocene alluvial fan (map unit al2. This coincidence suggests that surface ruptures propagating up through the Holocene fan diverged and split upward, in contrast to the narrower graben developed in the harder, older Bells Canyon till (map unit gcbt). The megatrench spanned the eastern margin normal fault and one splay fault, just north of their Y-shaped junction.

.

Table 1. Geologic unit abbreviations used in figures 2 and 3.

Abbreviation	Age[1]	Deposit
al1	late Holocene	stream alluvium
af1	late Holocene	fan alluvium
al2	early Holocene (7.8-9.5 ka)	stream alluvium
af4	late middle Pleistocene (ca. 150 ka)	fan alluvium
ca	Holocene- middle Pleistocene	colluvium and alluvium
cls	Holocene- middle Pleistocene	landslide deposit
alp	late Pleistocene (14-16 ka)	topset beds of Provo delta
lbg	late Pleistocene (16-17 ka)	beach gravels at Bonneville shoreline
gbco	late Pleistocene (ca. 18-26 ka)	outwash of Bells Canyon age
gbct	late Pleistocene (ca. 18-26 ka)	till of Bells Canyon age
gdct	middle Pleistocene (ca. 150-250 ka)	till of Dry Canyon age

[1] Geologic ages from Personius and Scott (1992). Numerical ages in parentheses are from correlation with regional geochronology, or from numerical ages obtained in the megatrench.

Site Geomorphology

The megatrench site is on the north flank of the latest glacial (Bells Canyon) lateral moraine complex, where the moraine is thinning. The moraine surface south of the trench was planed off by the transgression of the Bonneville shoreline (figure 3), so I expected to find thin shoreline gravels (or perhaps merely a boulder lag) overlying very bouldery till. In addition, the trench site is also overlapped by the south edge of a large alluvial fan (map unit af2 on figure 2) emanating from a range-front drainage to the north. Thus, although the bulk of the faulted deposit here is till, the surface should be underlain by an interfingering complex of Bonneville shoreline deposits and/or younger locally derived fan gravels. In the 50-meter-wide graben at the base of the scarps, I expected a thick sequence of sandy graben fill, based on the prior trenching of Woodward-Clyde Consultants (Swan and others, 1981). The northern part of the graben is occupied by planted blue spruce trees and is locally known as the “Christmas Tree Farm,” owned by Robert V. Despain of Sandy, Utah.

The trench site also occupies a transition in the morphology and structure of the Wasatch fault zone. South of the trench the fault zone includes a rather narrow graben, bounded by a 25-meter-high, west-facing main scarp on the east, and a ca. 10-meter-high, east-facing antithetic scarp on the west (figures 2, 3). As the main scarp approaches the megatrench site it begins to

separate into 3 subparallel scarps, each roughly 5-7 meters high. At the trench site only two of these scarps have completely separated, by about 30 meters horizontally, forming a gently sloping bench (figure 4). The trackhoe excavators used this bench to situate themselves while digging the trench; they could not have reached the scarp midpoint on the steep face of the 25-meter-high main scarp farther south.

Previous Trenching Study of Woodward-Clyde Consultants (1979)

The graben at the Christmas Tree Farm was the site of a four-trench study by Swan and others (1981). Swan and others excavated two trenches across the westernmost of the three west-facing scarps on the eastern side of the graben (figure 2b). They excavated a third trench across the antithetic (east-facing) scarp on the western margin of the graben. Their fourth trench was at the toe of the 22-meter-high main scarp south of the branching point, but it did not extend far enough up the scarp face to intersect the fault plane.

Swan and others (1981) recognized stratigraphic evidence for only two surface-faulting earthquakes, due to the poor differentiation of colluvial wedges and graben strata. The older event occurred shortly after 8,000-9,000 radiocarbon years Before Present (C14 yr BP). They found no datable organic material to help constrain the age of the younger event. Given the limitations of these trenches, Swan and others (1981) used an indirect method to calculate paleoearthquake recurrence. That is, they computed an average slip rate of 0.9 mm/yr based on a net vertical tectonic displacement of 13.5 meters across the graben developed on Bonneville-highstand deposits (assumed to be 14,500 years old). They then assumed that paleoearthquakes displayed a typical vertical displacement of 2 meters per event. From this they derived an average recurrence interval of 2,200 years by dividing the displacement per event (2 meters) by the average slip rate (0.9 mm/yr).

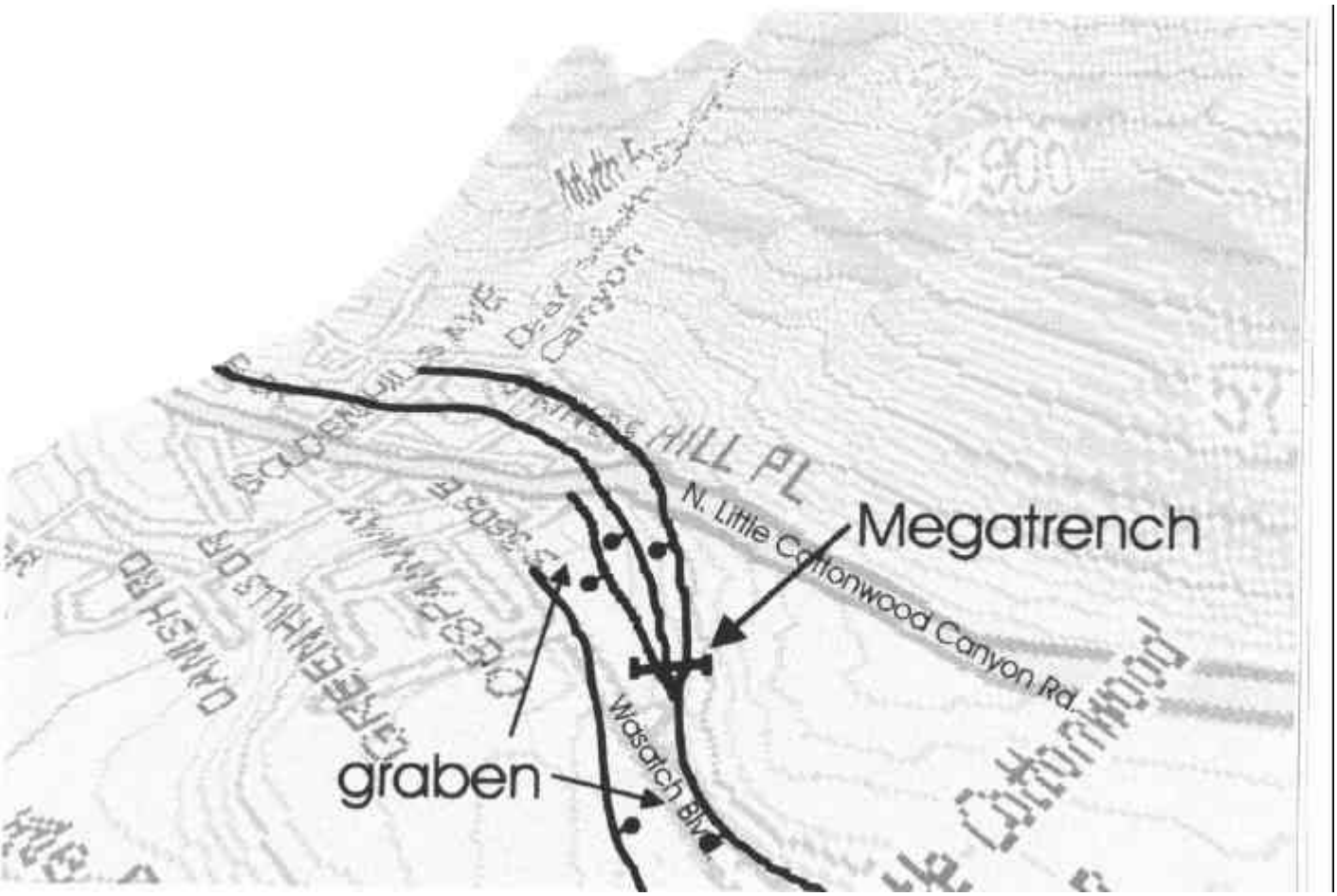


Figure 3. Three-dimensional perspective map of the megatrench site; contour interval 20 ft. North is toward upper left, scale varies in this map.

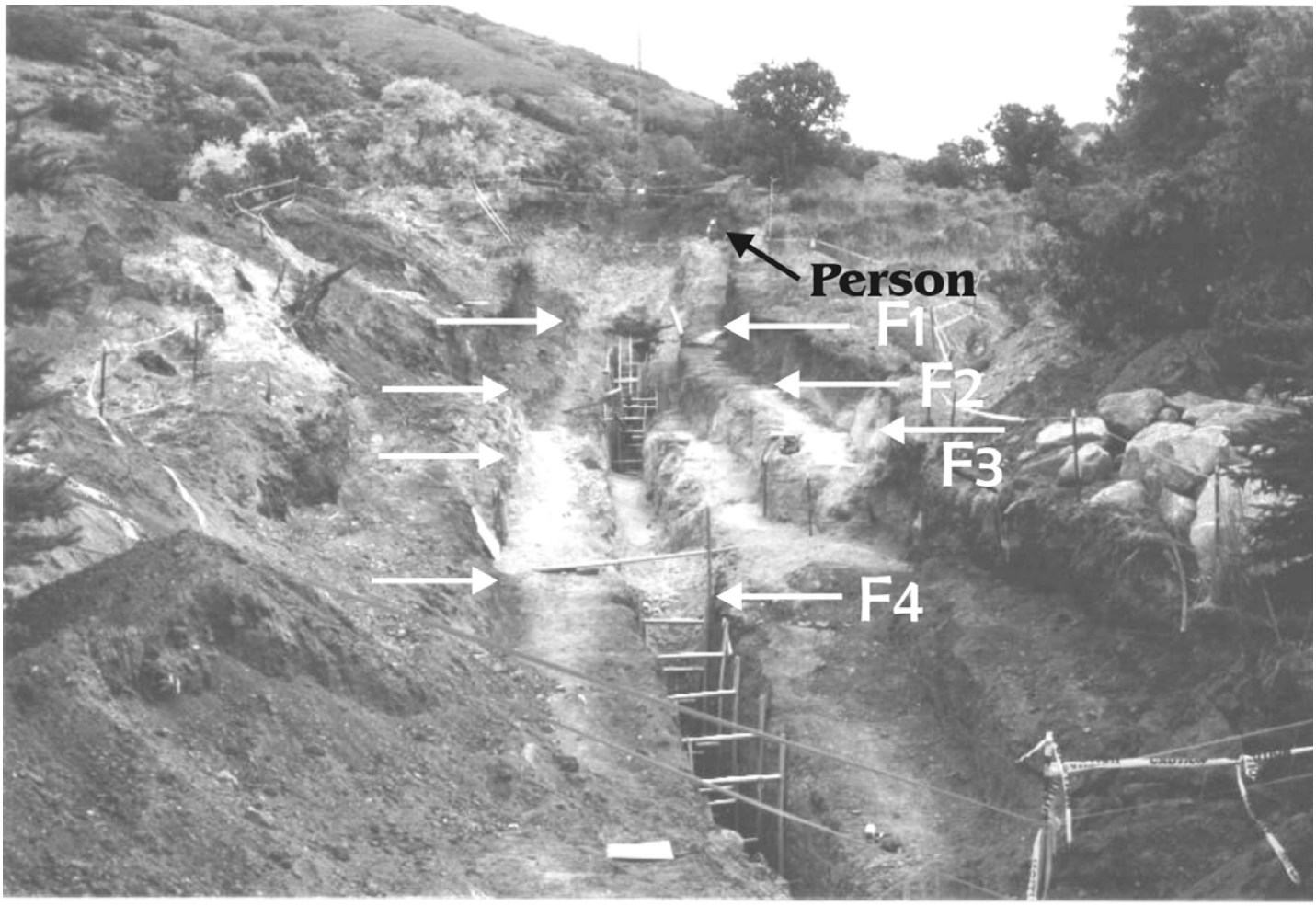


Figure 4. Photograph of the WFZ megatrench looking east from the toe of the trench. Note person for scale near head of trench on right-hand bench. Two major fault zones (F1 and F4, between white arrows) underlie the eastern and western fault scarps, respectively. Smaller faults F2 and F3 have no topographic expression. Quaternary deposits exposed in the trench define five distinct tonal bands. The uppermost dark band is distal Holocene alluvial fan and local slopewash. The first light band (downslope) is thin Lake Bonneville lacustrine sediments, which are in fault contact (across F1) with Holocene alluvium (next dark band). The second, thicker light band (center of photograph) is the same Bonneville lacustrine sediments, which were downfaulted 8 meters down-toward-the-viewer by fault F1. The final dark band (foreground in photograph) is more Holocene alluvium and colluvium, in fault contact with the lake beds along fault F4. Fault F4 has 9.5 meters of throw measured on the top of the lake beds. The inner slot at the lower center of the photograph was not deep enough to expose lake beds on the downthrown side of fault F4, but an auger hole encountered the top of lake beds 2.2 meters below the trench floor.

STRUCTURE

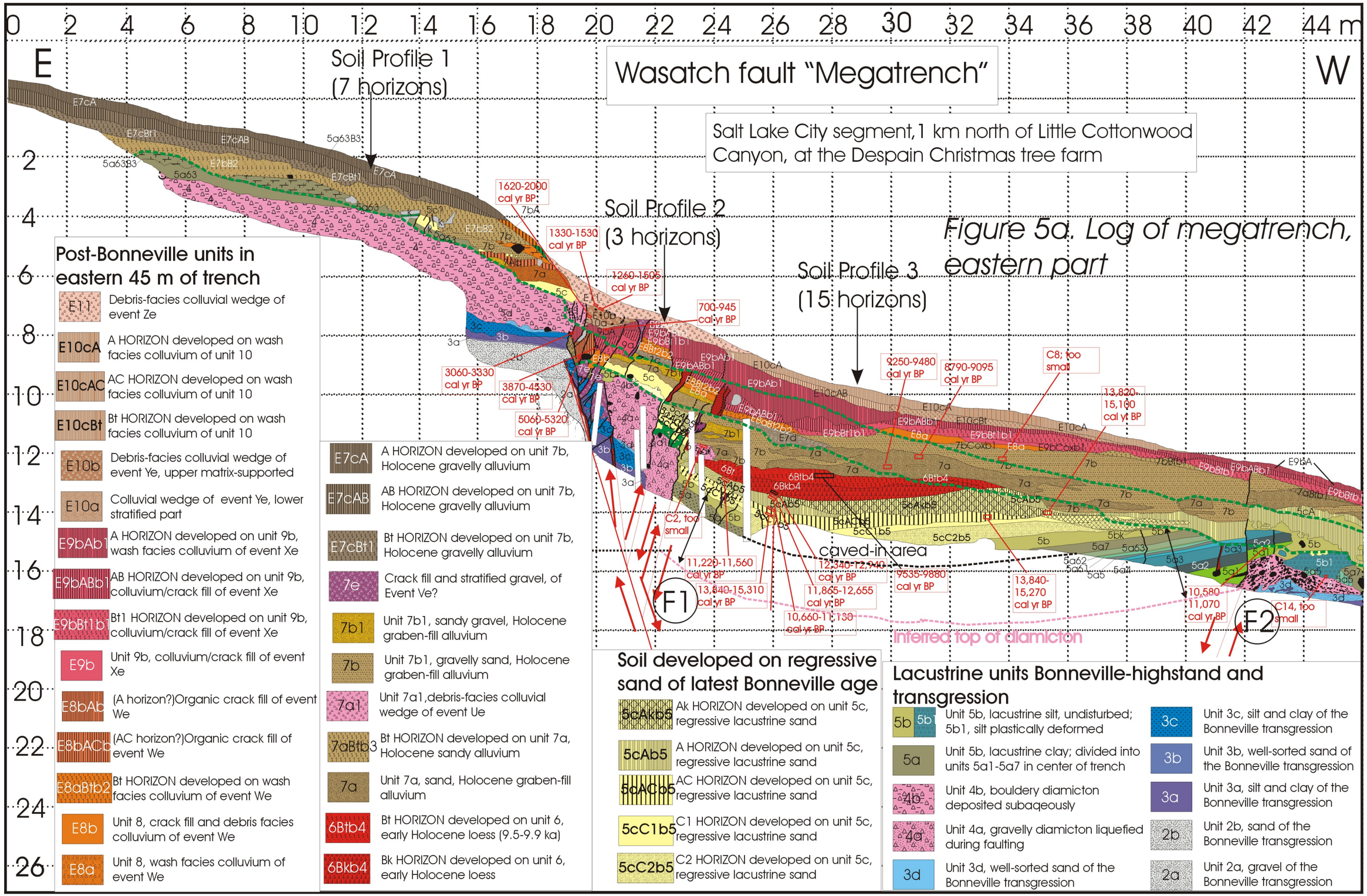
Overview

As I expected from the presence of two separate fault scarps along our trench line, there is a major, west-dipping normal fault beneath the eastern scarp (fault zone F1, figure 5) and the western scarp (fault zone F4). In addition, there are two east-dipping fault zones (F2, F3) that did not have topographic expression. Each fault zone contains one or more faults and is described below.

Fault zone F1

Fault zone F1 underlies the eastern, 7-meter-high scarp transected by the megatrench. Because this eastern scarp is higher and steeper than the western scarp cut by the trench, I expected it to have the larger fault and the most throw. Actually, fault zone F1 has 8.3 meters of throw measured on the top of unit 4, or about 1.3 meter more throw than scarp height. The decreased scarp height in relation to throw was caused by the deposition of colluvial units E8-E11 on the hanging wall but not on the footwall. By comparison, the gentler, 3.5-meter-high western scarp is underlain by a fault with nearly 10 meters of throw (described later).

Fault zone F1 has a rather unusual structure, containing both the expected west-dipping normal fault, but also two 1 to 1.5-meter-wide forward-toppled “domino” blocks bounded by apparent reverse faults.


Wasatch fault "Megatrench"
Salt Lake City segment, 1 km north of Little Cottonwood Canyon, at the Despain Christmas tree farm
Figure 5a. Log of megatrench, eastern part
E
W
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 m
Soil Profile 1 (7 horizons)
Soil Profile 2 (3 horizons)
Soil Profile 3 (15 horizons)
1620-2000 cal yr BP
1330-1530 cal yr BP
1260-1505 cal yr BP
700-945 cal yr BP
3060-3330 cal yr BP
3870-4330 cal yr BP
5060-5320 cal yr BP
9250-9480 cal yr BP
8790-9095 cal yr BP
C8, too small
13,820-15,100 cal yr BP
C2, too small
11,220-11,560 cal yr BP
13,840-15,310 cal yr BP
12,340-12,940 cal yr BP
11,865-12,655 cal yr BP
10,660-11,130 cal yr BP
9535-9880 cal yr BP
13,840-15,270 cal yr BP
10,580-11,070 cal yr BP
C14, too small
caved-in area
inferred top of diamicton
F1
F2
Post-Bonneville units in eastern 45 m of trench
E11 Debris-facies colluvial wedge of event Ze
E10cA A HORIZON developed on wash facies colluvium of unit 10
E10cAC AC HORIZON developed on wash facies colluvium of unit 10
E10cBt Bt HORIZON developed on wash facies colluvium of unit 10
E10b Debris-facies colluvial wedge of event Ye, upper matrix-supported
E10a Colluvial wedge of event Ye, lower stratified part
E9bAb1 A HORIZON developed on unit 9b, wash facies colluvium of event Xe
E9bABb1 AB HORIZON developed on unit 9b, colluvium/crack fill of event Xe
E9bBt1b1 Bt1 HORIZON developed on unit 9b, colluvium/crack fill of event Xe
E9b Unit 9b, colluvium/crack fill of event Xe
E8bAb (A horizon?)Organic crack fill of event We
E8bACb (AC horizon?)Organic crack fill of event We
E8aBtb2 Bt HORIZON developed on wash facies colluvium of event We
E8b Unit 8, crack fill and debris facies colluvium of event We
E8a Unit 8, wash facies colluvium of event We
E7cA A HORIZON developed on unit 7b, Holocene gravelly alluvium
E7cAB AB HORIZON developed on unit 7b, Holocene gravelly alluvium
E7cBt1 Bt HORIZON developed on unit 7b, Holocene gravelly alluvium
7e Crack fill and stratified gravel, of Event Ve?
7b1 Unit 7b1, sandy gravel, Holocene graben-fill alluvium
7b Unit 7b1, gravelly sand, Holocene graben-fill alluvium
7a1 Unit 7a1, debris-facies colluvial wedge of event Ue
7aBtb3 Bt HORIZON developed on unit 7a, Holocene sandy alluvium
7a Unit 7a, sand, Holocene graben-fill alluvium
6Btb4 Bt HORIZON developed on unit 6, early Holocene loess (9.5-9.9 ka)
6Bkb4 Bk HORIZON developed on unit 6, early Holocene loess
Soil developed on regressive sand of latest Bonneville age
5cAkb5 Ak HORIZON developed on unit 5c, regressive lacustrine sand
5cAb5 A HORIZON developed on unit 5c, regressive lacustrine sand
5cACb5 AC HORIZON developed on unit 5c, regressive lacustrine sand
5cC1b5 C1 HORIZON developed on unit 5c, regressive lacustrine sand
5cC2b5 C2 HORIZON developed on unit 5c, regressive lacustrine sand
Lacustrine units Bonneville-highstand and transgression
5b 5b1 Unit 5b, lacustrine silt, undisturbed; 5b1, silt plastically deformed
5a Unit 5b, lacustrine clay; divided into units 5a1-5a7 in center of trench
4b Unit 4b, bouldery diamicton deposited subaqeously
4a Unit 4a, gravelly diamicton liquefied during faulting
3d Unit 3d, well-sorted sand of the Bonneville transgression
3c Unit 3c, silt and clay of the Bonneville transgression
3b Unit 3b, well-sorted sand of the Bonneville transgression
3a Unit 3a, silt and clay of the Bonneville transgression
2b Unit 2b, sand of the Bonneville transgression
2a Unit 2a, gravel of the Bonneville transgression

Post-Bonneville units and their soils in western 15 m of trench

Colluvial deposits and their soils

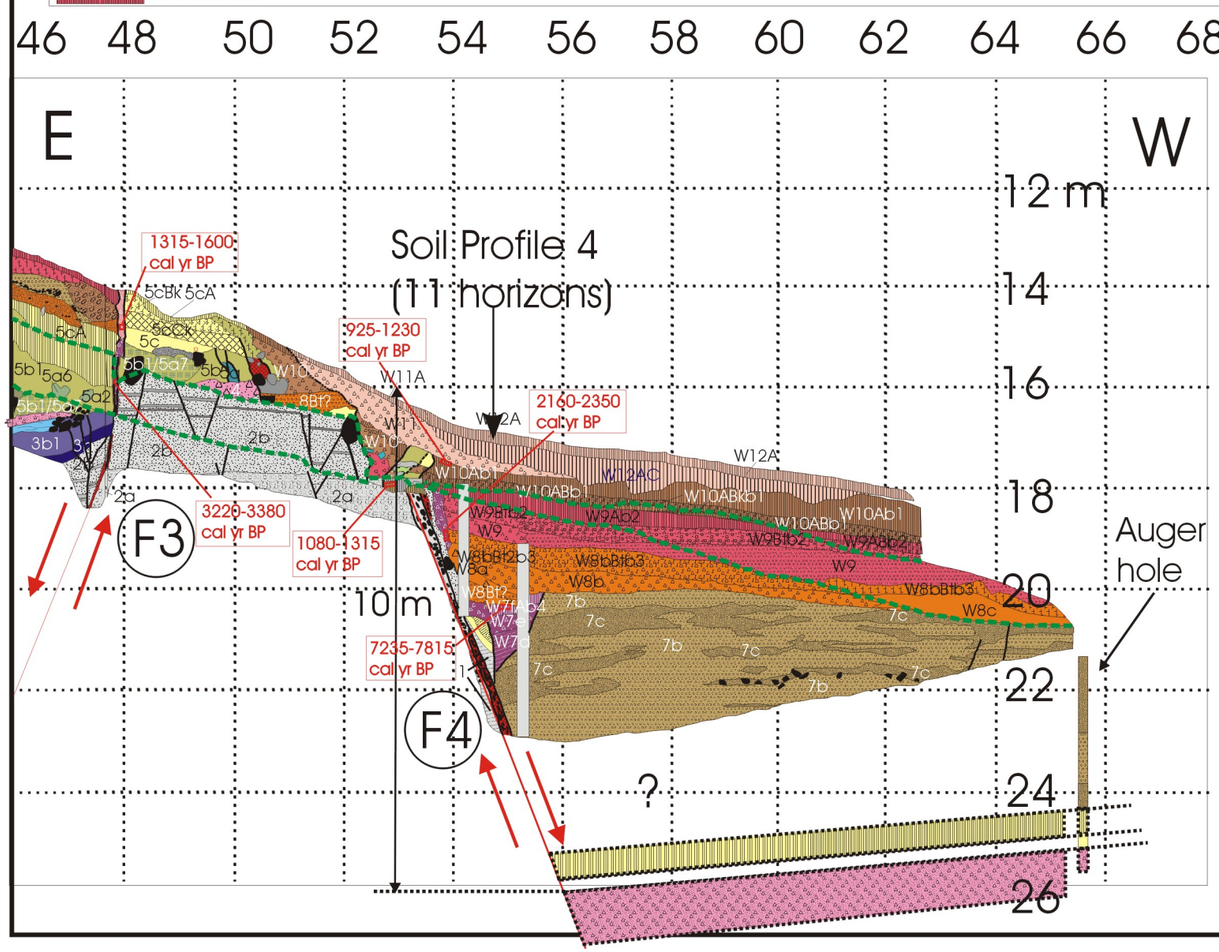
- W12A — A HORIZON developed in post-faulting graben-fill alluvium
- W12AC — AC HORIZON developed in post-faulting graben-fill alluvium
- W11 — Unit W11, debris-facies colluvium of event Zw
- W10Ab1 — A HORIZON developed on colluvium of event Yw
- W10ABb1 — AB HORIZON developed on colluvium of event Yw
- W10 — Unit 10, debris-facies colluvium of event Yw
- W9Ab2 — A HORIZON developed on colluvium of event Xw
- W9Btb2 — Bt HORIZON developed on colluvium of event Xw
- W9 — Unit W9, wash-facies colluvium of event Xw
- W8bBtb3 — Bt HORIZON developed on colluvium of event Ww
- W8b — Unit W8, wash-facies colluvium of event Ww
- W8a — Unit W8, debris-facies colluvium of event Ww
- W8c — Unit W8, massive silt (loess or fluvial overbank deposit?)

Early Holocene alluvium and Bonneville-age deposits

- W7fAb4 — A HORIZON developed on unit 7f, loess atop crack fill of event Vw
- W7e — Sandy gravel, disturbed; crack fill of event Vw?
- W7d — Sand, backtilted, disturbed; crack fill of event Vw?
- 1 — Unit 1, alternating lacustrine sand and clay of the Bonneville transgression

EXPLANATION OF SYMBOLS

- Fault (dashed where obscure)
- F4
- shear zone
- rock
- Bench
- Younger — Fissure or crack fill — Older
- 1315-1600 cal yr BP — C-14 sample and calibrated age in years BP (2 sigma range)



EXPLANATION OF COLORS & PATTERNS

COLORS indicate different parent materials (deposits)
PATTERNS indicate different soil horizons developed on deposits

Figure 5b. Log of megatrench, western part

NOTES: 1) Trench logged by J. McCalpin, A. Jones, C. Nelson, B. Black, G. McDonald, D. Batatian, B. Solomon; Sept. 16-Oct. 8, 1999.
2) Auger hole at W end of trench was drilled Oct. 5 with a Giddings hollow stem auger rig. Only cuttings were logged, and rig hit refusal at a depth of 15 ft.
3) Trench unit abbreviations begin with E (for the eastern 50 m of the trench) or W (for the western 15 m). The next number represents the major parent material package (1=oldest), followed by lower-case letters for parent material subunits. If the parent material is affected by soil format ion the horizon abbreviation is next, followed by the number of the buried soil (counting from the surface soil downward). Thus, unit E5cAb5 is in the eastern part of the trench, parent material 5 (lacustrine), subunit c (regressive sand), soil horizon A, belonging to the 5th buried soil beneath the surface.

These domino blocks are composed of intact stratigraphic sections of units 3-9 that broke off the footwall, slid down along fault F1 and toppled westward. The domino blocks farthest west have slid downward the most. The rotation of the dominoes has two results: (1) a small graben has formed between the normal fault F1 and the closest domino, into which units 3 through 10 have been progressively downfaulted through time (figure 5), and (2) the bounding faults of the dominoes, which are generally down-to-the-west, dip east and have the appearance of reverse faults, but they do not represent the effects of compressional tectonics. From a tectonic standpoint they may not qualify as faults because they are rootless and function more like landslide failure planes. The westward toppling of the dominoes has evidently continued up to Event Zw, if my interpretation is correct that proximal unit E10 is preserved in a graben overlying the pull-away zone.

Fault zone F2

Fault zone F2 contains a single, subvertical, down-to-the-east antithetic fault at 42mH (meters horizontal) (figure 5). Total throw is 0.4 meter measured on the top of unit 5cAb5.

Fault zone F3

Fault zone F3 bounds the western side of the prominent horst between 48-54mH and contains several down-to-the-east (antithetic) faults. The eastern side of the horst is bounded by fault zone F4. The horst brings early transgressive Lake Bonneville gravels and sands (unit 2) up to within 1.5 meters of the ground surface, whereas east of F2 and F3 the same beds are beneath the trench floor, so they are at least 6 meters below the ground surface. Down-to-the-west throw measured on the top of unit 2b is 1.6 meters on the main fault and 2.0 meters across the entire fault zone. The upper part of fault F3 is marked by a 10 to 15-centimeter-wide fissure filled with organic material.

The most notable aspect of the horst is its lack of surface expression. Wash-facies colluvium from upslope (units E8 and E9, shed from fault zone F1) has effectively buried the 2 meters of structural relief. However, the most recent faulting event on F3 must postdate unit E9, because the tension fissure cuts unit E9 and reaches the ground surface. No scarp-derived colluvium from fault F3 lies atop unit E9, so I infer that the latest faulting on fault F3 created a tension fissure with no net vertical displacement.

Fault zone F4

Fault zone F4 underlies the relatively subdued, 3.5 meter-high western scarp. However, the slope and height of this scarp are deceiving. The slope angle is evidently gentle because the footwall is composed mainly of the loose sand of units 2 and 5, not due to the absence of recent faulting. The scarp height is small because the lower part of the scarp was buried by deposition of up to 5 meters of Holocene graben-fill alluvium. In fact, this 3.5-meter-high scarp is underlain by a normal fault with nearly 10 meters of throw measured on the top of unit 4 (diamicton).

Unlike fault zone F1, fault zone F4 does not contain structural complexities such as domino blocks. Instead, the zone is dominated by a single, planar normal fault that dips 75° west (figure 5b). The fault is defined by a 10 to 15-centimeter-wide zone where gravel clasts of unit 2a have been rotated parallel to the fault (shear fabric). A few blocks of footwall material are present, for example a block of units 5cA/5cC, as well as one undifferentiable crack fill higher up (unit cf). As the fault approaches the surface its expression changes to include several antithetic (east-dipping) faults that disrupt unit W10. The main normal fault is difficult to trace within 2 meters of the modern ground surface, either due to human disturbance associated with old mining activities, or because the soft sands of unit 2b on the footwall collapsed during the latest 2 faulting events. However, the upward transition from fault contact to depositional free face contact at the base of the youngest colluvial wedge (unit W11) is well preserved.

Total throw across fault zone F4 was reconstructed by projecting unit contacts in the auger hole at the western end of the trench back to the main normal fault plane at a dip angle of 6° east. This dip angle mimics that of “backtilted” lenticular sand beds within unit 7, and is a minimum value, because it assumes that backtilt angles do not increase with depth to the top of unit 4.

STRATIGRAPHY, SOILS, AND GEOCHRONOLOGY

The stratigraphy exposed in the trench was not the thin veneer of alluvium/beach gravels over till that I expected. On the upthrown sides of both fault scarps, I never encountered Bells Canyon till, even though I exposed up to 7.5 meters of stratigraphic thickness beneath each scarp (figure 5). Instead, the upthrown blocks exposed only Bonneville lake sediments, which varied in facies from well-laminated clays, to massive sands, to well-stratified (beach?) gravels, to diamictons composed of granite boulders in a matrix of lacustrine silt. In general the upper 2 meters of the lake beds coarsened upward, indicating a regressive sequence. The failure to expose till in the trench is not critical, because I only needed to expose the top of the Bonneville lake

beds to capture all the post-Bonneville faulting events. From that standpoint much of the trench was deeper than necessary; for example, it exposed up to 7 meters of lake sediments in some places, when 1 meter would have been sufficient.

Mapping Conventions

The unconsolidated map units defined in this trench include both parent materials unaffected by soil formation (e.g., unit 7a), and parent materials that have been affected by soil formation (e.g., unit 6Btb4). In the latter group the map units are soil horizons defined by changes in soil horizon properties, rather than by a change in parent material sedimentology. Horizons were defined according to the U.S. Soil Conservation Service (1994) and Birkeland (1999). In each map unit abbreviation, E and W indicate lenticular colluvial units that exist only in the eastern and western parts of the trench, respectively. The next number represents the deposit number (1 = oldest), followed by the soil horizon abbreviation (if any). The final part of the map unit designation indicates whether the soil horizon is part of a buried soil (i.e., not the surface soil) and if so, the number of the buried soil, with "b1" indicating the uppermost (youngest) buried soil. Thus, the map unit designation "6Btb4" indicates that the parent material is unit 6 (loess), the soil horizon is a Bt horizon (textural B horizon defined by clay accumulation), and the Bt horizon is part of the fourth buried soil counting down from the ground surface. I use this same naming convention throughout the trench.

The unconsolidated deposits in the trench fall into four distinct genetic groups, which also form an age sequence. [Hereafter in this report, ages are cited in either radiocarbon years (C14 yr BP) or in dendro-calibrated years (cal yr BP). The latter are also cited in "ka"= kiloannum Before Present, so that 10,000 cal yr BP = 10 ka. Hereafter, all ages cited in ka are calibrated years]. These groups are, from oldest to youngest: (1) lacustrine sediments deposited in shallow water near the time of the Bonneville highstand, 14,500-15,500 C14 yr BP (17,200-18,800 dendro-calibrated years Before Present, or 17.2-18.8 ka) comprising units 1-5; (2) loess deposited in the early Holocene after Lake Bonneville desiccated, around 9.5-12 ka, unit 6 (see table 2 for numerical ages); (3) alluvial gravels and sands of the mid-Holocene alluvial fan north of the trench, which includes graben-fill sediments, deposited between ca. 5 ka and 9 ka, unit 7; and (4) colluvial wedges and crack fills deposited in response to surface-faulting earthquakes, generally since 5.5 ka, units 8-12. Below, I describe each stratigraphic group separately.

Lacustrine Stratigraphy

Units 1-5 compose a subaqueous transgressive-regressive lake sequence punctuated by two slope failure episodes (units 4, 5b1). Based on the location of the trench below the Bonneville highstand shoreline but above the Provo shoreline, these lacustrine units were deposited between the last transgressive phase to the Bonneville highstand and the subsequent rapid fall to the Provo shoreline accompanying the Bonneville flood

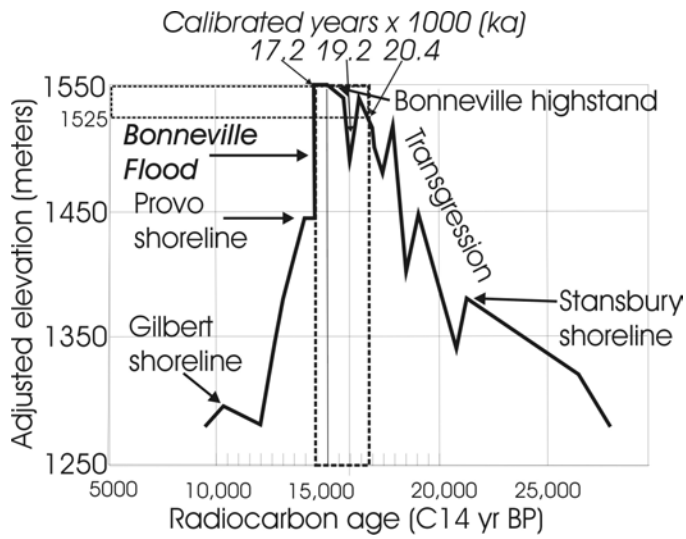


Figure 6. Elevation of the Lake Bonneville water surface (adjusted for isostatic rebound) as a function of radiocarbon years. This diagram (from Oviatt, 1997) is a simplified lake level curve based on many radiocarbon ages (not plotted). The Bonneville highstand shoreline was occupied from about 14,500 to 15,500 C14 yr BP, equivalent to 17,200-18,800 calibrated years BP (or 17.2-18.8 ka) (Stuiver and Reimer, 1993). The rapid fall to the Provo shoreline during the Bonneville flood occurred about 17.2 ka. The dotted boxes show when water levels were higher than the present elevation of the megatrench, from 14,500 to 16,800 C14 yr BP. This age range suggests, in a general way, that the site was under water and receiving lacustrine deposition from about 17.2-20.4 ka. However, post-Bonneville faulting has created 18 meters of down-to-the-west displacement. Unfortunately, I do not know the absolute (geodetic) value of the displacement vector relative to Lake Bonneville.

(ca. 17.2 ka) (see figure 6). Detailed unit descriptions are given in appendix 1.

The oldest unit in the trench (unit 1) is exposed in only two small areas, in the footwall of fault zone F4 at the deepest part of the trench, and as a block slightly higher in the hanging wall (figure 5, 20-22 meters on the vertical scale, 54-56 meters on the horizontal scale; hereafter abbreviated as 20-22mV, 54-56mH). This unit is composed of laminated to thin-bedded fine to coarse sand with occasional cross beds, representing a nearshore (swash zone) environment. Unit 2 is in the footwalls of both fault zone F1 and F4. The lower part of

Table 2. Radiocarbon age estimates from the megatrench.

Field No.	Unit	X coord.[1]	Y coord.[1]	Material	Lab. No.[2]	Lab. C-14 age (C-14 years BP)	Calibrated Age (±2 sigma, calendar years BP)[3]	Event Constraint[4]
C1	6Btb4	28.5	-12.9	charcoal	β-139254	8,680±60	9,535-9,880	6 soil, upper
C3	5cAb5	24.2	-12.8	charcoal	β-158117	9,960±50	11,220-11,560	5 soil, close minimum
C5	7c	29.9	-12.4	charcoal	β-158118	8,350±50	9,250-9,480	7 alluv., lower
C6	7c	30.8	-12.1	charcoal	β-139253	8,070±50	8,790-9,095	7 alluv., middle
C9	6Bkb4	26.0	-13.3	A horiz.	β-158120	10,620±70	12,340-12,940	5 soil, v. close minimum
C10	5cAkb5	26.0	-13.3	A horiz.	β-139255	10,320±60	11,865-12,655	5 soil, v. close minimum
C11	5cAb5	26.0	-13.4	A horiz.	β-158121	9,540±60	10,660-11,130	5 soil, close minimum
C12	5cAb5	25.8	-13.8	A horiz.	β-139256	10,260±330	10.870-13,000	5 soil, middle
C13	5cACb5	25.8	-14.1	AC horiz.	β-158122	12,150±70	13,840-15,310	5 soil, bottom
C15	E9bAb1	20.3	-7.8	A horiz.	β-139244	920±60	700-945	Xe, close maximum
C16	E10a	19.7	-7.4	Org. gravel	β-139243	1,890±80	1,620-2,000	Ye, close maximum
C17	E10b	20.2	-7.1	A horiz.	β-139242	1,440±70	1,260-1,505	Ze, close maximum
C18	E11	20.2	-7.0	A horiz.	β-158124	1,540±40	1,330-1,530	Ze, close minimum
C19	E9bAb1	19.2	-8.0	A horiz.	β-158125	3,000±40	3,060-3,330	Xe, average
C20	E8Ab2	19.5	-8.7	A horiz.	β-139246	4,560±40	5,060-5,320	We, average
C21	E9bABb1	20.0	-8.4	A horiz.	β-139245	3,820±120	3,870-4,530	We, close minimum
C22	W9Ab2	53.5	-18.0	A horiz.	β-139249	1,310±60	1,080-1,315	Yw, close maximum
C23	W10Ab1	54.6	-17.5	A horiz.	β-139248	1,130±70	925-1,230	Zw, close maximum
C24	W9Ab2	54.6	-18.9	A horiz.	β-158126	2,280±40	2,160-2,350	Yw, close maximum
C25	W7fAb4	55.5	-20.3	A horiz.	β-139250	6,640±180	7,235-7,815	Ww, close maximum
C25a	Fissure fill, older	48.05	-15.9	A horiz.	β-139252	3,090±40	3,220-3,380	Ym, close maximum
C26	5cAC	33.0	-14.14	charcoal	β-158127	12,160±60	13,840-15,270	5 soil, middle
C26a	Fissure fill, younger	48.0	-15.0	A horiz.	β-139251	1,570±70	1,315-1,600	Zm, close maximum
C27	5a1 (5cAC?)	42.72	-15.15	charcoal	β-158128	9,480±50	10,580-11070	5 soil, middle
C28	5cAkb5	34.8	-14.0	charcoal	β-158129	11,980±50	13,820-15,100	5 soil, middle

[1] Coordinates on the trench log, figure 5
[2] Lab number from Beta Analytic, Inc., Miami, FL
[3] Calibration from CALIB 4.0 (Stuiver and Reimer, 1993)
[4] Capital letter denotes paleoearthquake, with Z as most recent on a given fault zone; lower-case letter denotes fault zone ("e" for F1; "m" for F2 and F3; "w" for F4). Not every paleoearthquake ruptured all four fault zones, so Event Ye, for example, may not be the same event as Event Yw.

the unit (unit 2a) is a subangular, cobbly sandy gravel with a clean medium-coarse sand matrix, at least 2.2 m thick east of F1. The angularity of the gravels, their large size (mean diameter = 10 centimeters), and the lack of granitic clasts from the Little Cottonwood stock (dominant lithology exposed in Little Cottonwood Canyon) suggest they represent shoreline gravels transported southward by longshore drift, from Paleozoic outcrops farther north. The upper part of the unit (unit 2b) is a gray coarse sand with rare clasts, very well sorted and well stratified in planar beds. The decrease in grain size from unit 2a to 2b implies a local increase in water depth, probably associated with continued transgression of the shoreline to the Bonneville highstand, a trend which continued with deposition of unit 3.

Unit 3 is on both sides of (and within) fault zone F1 and on hanging wall of fault F3. Presumably the unit also once existed on the footwall of F3 but was later eroded. Unit 3 is a fine-grained sequence divided into four parts. Units 3a (oldest) and 3c are well-stratified, well-sorted silts, with planar beds ranging from 1-2 centimeter thick to millimeter-scale laminations. These units represent deposition from suspended load in quiet (deep?) water conditions, probably during the early occupation of the Bonneville highstand shoreline. Units 3b and 3d (youngest) are clean, coarse sands. The bedding in unit 3d is folded, either by liquefaction or by soft-sediment loading of the overlying diamicton (unit 4). Total unit thickness is about 0.6 meters.

Unit 4 is an anomalous deposit in the lacustrine sequence. Like unit 3, it is on both sides of fault zone F1 and in the hanging wall of fault F3. In general, unit 4 is a matrix-supported diamicton containing granitic boulders up to 1 meter in diameter. The larger part of unit 4 (unit 4b) is exposed on the footwall of fault zone F1 (figure 5), where it overlies (and deforms) unit 3 and underlies attenuated sections of units 5a and 5c (regressive sand, described later). The deposit is a diamicton composed of a pale yellow-white silt matrix (resembling unit 3) containing clasts up to 1 meter in diameter. Almost all the clasts larger than 30 centimeters diameter are well-rounded granitic clasts derived from the Little Cottonwood stock, whereas the smaller clasts are a mix of granitic and Paleozoic rocks. I interpret unit 4 as a debris flow that entered the lake, but it is unclear whether the debris flow was seismically triggered. One nonseismic explanation for the debris flow would be that it occurred during the last minor regression (termed regression U2 by Oviatt, 1997) just before final occupation of the Bonneville highstand (figure 6). If it were triggered by an earthquake, that paleoearthquake would be the oldest for which I have even indirect evidence at this site (Event S?).

After deposition of the diamicton, fine-grained, quiet-water deposition continued at the megatrench site (unit 5). Subunit 5a is mainly pale yellow to olive (reduced?) lacustrine clay and silt, very well sorted and laminated. In the center of the trench subunit 5a is further subdivided into cm-scale beds 5a1-5a7 (figure 5). Subunit 5b is a lacustrine silt, considerably coarser, more massively bedded, and more oxidized than subunit 5b. I interpret subunits 5a and 5b as offshore, deep-water sediments deposited when Lake Bonneville stood at the highstand shoreline.

Between fault zones F2 and F3 unit 5b contains large granite boulders embedded in a highly contorted, pale yellow to green silt matrix. These boulders, and the severe soft-sediment deformation of units 5a, 4, and 4, suggest that a paleoearthquake occurred when unit 5a formed the lake floor. The earthquake (Event T in the megatrench chronology; discussed later) evidently created an east-facing subaqeous scarp by slippage on fault zone F2, and that formed a “backstop” for boulders rolling underwater from the major fault zone F1 farther east. The heavy boulders came to rest against the scarp and either were incorporated into or pressed down onto unit 5b.

Sediment deposited after Event T is 2.2 meters of yellow (oxidized) massive, medium-coarse sand with low-angle foreset beds dipping 5-6 degrees west. This subunit is the youngest lacustrine deposit in the trench, and presumably was deposited when lake level rapidly regressed from the Bonneville highstand shoreline

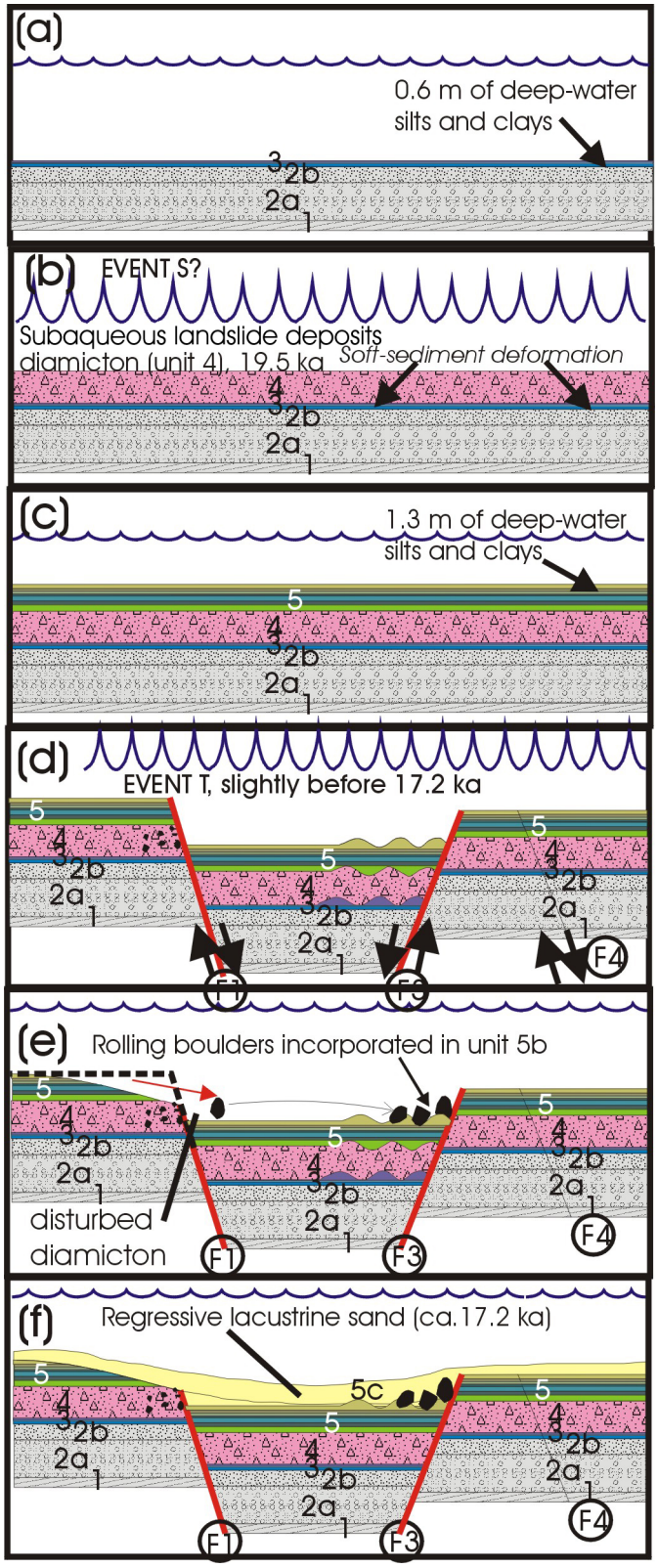


Figure 7. Inferred lacustrine history of the megatrench site. (a) Deep-water silts and clays at the Bonneville highstand, ca. 19.5-20.4 ka; (b) Diamicton deposited (Event S?); (c) Deep-water deposition continues; (d) Event T occurs, forms graben in lake floor; (e) Diamicton is faulted and exposed in free face of F1, isolated boulders roll onto soft clays of unit 5b; (f) regressive sand buries turbidite and fills in graben, during Bonneville flood ca. 17.2 ka.

(above the trench site) to the Provo shoreline (below the trench site) during the Bonneville flood. Normally in the Bonneville Basin, the regressive sand deposited between the Bonneville and Provo shorelines is only about 1 meter thick (Scott and others, 1982), but between faults F1 and F3 in the megatrench subunit 5c is up to 2.2 meters thick. I infer that the sand is abnormally thick there for two reasons: (1) the sand filled a graben created during faulting event T (figure 6d), and (2) the shoreline stayed near the WFZ trace longer than usual, because its downfaulted and backtilted topography sloped more gently than elsewhere on the lake floor.

Soils

A long period of subaerial exposure of unit 5 is indicated by the 1.3 meter-thick soil profile developed on unit 5c. Unit 5c is the oldest unit for which I defined map units based on soil horizons, although that practice is common in overlying units 6-12. Counting down from the surface, the soil developed on unit 5 is the fifth buried soil beneath the present ground surface (b5).

The soil profile developed on unit 5 plays an important role in the reconstruction of the tectonic history at the megatrench site, so I describe it herein in detail. First, like many soil profiles in fault zones, the soil and its component horizons are not exactly parallel to the boundaries of the parent material subunits in which the soil is developed. This angular discordance, seen particularly between 34mH and 40mH, results when parent materials are folded or tilted, then eroded to a gently sloping surface, upon which the soil profile then forms. In such a case, the soil horizons tend to forms at a constant depth below the ground surface, which brings a given horizon into varying stratigraphic levels of the tilted parent materials along a dip section, such as the trench. For example, soil horizon 5cAb5 is developed on the uppermost part of parent material 5c between 26-28mH, but traced westward this soil horizon is developed on successively deeper parts of unit 5c, until at 40mH the horizon is developed on unit 5b. This cross-cutting relationship indicates that soil formation postdates the folding of unit 5. In contrast, the soil horizons in unit 5 between 22-24mH appear to be folded along with the parent materials, indicating that this drag along the fault postdates both the parent material and the soil developed on it.

A second potentially confusing relationship is the overprinting of a younger soil's properties onto an older soil. The best example of this in the megatrench is the overprinting of pedogenic calcium carbonate from buried soil "b4" (developed in unit 6) onto the uppermost part of buried soil b5. The uppermost soil horizon in buried soil b5 is horizon 5cAkb5, a black, organic A horizon that contains stringers and blebs of white calcium carbonate. Calcium carbonate is much too soluble to normally precipitate in a well-developed A horizon, which is typically well-leached by infiltrating rainwater and has an acid pH from the breakdown of organic matter. The calcium carbonate contained in horizon 5cAkb5 is derived from overlying soil b4, which has as its lowest horizon unit 6Bkb4, a B horizon containing pedogenic calcium carbonate. In other words, as soil b4 was forming at the ground surface, carbonate was infiltrating with rain water and traveling downward until it was precipitated at a depth dictated by the average depth of wetting events. This depth just happened to coincide with the A horizon of older soil b5.

Geochronology

The ages of lacustrine deposits in the megatrench are indicated by eight radiocarbon age estimates, but they can also be cross-checked by the regional radiocarbon chronology of Lake Bonneville. In the following discussion, I compare the calibrated radiocarbon ages from the megatrench (calibrated with the CALIB 4.0 computer program of Stuiver and Reimer, 1993) to calibrated radiocarbon ages from the Lake Bonneville regional radiocarbon chronology (figure 6).

Unit 5 yielded eight radiocarbon ages, four from small pieces of charcoal and four from bulk soil organic material. The stratigraphically lowest sample came from unit 5a1 (table 2, sample C27, charcoal) and yielded a calibrated age (Stuiver and Reimer, 1993) of 10,580-11,070 cal yr BP. By comparison, six radiocarbon ages from higher stratigraphic positions in unit 5 yielded ages older than that of C27. Therefore, I infer that the small piece of charcoal in unit 5a1 was intrusive (from bioturbation or root intrusion), and actually dated organics related to the overlying soil horizon 5cAb5.

The next lowest three samples from unit 5 came from the 5cACb5 horizon (table 2, sample C13, soil; C26, charcoal) and from horizon 5cAkb5 (table 2, sample C28, charcoal), developed on the middle part of unit 5c. These three samples yielded essentially identical ages of 13,840-15,310, 13,840-15,270, and 13,820-15,000 cal yr BP, respectively (2-sigma age ranges). These ages are 3,000-4,000 years younger than the age of Bonneville Flood (17.2-18.8 ka), and suggest that organic material in this soil accumulated over several thousand years.

The remaining four samples from the unit 5 soil are from the 5cAb5 horizon (table 2, C3, C12, C12) and the 5cAkb5 horizon (table 2, C10). They yielded a series of ages in which the mean ages are stratigraphically reversed, but all overlap at the one-sigma limit and range from 10,660-11,130 to 11,865-12,855 cal yr BP. These ages are mainly from dispersed organic material in the A

horizon and represent organics that accumulated as the 1 meter-thick, cumulic A horizon developed over millennia after exposure of the lake bottom ca. 17.2 ka.

Previous radiocarbon dating of thin buried soils in WFZ trenches by many workers (see Machette and others, 1992 for a synthesis; also McCalpin and Nishenko, 1996) concluded that the bulk organic material in those 5-10 centimeter-thick A horizons has a mean residence age of ca. 200 years. However, soil 5 is 10-20 times thicker than those thin soils, and may have occupied a flat bench or swale onto which sediments and organic material were slowly added over millennia (a cumulic soil). Therefore, I did not try to correct the raw or calibrated radiocarbon ages for mean residence time of carbon. The carbon throughout the soil accumulated over millennia rather than centuries. Notably, the soil on unit 5 does not contain a B horizon. This lack might be explained by slow cumulic deposition, which continually raised the ground surface and prevented formation of a stable B horizon.

Loess

Unit 6 is comprised of a massive silt that lies unconformably on buried soil b5, and is buried by alluvium of unit 7 (figure 5). Its stratigraphic position atop a well-developed soil indicates it is a subaerial deposit, but its grain size and lack of clasts or stratification indicate it is not a fluvial deposit. I interpret unit 6 as a loess, although it may be loessial silt retransported into a topographic depression such as an ephemeral sag pond. Given the degree of pedogenic clay accumulation in this unit, I cannot be more specific about its depositional environment. However, its stratigraphic position coincides with that of early Holocene loess deposits exposed in trenches at American Fork (Forman and others, 1989) and at Brigham City (McCalpin and Forman, in press).

A strong soil profile is developed in unit 6, composed of horizons 6Btb4 (textural B horizon) and 6Bkb4 (B horizon with carbonate). In addition, the parent material for both horizons has abundant small angular vesicles, which is typical of loess deposits.

Unit 6 pinches out to the east and west and thus has the shape of a lens. However, this shape is partly the result of faulting of the eastern margin of the unit and erosion of the western margin of the unit by alluvial unit 7. Unit 6 occupies the axis of a syncline in the top of buried soil 5, so some of its lenticularity may be a primary depositional feature.

I obtained two radiocarbon ages from unit 6. The lower sample came from the 6Bk soil horizon, consisted of bulk soil organics, and yielded an age of 12,340-12,940 cal yr BP. The higher sample was a small piece of charcoal from soil horizon 6Btb4 and yielded an AMS radiocarbon age of 9,535-9,880 cal yr. BP. The age of the lower sample is older than that of the four ages from underlying horizons 5cAkb5 and 5cAb5 (10,660-13,000 cal yr BP). The age of the upper sample could either date the deposition of the upper part of parent material 6 (if the charcoal was detrital) or the later development of buried soil b4 on unit 6 (if the charcoal was intrusive).

Alluvial Units

The most laterally extensive unit exposed in the trench is a sequence of alluvial sandy gravels and gravelly sands that comprise unit 7. During the initial logging of the trench the alluvial deposit sequences in the eastern, central, and western thirds of the trench were given different unit numbers, because their correlation across the major faults was unclear. By the end of logging, however, it became apparent that all the alluvium belonged to a single, albeit dismembered, blanket of alluvial-fan sediments associated with the mid-Holocene alluvial fan mapped by Personius and Scott (1992; map unit al2 in figures 2a, 2b) north of the megatrench site.

Instead of numbering each sand and gravel bed in unit 7 in stratigraphic order, I labeled multiple beds of similar grain size with the same unit designation. Thus, sandy beds at the base of the alluvium are unit 7a and gravelly beds that comprise most of the middle of unit 7 are unit 7b. Sand beds near the top of unit 7 in the western part of the trench are labeled unit 7c.

Several subunits of unit 7 could be interpreted as either alluvium, debris-facies colluvium, or crack fill. For example, unit 7a1 forms a small lens against fault zone F1 and may be a colluvial wedge. Unit 7e in fault zone F1 is apparently crack fill, although its texture is identical to that of unit 7b. Unit 7 in fault zone F4 is composed of three slightly disturbed beds of sand (unit W7d), gravel (unit W7e), and silt with an A horizon (unit W7fAb4) The disturbance to bedding and texture is small, so it is ambiguous whether these beds should be interpreted as intact blocks of unit 7 alluvium downdropped into a graben, or disaggregated blocks of unit 7 that fell to a crack and thus should be labeled as crack fill. These units are discussed further in the colluvial deposits section.

Although the alluvium assigned to unit 7 throughout the trench is all derived from the same alluvial fan north of the trench site, it is probable that the exposed strata are older in the eastern part of the trench than in the central part, and older in the central part than in the western part. My reasoning for this is that fan deposition is typically restricted to the topographically lowest parts of the terrain. Once faulting creates a scarp, deposition should be restricted to the downthrown block. Following this logic, the part of unit 7 that has been uplifted the

most (that is, in the eastern one-third of the trench, on the footwall of fault zone F1) should represent only the oldest part of the alluvial fan sequence. By this same logic, unit 7 in the central one-third of the trench contains both these oldest fan deposits and somewhat younger deposits, but not the youngest fan deposits, which should only be found in the western one-third of the trench, which is currently at grade with the graben floor. Thus, it is possible that the part of the mid-Holocene alluvial-fan section exposed in the eastern third of the trench correlates with fan deposits that are beneath the floor of the far western part of the trench.

The way to test this hypothesis is to radiocarbon date unit 7 throughout the trench. Unfortunately, datable material was only found in unit 7 in the central part of the trench. Charcoal samples from the bottom and middle of unit 7 yielded AMS radiocarbon ages of 9,250-9,480 cal yr BP and 8,790-9,095 cal yr BP, respectively (2-sigma age ranges). Because this charcoal is not from a soil horizon it is probably not intrusive, so I favor a detrital origin and believe it dates the deposition of the lower and middle parts of unit 7.

The end of unit 7 deposition cannot be dated directly. However, the age of the oldest colluvium that overlies unit 7 forms a minimum age constraint. In fault zone F4 (figure 5b), the first faulting event younger than unit 7 formed a tension fissure into which units W7d, W7e, and W7f were deposited. Subsequently a soil A horizon formed (W7fAb4) and this horizon was later buried the unit W8 colluvial wedge. The A horizon yielded a calibrated age of 7,235-7,815 cal yr BP, which postdates unit 7 by the time needed to fill the fissure and to develop the A horizon. Thus, it appears that the unit 7 alluvial fan ceased deposition at this site about 7,500-8,000 cal yr BP.

Summary of the Pre-Colluvial Stratigraphy

Deposits in the megatrench older than about 8 ka are dominantly (with the exception of units 7a1) lacustrine, eolian, and alluvial. I refer to this as the "pre-colluvial" stratigraphy. As shown in figure 8, units 5a and 5b were probably deposited during the Bonneville highstand and unit 5c during the Bonneville Flood (17.2 ka). Radiocarbon age estimates from the soil on unit 5c are as young as 10.7 ka, indicating a 6.5-ky period of soil formation. During this time period I find no evidence for scarp-derived colluvium, despite the proximity to fault zone F1 which shed four colluvial wedges later in the Holocene.

If the radiocarbon ages from units 5 and 6 are accurate, the unit 6 loess was deposited and its strong soil was formed in only about 1,000 years. This rate of soil development is anomalous compared to soils earlier and later in the Holocene, and argues that soil-forming processes were accelerated by some mechanism between 10 and 11 ka. Two factors were probably involved: (1) the loess may have included a significant clay component, transported as silt- or sand-size aggregates, which infiltrated into the soil profile and produced good B horizon structure, and (2) salts from the exposed lake floor may have been incorporated in the eolian dust, which would have added sodium to the soil and encouraged clay dispersion, again building up soil texture.

Alluvial-fan sediments of unit 7 were deposited from about 9.5 ka to 8 ka. This time period roughly coincides with the period of maximum warming in the early Holocene, previously termed the Altithermal or Hypsithermal interval.

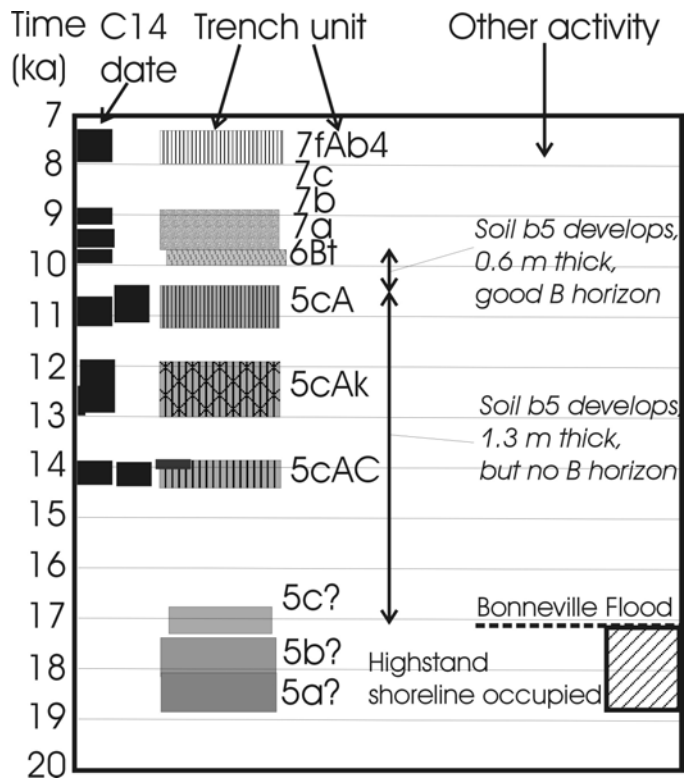


Figure 8. Calibrated C-14 ages (black boxes along vertical axis) from the "pre-colluvial" part of megatrench stratigraphy, compared to Lake Bonneville fluctuations and soil development. Box height represent 2-sigma age range. If unit 5c represents regressive sands from the Bonneville Flood, then soil b5 required about 6,500 years to form, compared to about 1,000 years for soil b4.

Colluvial Units

Colluvial deposits are present at fault zones F1 and F4, and include colluvial wedges and crack fills. Each sequence overlies or cross-cuts unit 7 alluvium. However, because these two sequences of colluvial deposits are not in physical contact their correlation is

uncertain. Accordingly, each sequence is numbered independently, with units E8-E11 at fault zone F1 and W7-W12 at fault zone F4. In the following discussion I first describe colluvial units in the eastern and central parts of the trench from youngest to oldest, and then discuss units in the western end.

Colluvium in the Eastern and Central Parts of the Trench

At fault zone F1 the youngest colluvial wedge (unit E11) overlies the fault trace and is in depositional contact with the footwall, thus it must postdate the most recent event (MRE) on fault zone F1 (Event Ze). Unit E11 contains organic material throughout, probably derived from erosion of the surface A horizon upslope from the free face. The unit E11 wedge extends about 7 meters downslope from fault zone F1 where it pinches out. The age of unit E11 is constrained by two AMS radiocarbon dates. The base of the unit dates at 1,330-1,530 cal yr BP. (C18 in table 2), whereas the top of underlying unit E10b dates at 1,260-1,505 cal yr BP (C17 in table 2). These ages overlap in the range 1,330-1,505 cal yr BP. By comparison, the MRE on this fault segment was dated by Black and others (1996) between 1,100-1,550 cal. yr B.P. (mean age 1,300 cal. yr B.P.). Thus, my bracketing dates on the MRE agree well with previous estimates.

Underlying the MRE wedge is a faulted colluvial wedge (unit E10) composed of a matrix-supported gravelly upper half (unit E10b) and a better stratified, darker (more organic), clast-supported lower half (unit E10a). This wedge predates the MRE (Event Ze) and postdates the penultimate event (PE), or Event Ye. The proximal part of unit E10 is much smaller in volume than unit E11, extending only about 2 meters downslope from the main fault in fault zone F1. However, a more distal (wash-facies) equivalent to unit E10 (unit E10c) extends from 24.5-40mH (figure 5). These two facies are inferred to be parts of the same colluvial deposit, a portion of which was eroded away between 21.5-24mH. Note that the “missing” part of unit E10 between 21.5-24 mH coincides with a structurally uplifted domain in which subjacent units (such as E8Bt2) are uplifted as much as 1 meter relative to outside the domain. Thus, I interpret units E10a, E10b, and E10A as being part of a single colluvial wedge that extends nearly 20 meters downslope from fault zone F1 before pinching out.

Organic material from the uppermost part of unit E10b yielded an AMS date of 1,260-1,505 cal yr BP. This date indicates that the surface of unit E10b was buried by the deposition of unit E11 at that time, so the date constrains Event Ze to be about 1,260-1,505 cal yr BP. A second sample from the E10a/E10b contact yielded an AMS age of 1,620-2,000 cal yr BP. This age shows that the base of unit E10 is older than 1.6-2 ka, and thus the PE (Event Ye) must be somewhat older than 1.6-2 ka.

The next oldest colluvial deposit (unit E9) forms the largest colluvial wedge in the trench, extending from fault zone F1 to fault zone F2, a horizontal distance of 25 meters, and is up to 2 meters thick. A moderately strong buried soil (soil b1, composed of horizons E9A/E9AB/E9Bt) is developed through the entire thickness of the unit. Due to the thick (cumulic?) accumulation of organic matter and the faulting of unit E9 by down-to-the-east strands of fault zone F1, I could not define the facies contact between proximal (debris-facies) and distal (wash-facies) colluvium in this unit. Unit E9 predates Event Ye and postdates Event Xe. An AMS age on the uppermost part of the strong A horizon (E9Ab1) yielded a date of 700-945 cal yr BP. This age is younger than the two overlying dates previously cited, and is assumed to be contaminated with younger (intrusive?) carbon. I collected two samples from the middle and bottom of horizon E9ABb1, which yielded ages of 3,060-3,330 and 3,870-4,530 cal yr BP. Strict reliance on these dates would indicate that Event Ye occurred after ca. 3.1 ka, and before the 1.6-2 ka date from unit E10. By comparison, Black and others (1996) reported an age of 2,100-2,800 cal yr BP (mean age 2,450 cal yr BP) for the penultimate event (event Y) on this fault segment. The Black and others (1996) constraints on Event Y thus overlap mine, but form a tighter age constraint.

The next oldest colluvial deposit in fault zone F1 is unit E8, which I interpret as mainly crack fill, although some of the material may be parts of a scarp-derived wedge that has been downfaulted into fault zone F1. Because unit E8 has been faulted three times (Events Ze, Ye, and Xe), its original geometry is difficult to establish. After deposition of unit 8 but before deposition of unit 9, a thin textural B horizon (unit E8Bt2b2) formed, which comprises buried soil b2. Unit E8 predates Event Xe and postdates Event We. A sample of dispersed soil organics from the stratigraphically lowest part of unit E8A yielded an AMS age of 5,060-5,320 cal yr BP (C20 in table 2). If this age is uncontaminated, it implies that Event We occurred slightly before 5.1-5.3 ka, and that Event Xe occurred sometime between 3.9-4.5 ka (sample C21 in table 2) and 5.1-5.3 ka. By comparison, Black and others (1996) date their event W between 4,950-5,750 cal yr BP (mean age 5,300 cal yr BP). Thus, my event W correlates well with their event W. Unit E8 also contains a thin, stratified alluvial gravel that extends discontinuously as far west as 40mH. This deposit is correlated with colluvial units near fault zone F1 because it occupies a similar stratigraphic position, above unit 7 alluvium and below unit 9 colluvium. However, the alluvium could be slightly older or younger than the colluvium.

The oldest colluvial deposits include unit 7a1 and unit 7e. The former may be a colluvial wedge (unit 7a1) shed from fault zone F1 at 23.5mH. This small wedge-shaped diamicton with downslope clast fabric lies atop unit 6 and interfingers with the basal alluvium of unit 7. It might be argued that this small pocket of gravel is merely a channel of poorly sorted alluvium (debris flow?) exposed in cross-section. However, retrodeformation analysis of fault zone F1 (described later) demonstrates that there must have been a faulting event post-unit 6 and pre-unit 7 to account for stratigraphic relations in fault zone F1.

Unit 7e is broadly defined as older crack-fill deposits that underlie unit 8 crack fill and colluvium. These crack-fill deposits extend to the bottom of the trench and may include more than a single unit, but repeated faulting has thoroughly mixed the deposit.

In summary, the small graben in fault zone F1 contains four colluvial deposits (units E11, E10, E9, and E8) the ages of which compare relatively well with those of the four latest events dated by Black and others (1996) 3 kilometers farther south on the Salt Lake City segment. The agreement is best for Events Z and W, and poorer for Events Y and X. The colluviums from the older two events have been so deformed by the younger two events that it is difficult to tell which unit a radiocarbon sample was obtained from. However, it should be emphasized that the megatrench was not sited to optimize dating of the four latest events, but rather the older Holocene and latest Pleistocene events. Older crack fill exists (unit 7e) but cannot be differentiated into subunits.

Colluvium in the Western End of the Trench

Colluvial deposits in the western end of the trench are scarp-derived colluvial wedges and cracks fills associated with fault zone F4 (figure 5). The youngest two deposits are W11 (proximal, debris-facies colluvium deposited after Event Zw) and unit W12, which is finer grained, better stratified, and overlies unit W11. During initial logging I interpreted unit W12 as post-Event Zw graben-fill alluvium. However, the westward slope of the top of unit W12 and its position slightly above the graben floor suggest it is more likely wash-facies colluvium. Unit W12 carries a weak soil (A/AC horizons) and is composed of map units W12A and W12AC. I was unable to find any radiocarbon-datable material in units W11 or W12, but a radiocarbon sample from the top of underlying soil horizon W10Ab1, directly beneath unit the W11 colluvial wedge, yielded an AMS age of 925-1,230 cal yr BP (C23 in table 2). This age indicates that the MRE colluvium buried the underlying soil about 0.9-1.2 ka, which forms a close maximum limiting age on Event Zw. Such an age range is several hundred years younger than the age range for the MRE on fault zone F1 (1,330-1,505 cal yr BP.) but partially overlaps the age range inferred by Black and others (1996) (1,100-1,500 cal yr BP.).

The next older colluvium (unit W10, on the footwall of fault zone F4) has three parts: (1) a proximal, debris-facies part, (2) an underlying tension crack fill that extends 0.6 meters below the bottom of the wedge, and (3) a finer, wash-facies part (between 54mH and the western end of the trench) that is affected by soil formation. The wash facies is divided into map units W10Ab1, W10ABb1, and W10 (figure 5). The proximal and distal parts of unit W10 are separated by a zone of fault-bounded blocks of footwall stratigraphic units, indicating that this colluvium has been faulted at least once. Organic material from the bottom of the tension crack yielded a radiocarbon age of 2,160-2,350 cal yr BP. This age should provide a very close maximum age constraint on Event Yw. By comparison, Black and others (1996) dated their penultimate event at 2,100-2,800 cal. yr B.P. (mean age 2,450 cal yr BP), so my age estimate for Event Y overlaps theirs. The radiocarbon age of the tension crack part of unit W10 does not correlate with any of the radiocarbon ages obtained from fault zone F1, yet the stratigraphic context of the crack fill is much easier to relate to a paleoearthquake than the mixed stratigraphy adjacent to fault F1.

Beneath unit W10 is a similar looking, poorly sorted colluvial deposit shed after Event Xw. This deposit (unit W9, figure 5) carries an even better developed soil than does unit W10, being composed of horizons W9Ab2, W9Btb2, and W9. Only the part of unit W9 within about 2 meters of the fault plane is scarp-derived colluvium (unit W9a). West of that point unit W9 becomes moderate to well stratified and must represent a coeval fluvial facies that aggraded contemporaneously with the scarp-derived colluvium. I AMS dated a small piece of A horizon in the F4 fault zone (unit W9Ab2) at 1080-1315 cal yr BP (C22 in table 2). Either our correlation of this small chunk of soil with W9Ab2 is incorrect, or the sample (adjacent to a krotovina) is contaminated with younger carbon.

The next oldest unit (W8) is complex and is composed of three contemporaneous facies. Nearest to the fault plane this deposit is coarse debris-facies colluvium (unit W8a) that contains blocks of footwall material. Most of the lateral extent of unit W8 is a matrix-supported gravelly sand, probably wash-facies colluvium (unit W8b). The farthest west part of unit (W8c) is a massive silt, either a fine-grained alluvial swale fill (overbank facies?) or reworked loess. The soil developed on unit W8 is the third buried soil beneath the surface (b3) and is missing it's A or AB horizon. Instead, the uppermost horizon is a Bt horizon (unit W8bBtb3), with a lower Bt2 horizon (unit W8bBt2b3) developed between 55-56mH. I could not find any datable material in unit W8.

The oldest colluvial deposit associated with fault zone F4 forms a downward-tapering wedge adjacent to the fault plane (figure 5b). I have numbered this deposit "7," the same number used for the Holocene alluvium, for several reasons: (1) the two lower units (W7d and W7e) resemble units 7c and 7b, respectively, that is they are fluvial sands and gravels; (2) however, their fabric and texture suggest they may be disturbed correlatives of units 7b and 7c that fell down into a tension fissure; and (3) the uppermost unit (W7fAb4) is an A horizon developed in a massive silt that has no counterpart within alluvial unit 7, although it does resemble the massive silt of unit W8c. The sequence of events here appears to be: (1) the fissure forms during Event Vw, (2) blocks of unit 7 drop into the fissure from a small free face, but do not completely fill the fissure before the free face is completely degraded, (3) silt blows into the fissure and fills it up to ground level, and (4) an A horizon forms on the silt.

Clearly, this fissure-filling material and its soil (unit W7fAb4) must postdate alluvial unit 7 and predate the deposition of the proximal colluvial wedge of unit W8 (unit W8a), by a sufficient amount of time to form a soil on the crack fill. If unit W8 was deposited after Event Ww, then units W7d-7f must have been deposited after Event Vw. An AMS age from bulk matrix of unit W7fAb4 yielded an age of 7,235-7,815 cal yr BP. Thus, Event Vw must have occurred before 7.2-7.8 ka and Event Ww must have occurred shortly after 7.2-7.8 ka, because proximal colluvium shed from its free face (unit W8) buried the dated soil. This constraint implies that Event Ww is ca. 2,000 years older than event We on fault zone F1 (dated about 5,060-5,320 cal. yr BP) and event W of Black and others (1996; dated about 5,300 cal yr BP). Therefore, it appears that Black and others' (1996) events W and X (5.3 ka and 3.95 ka, respectively) correlate with only one event on fault zone F4, the event that shed colluvial unit W9. Because unit W9 did not yield any datable material, I do not know if my Event Xe correlates with Black and others' (1996) 5.3 ka event or 3.95 ka event.

Soil Profile Development

The degree of soil profile development on deposits in the megatrench holds additional clues as to the timing of depositional and faulting events. Previous studies on the WFZ (McCalpin and Berry, 1996; McCalpin and Forman, in press), the East Cache fault (McCalpin, 1994), and other normal faults (Machette, 1978, 1988; Berry, 1990; Birkeland and others, 1991, pp. 44-48; Gerson and others, 1993; Birkeland, 1999) had used soil development as a basis for estimating the sequence and crude timing of paleoearthquakes.

Estimating soil development times is not critical for determining the timing of the latest four events (W-Z) on the Salt Lake City segment because I have sufficient radiocarbon ages in this time period. In addition, in only 5,000 years soils develop so little pedogenic clay that the amount is similar to the uncertainty in primary clay estimates, throwing quantitative analysis results in doubt. However, the older Holocene and latest Pleistocene soils in the megatrench have had more development time, thus making quantitative soil analysis (table 3) a viable technique for establishing the timing of older paleoearthquakes.

The best-developed soil in the pre-colluvial stratigraphy is that developed on unit 6, with some additional clay infiltrating down into the top of unit 5 and thus "overprinting" the upper soil (horizon 6Bkb4) onto the lower soil (horizon 5cAkb5) (figure 9). The loess (unit 6) and its soil must have developed in a brief time, bracketed by the maximum age of charcoal in upper unit 5 (11,560 cal yr BP) and minimum age of charcoal in lowermost unit 7 (9,250 cal yr BP). This ≤2,310 year time span does not seem sufficient to deposit the loess and to develop the moderately strong Bt/Bk soil profile, at modern rates of soil development. For example, soil horizons 6Btb4, 6Bkb4, and 5cAkb5 are all enriched in secondary (pedogenic) clay (an

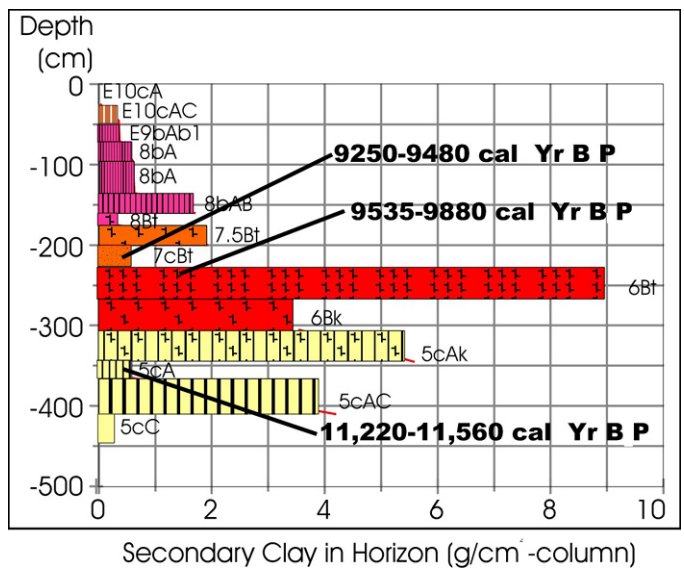


Figure 9. Estimated mass of secondary (pedogenic) clay (g per cm² column) in Soil Profile 3 (15 horizons; see figure 5) at 29 mH in the megatrench. Secondary clay amounts are from table 3 Soil horizon abbreviations are to right of histogram bars and match the trench log (figure 5). Radiocarbon ages (in bold) are all on charcoal and show the time available for soil development.

Table 3. Clay content of four soil profiles, with estimates of primary and secondary clay and estimated soil development times.

Profile	1 horizon	Total Clay Content	Gravel Content	Corr. Clay Content	Prim. Clay Content	Second Clay% Content	Horiz. Thickness (cm)	Depth (cm)	Bulk Dens. (g/cm^3)	Grams Clay	Accum. Rate	Soil Time (g/ky)	Cum. Time (ky)	C-14 Age (ka)
	E11A1	0.16	0.11	0.14	0.14	0.00	25	25	1.34	0.09	0.27	0.34	0.34	
	E11AB	0.16	0.18	0.13	0.10	0.03	30	55	1.47	1.40	0.27	5.20	5.54	
	E11B1	0.14	0.11	0.12	0.10	0.02	20	75	1.53	0.76	0.27	2.80	8.34	1.3-1.5
	E10B2top	0.11	0.27	0.08	0.10	-0.02	25	100	1.36	-0.66	0.27	-2.44	5.90	1.3-1.5
	E10B2bot	0.17	0.03	0.16	0.10	0.06	25	125	1.61	2.61	0.27	9.67	15.58	1.6-2.0
	E9B3	0.16	0.17	0.13	0.10	0.03	45	170	1.57	2.27	0.27	8.42	23.99	
	E8AB	0.08	0.31	0.06	0.10	-0.04	25	195	1.54	-1.72	0.27	-6.39	17.60	5.1-5.3
	5bB3	0.16	0.07	0.15	0.10	0.05	20	215	1.41	1.39	0.27	5.13	22.73	19.5
Profile	2													
	7AB	0.15	0.34	0.10			45		1.62					
	7Bt1	0.15	0.31	0.10			20		1.56					
	7Bt2	0.14	0.17	0.12			15		1.45					
Profile	3													
	9cA	0.14	0.34	0.09	0.10	-0.01	25	-25	1.37	-0.27	0.42	-0.64	-0.64	0
	9cAC	0.14	0.27	0.10	0.10	0.00	20	-45	1.49	0.05	0.42	0.12	-0.53	
	8bAupper	0.14	0.27	0.10	0.10	0.00	25	-70	1.52	0.06	0.42	0.15	-0.38	
	8bAmid	0.14	0.23	0.11	0.10	0.01	25	-95	1.41	0.30	0.42	0.71	0.34	
	8bAlower	0.14	0.24	0.11	0.10	0.01	40	-135	1.41	0.33	0.42	0.78	1.12	
	8bAB	0.15	0.29	0.11	0.07	0.04	25	-160	1.51	1.40	0.42	3.33	4.45	
	8Bt	0.12	0.40	0.07	0.07	0.00	15	-175	1.58	0.05	0.42	0.11	4.57	
	7.5Bt	0.13	0.31	0.09	0.05	0.04	25	-200	1.66	1.63	0.42	3.88	8.45	
	7cBt	0.09	0.37	0.06	0.05	0.01	25	-225	1.57	0.28	0.42	0.67	9.12	8.8-9.1
	6Bt	0.36	0.00	0.36	0.20	0.16	40	-265	1.4	8.96	3	2.99	12.11	9.5-9.9
	6Bk	0.26	0.00	0.26	0.20	0.06	40	-305	1.35	3.24	3	1.08	13.19	
	5cAk	0.18	0.00	0.18	0.08	0.10	40	-345	1.32	5.28	3	1.76	14.95	17.2
	5cA	0.09	0.00	0.09	0.08	0.01	20	-365	1.47	0.29	3	0.10	15.04	17.2
	5cAC	0.14	0.00	0.14	0.08	0.06	45	-410	1.44	3.89	3	1.30	16.34	17.2
	5cC1	0.08	0.00	0.08	0.08	0.00	35	-445	1.35	0.00	3	0.00	16.34	17.2
Profile	4													
	W12A	0.09	0.46	0.05					1.5	0.04				
	W12AC	0.07	0.49	0.04					1.57					
	W11	0.14	0.19	0.11					1.57					
	W10Ab1	0.14	0.24	0.11					1.51					
	W10ABkb1	0.13	0.15	0.11					1.66					
	W9Ab2	0.18	0.22	0.14					1.57					
	W9Btb2	0.13	0.26	0.10					1.58					
	W9	0.15	0.19	0.12					1.57					
	W8aBtb3	0.15	0.12	0.13					1.45					
	W8aBt2b3	0.16	0.16	0.13					1.61					
	W8	0.15	0.16	0.13					1.57					

NOTES:

Profile 1—Primary Clay Content is estimated from clay content of horizon least affected by soil formation . Secondary Clay Content equals Total Clay Content minus Primary Clay Content. Negative values for Secondary Clay Content are allowed to stand in this example, which is a test of the reasonableness of Shroba's (1987) clay accumulation rate of 0.27 grams per cm^2 per ky. For Holocene colluvium (units E8-E11), Shroba's (1987) clay accumulation rate predicts ages 3-6 times too old compared to radiocarbon ages. This discrepancy is probably caused by using too low a value for Primary Clay Content. In contrast to Shroba's soils that formed on stable geomorphic surfaces, the colluvial deposits at the megatrench are derived from erosion of older soils exposed in the fault free face, and those older soils already contain Secondary (pedogenic) Clay. Unlike Carver and McCalpin (1996, p. 208), I have not explicitly tried to correct for those recycled soil constituents.

Profile 2—No quantitative calculations were made on this partial profile.

Profile 3—Calculations are identical to those in Profile 1, except: (1) Shroba's (1987) clay accumulation rate for colluvial soils has been increased by 60% to account for footslope enrichment processes (McCalpin and Berry, 1996), and (2) the clay accumulation rate for units 5 and 6 was adjusted until the age predicted for horizon 5cC1 approached its estimated age of 17.2 ka. This requires a clay accumulation rate of ca. 3 g/cm^2/ky, or 11 times the post-Provo average of Shroba (1987) for stable geomorphic surfaces.

Profile 4—No quantitative calculations were made on this profile.

estimated 8.96 g/cm^2, 3.24 g/cm^2, and 5.28 g/cm^2, respectively). Estimated total pedogenic clay is thus 17.48 g/cm^2. At an average post-Provo clay accumulation rate of 0.27 g/cm^2/ky (Shroba, 1987), this clay would have required 65 ky to form. However, the charcoal ages indicate less than about 2 ky of soil development time.

One source of uncertainty in the above calculation is the primary clay content of the three soil horizons. I assumed that unit 5 contained 8 percent primary clay, based on the clay content of unit 5cC, and that unit 6 contained 20 percent primary clay, based on Shroba (1987). However, the loess may have been affected by footslope "enrichment" processes, which McCalpin and Berry (1996) show increases soil formation rates by a factor of about 1.6 along the WFZ. Thus, it may be more appropriate to normalize the 17.48 g/cm^2 of clay by dividing by 1.6, yielding 10.9 g/cm^2 of secondary clay. However, to accumulate 10.9 g/cm^2 of clay in only 2.31 ky requires a clay accumulation rate of 4.72 g/cm^2/ky, or about 17 times the average post-Provo clay accumulation rate of 0.27 g/cm^2/ky. This accelerated rate of soil formation was also observed at the Brigham City trench site on the WFZ (McCalpin and Forman, in press), where the rate from 13-8 ka was about 9 times the average post-Provo rate.

Post-Trenching Geophysics

After the megatrench was backfilled in September 1999, Dr. Gerard Schuster and colleagues at the University of Utah performed a seismic refraction survey 20 meters north of and subparallel to the western two-thirds of the megatrench. They identified three "low-velocity zones" (LVZs) which they interpreted as colluvial wedges. The stratigraphically highest LVZ was inferred to represent the scarp-derived colluvium shed from fault zone F4 (units W12 through W8 of this study). Two deeper LVZs were imaged several meters below the floor of the trench west of fault zone F4, and were inferred to be older colluvial wedges.

I do not believe that these two lower LVZs are scarp-derived colluvium, and I generally question the assumption that the lowest-velocity deposits in a normal fault zone are scarp-derived colluvium. My objections to the assumption are based on two beliefs: (1) that bulk density of deposits in the megatrench correlates with gravel content (see table 4), not with deposit origin, and (2) that P-wave velocity of deposits should be proportional to their bulk density.

Table 4 shows the bulk densities of 31 soil samples from various deposit facies in the megatrench. The table lists the two lowest-density facies first (loess, unit 6; regressive sand, unit 5c), followed by colluvium and alluvium in order of increasing age. It is apparent that the two gravel-free facies (loess, mean density 1.38±0.04 g/cm^3) and regressive sand (mean density 1.39±0.07 g/cm^3) are much less dense than any of the gravel-bearing facies (mean densities from 1.51±0.07 to 1.62±0.05 g/cm^3). Among the gravel-bearing facies, the four colluvial wedges mainly derived from unit 7 are only slightly less dense (mean densities from 1.51±0.07 to 1.56±0.03 g/cm$^{3)}$ than the alluvium itself (mean density 1.62±0.05 g/cm^3. Therefore, I interpret all the LVZs at the megatrench as clast-free sands or silts, of either eolian or lacustrine origin. In future studies, I would encourage geophysicists to make in situ P-wave velocity measurements in the trench before it is backfilled, so they can calibrate their deeper geophysical surveys based on the velocities of known fault zone deposits.

Table 4. Bulk density (grams per cm^3) of various facies in the megatrench.

Facies	Sample	Density (g/cm^3)	Mean	sigma
loess	6Bt	1.4	1.38	0.04
	6Bk	1.35		
regressive sand	5cA	1.47	1.39	0.07
	5cAK	1.32		
	5cAC	1.44		
	5cC1	1.35		
colluvium, post-Event Z	W12A	1.5	1.53	0.04
	W12AC	1.57		
	W11	1.57		
	E11AB	1.47		
	E11B1	1.53		
colluvium post-Event Y	W10Ab1	1.57	1.55	0.11
	W10ABkb1	1.66		
	E10B2	1.36		
	E10B2	1.61		
colluvium, post-Event X	W9Ab2	1.57	1.56	0.03
	W9Btb2	1.58		
	W9	1.57		
	9cAC	1.49		
	E9B3	1.57		
colluvium, post-Event W	W8aBtb3	1.45	1.51	0.07
	W8aBt2b3	1.61		
	W8	1.57		
	8bA	1.52		
	8bA	1.41		
	8bA	1.41		
	8bAB	1.51		
	8Bt	1.58		
	E8AB	1.54		
Early Holocene fan alluvium	soil 7cBt	1.57	1.62	0.05
	7.5Bt	1.66		

SEQUENCE OF FAULTING EVENTS

Overview

I reconstruct the sequence of faulting events on fault zones F1 and F4 by use of graphic retrodeformation sequences, in which a series of cross-sections are generated "back in time" by progressively removing, step by step, the youngest deposits and then reversing movement on the fault planes to achieve the pre-faulting geometry. For faults F2 and F3 I directly inferred the small number of displacement events without a retro sequence.

Fault Zone F1

The common interpretational paradigm used on normal faults is that each faulting event is followed rapidly by deposition of a crack fill and/or colluvial wedge deposit. Past trenching investigations on the WFZ (Machette and others, 1992) have shown that soils typically have sufficient time (1,000-3,000 years) to form on a colluvial deposit before it is buried by the next one. Therefore, merely counting the colluvial deposits and their associated soils should yield the number of faulting events. In fault zone F1 (figure 5) there are four colluvial deposits excluding the deep crack-fill mélange of unit 7e (from top to bottom, units E11, E10, E9, and E8). Unit E11 has the typical wedge-shape of a scarp-derived colluvial wedge, while the other units becomes progressively deformed due to their sagging down into a small graben created by blocks of sediment (domino blocks) pulling away from the fault footwall. The radiocarbon age constraints on these four most recent events are listed below:

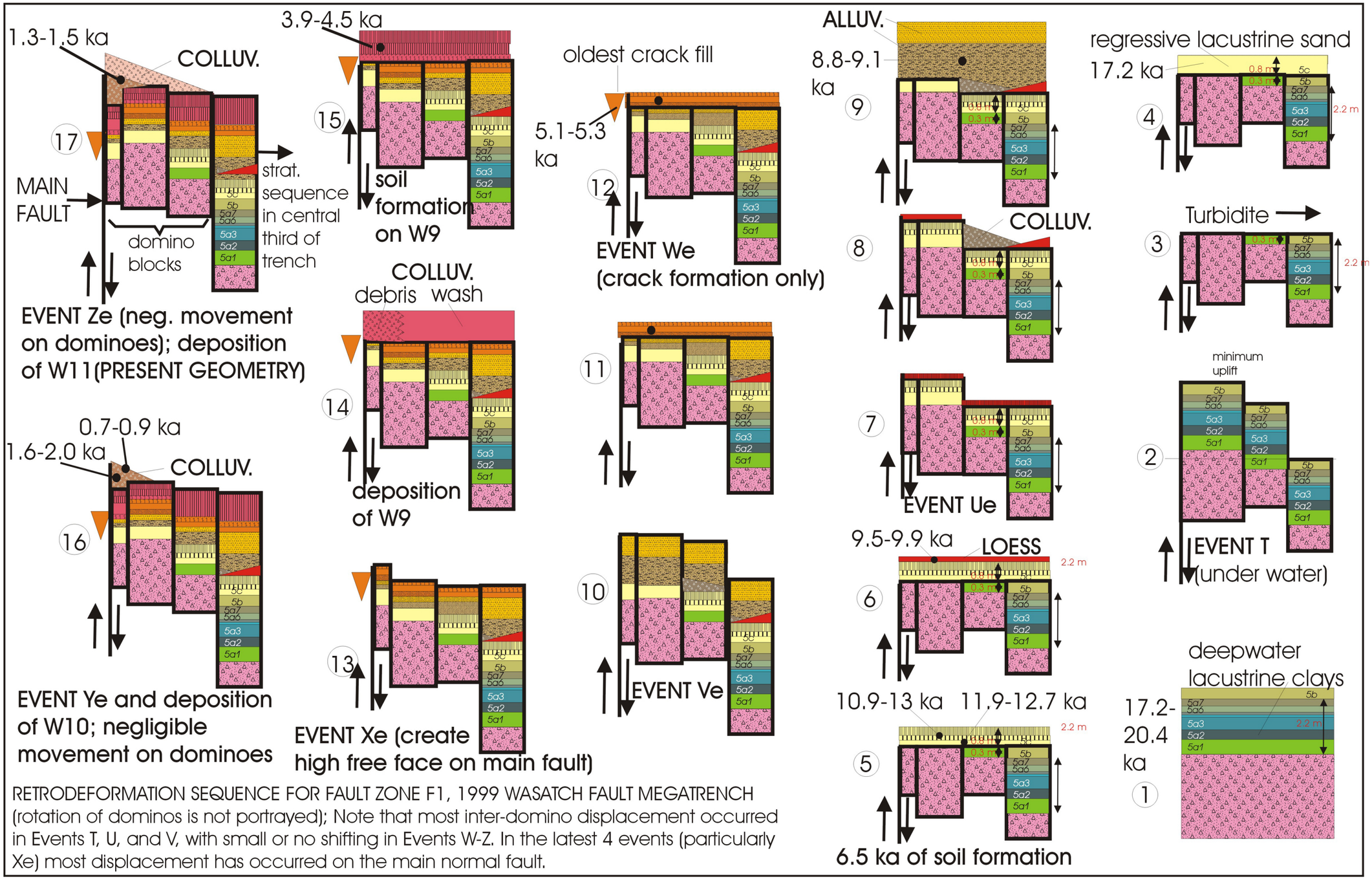
Table 5. Summary of age constraints on the latest four faulting events on fault zone F1.

Event	Colluvial Unit	Min. Age (cal yr BP)	Max. Age (cal yr BP)
Ze	E11	1,330-1,530	1,260-1,505
Ye	E10	1,620-2,000	[bad date]
Xe	E9	3,060-3,330, 3,870-4,530	none close
We	E8		5,060-5,320 (close)

In addition, a small suspected colluvial wedge (unit 7a1) is interbedded with the basal part of alluvial unit 7 (at 23.5mH; figure 5). If this deposit is a colluvial wedge and is correlative with all of unit 7e farther east, then there is evidence for only one paleoearthquake between ca. 17.2 ka (age of unit 5c) and ca. 5 ka. Fortunately, there is another independent line of evidence for vertical displacements in fault zone F1, and that is the attenuation of the stratigraphic section in the domino blocks in relation to the same section farther west in the trench. A cursory examination of figure 5 shows that, in the center of the trench clayey units 5a and 5b reach an aggregate thickness of 2.2 meters, unit 5c is 1.9 meters thick, unit 6 is 1 meter thick, and alluvial unit 7 is 1.9 meters thick. In contrast, some of these units are entirely missing atop the dominoes, while others exist, but at reduced thicknesses. For example, unit 5c is only 0.6 meters thick atop the western domino but contains soil horizons 5cAb5, 5cACb5, and 5cCb5, whereas atop the adjacent domino to the east, only 0.4 meters of unit 5cCb5 exists. In order to explain this difference in deposit and soil thickness I postulate that unit 5c and its soil once existed atop both dominos, but at some time before the deposition of alluvial unit 7 the eastern domino was elevated by faulting with respect to the western domino, and the upper part of unit 5c and its soil were eroded. The basic assumption here is that, since units 5b and 5c exist in the farthest eastern part of the trench, they also existed at one time across the entire length of the trench.

Following this line of reasoning, I constructed a series of schematic cross-sections that progress backward in time from the present trench geometry in fault zone F1 (figure 10). I simplified the diagrams by straightening out the domino-bounding faults and removing the forward rotation of the dominos. Because the differential erosion of the domino tops was caused by differential vertical displacement on their bounding faults, I felt that neglecting the rotation was justified, as long as I preserved the vertical displacements. To move backwards in time with the sequence, I started with the present (schematic) geometry of the domino and removed the youngest deposit. I then reversed the movement on the faults until the base of the youngest remaining unit was horizontal. Finally, I increased the stratigraphic thickness of that unit on any structural block where the present thickness is less than the thickness outside of fault zone F1. This step is equivalent to assuming that each deposit and soil horizon originally covered the fault zone with constant thickness. The stratigraphic thickness added in this step also equals, by definition, the vertical displacement of the fault blocks in the preceding step.

The retrodeformation sequence relies on both colluvial wedges, crack fills, and differences in thickness of units E9 and E8 to reconstruct the latest four faulting events (Events Ze, Ye, Xe, We). Differential thickness of unit 7 alluvium across the dominoes requires a significant displacement event (Event Ve) between units 7 and 8. The absence of unit 6 on the dominoes, and the existence of colluvial wedge 7a1, requires an event following deposition of unit 6 (Event Ue). Finally, the



RETRODEFORMATION SEQUENCE FOR FAULT ZONE F1, 1999 WASATCH FAULT MEGATRENCH (rotation of dominos is not portrayed); Note that most inter-domino displacement occurred in Events T, U, and V, with small or no shifting in Events W-Z. In the latest 4 events (particularly Xe) most displacement has occurred on the main normal fault.

Figure 10. Retrodeformation sequence for fault zone F1. Colors and patterns match those in figure 5.

absence of units 5a and 5b on the dominoes requires an event between units 5b and 5c. A subaqueous event in this same time span (Event T) was previously inferred from the granite boulders embedded in unit 5b and associated soft-sediment deformation. Inclusion of these three displacement events within the time period 20 ka to ca. 5 ka satisfies all the present geometric constraints, without the need for additional displacement events. Using the principle of parsimony, our interpretation is that as few as 7 displacement events can adequately explain the present geometry of fault zone F1, and that there is no need to postulate additional events. The only ambiguity is whether the unit 4 debris-flow deposit was triggered by an eighth earthquake (Event S?).

The timing of these three unambiguous pre-5 ka displacement events is constrained by sparse radiocarbon ages. Event Ve occurred after 8.8-9.1 ka but before 5.1-5.3 ka, that is, late during the deposition of alluvial unit 7**.** Event Ue occurred shortly after the formation of buried soil 4 on unit 6, dated at 9.5-9.9 ka. Event T must have occurred while this site was still submerged beneath Lake Bonneville. The center of the trench is presently at an elevation of 5,160 feet (1,573 m), or roughly 80 feet (25 m) below the Bonneville highstand shoreline as carved on the north lateral moraine of Little Cottonwood Canyon. According to Oviatt (1997) the lake shoreline was within 25 meters of the highstand elevation only for a short time between ca. 17.2 ka (Bonneville flood) and 20.4 ka (figure 6). Therefore, the shoreline was only within 25 meters of the highstand between 17.2 ka and 20.4 ka, which form tight age brackets on Event T.

Fault Zone F2

Fault zone F2 has a total throw of 0.4 meters measured on the top of unit 5cA. Throws measured on units higher and lower are essentially identical, and there are no colluvial wedges preserved along the fault. This geometry suggests that the entire 0.4 meters of throw occurred in a single event that must postdate unit 8b. Two events (Event Ze, Ye) fall into this time interval on fault zone F1, so the displacement on F2 may be contemporaneous with either event. I did not collect any radiocarbon samples to try and constrain the age of this event, because the fault is such a minor structure, and it was deemed unlikely that a surface-rupturing event would cause movement on this fault without also causing movement on the major fault zones F1 or F4, the chronologies of which were dated in detail.

Fault Zone F3

Fault zone F3 does not contain any colluvial wedges from which to infer the number of events that have contributed to its 2 meters of throw. However, the upper part of the fault is marked by a 10 to 15-centimeter-wide fissure filled with organic material. I identified a higher, looser, younger, more organic fissure fill in the upper 1 meter of the crack, underlain by a lower, denser, and less organic crack fill. My inference was that each crack fill deposit accumulated rapidly after a faulting event from A or AC horizon soil material falling into the crack from the surface soil. Accordingly, I dated the lowest parts of the upper and lower crack fill deposits. The upper crack fill deposit yielded an AMS age of 1,315-1,600 cal yr BP. This age is quite similar to the closely limiting maximum age of 1,260-1,505 cal yr BP on Event Ze on fault zone F1, and suggests that this fissure may have opened during that event.

The older crack fill unit yielded an AMS age of 3,220-3,380 cal yr BP. This age does not exactly coincide with any date from fault zone F1, and I am not sure why. One possibility is that the dated soil material fell into the crack during Event Ye (ca. 2.5 ka), but contained soil carbon with an abnormally long mean residence time (ca. 1,000 years). Another possibility is that the dated soil material fell into the crack during Event X of Black and others (1996; ca. 4.9 ka), but was later burrowed and younger carbon was mixed in..

Fault Zone F4

Due to the simple geometry of fault zone F4, the chronology of all displacement events younger than alluvial unit 7 can be reconstructed from colluvial-wedge evidence. However, the trench was not deep enough on the hanging wall of F4 to expose the stratigraphic levels at which evidence for the three pre-5 ka events might be found (that is, the base of unit 7 and lower). The retrodeformation sequence (figure 11) is based on several assumptions: (1) the free face created during each event W-Z had to be at least as high as the thickness of the colluvium deposited after the event (units W8-W11, respectively), (2) the free faces created during Events Ww and Xw were composed only of unit 7 alluvium, that is, unit 5 did not daylight, (3) the free faces of Events Yw and Zw did daylight unit 5 in the free face, and (4) by the present time, erosion has removed all of unit 7 from atop the F3/F4 horst. As shown by the retrodeformation sequence (figure 11), removal of colluvial units W11, W10, E9, and W8, and reversal of displacement according to the rules listed above only removes 7.5 meters of the 10 meters of total throw on this zone, or about 1.8 meter per event. This amount of throw is somewhat less than the 2 meters per event that is typical of paleoearthquakes on the WFZ, but if the same events simultaneously ruptured fault zone F1 by an additional 1 meter, then the net down-to-the-west displacement would have summed to about 2.8 meters per event. By comparison, the total throw of 18.3 meters on faults F1 and F4, if divided among 7 events, averages 2.6 meters per event.

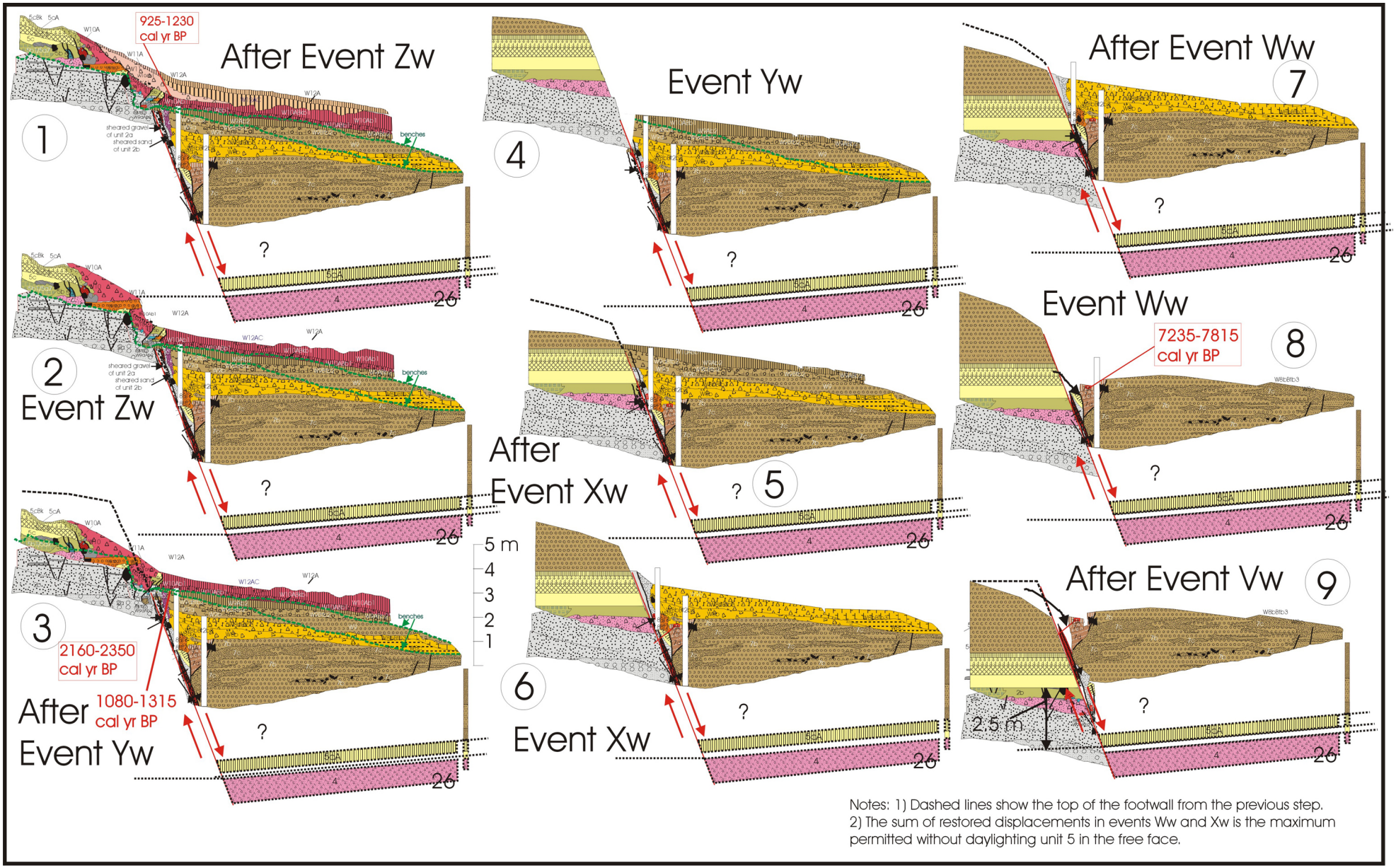


Figure 11. Retrodeformation sequence for fault zone F4.

Notably, after "removal" of the latest four events (Zw, Yw, Xw, Ww) there is still 2.5 meters of throw that must be accounted for by pre-5 ka events on fault zone F4, according to the retro sequence. This 2.5 meters of throw must be attributed to Events Vw, Uw, and Tw, but the relative proportions to assign to each event are unknown, because the direct evidence for these events (colluvial wedges, crack fills) is beneath the trench floor. The schematic retrodeformation sequence of figure 7 implies Event T may not have ruptured fault F4. However, this figure was drawn before Schuster's seismic tomography profile indicated a thick section of low-velocity sediments beneath the trench floor here. If those low-velocity sediments are a thickened (>2 meters thick) section of unit 5 regressive sands, then some or all of the "missing" 2.5 meters of throw may have occurred in Event T.

Obviously, many other scenarios are also possible, given the limited constraints posed by the reconstruction of the latest four events (figure 11) on the one hand and the projection of auger hole contacts to fault zone F4 on the other hand. I cannot even prove that there were not additional events besides Tw, Uw, and Vw in the time period 7-17 ka, since I did not expose that part of the stratigraphic section. However, because there are only 2.5 meters of "missing" throw to account for, and already three candidate events (Tw, Uw, Vw) that could have caused that throw, there is not a compelling need for an additional faulting event in addition to the three already recognized.

Table 6 summarizes the age control on the latest four paleoearthquakes on fault zone F4. The letters used correlate with the same letters used for fault zone F1 (that is, Event Zw is correlated with Event Ze, etc.).

Table 6. Summary of age constraints on the latest four faulting events in fault zone F4. All ages in calibrated years B P.

Event	Colluvium	Min. Age	Max. Age
Zw	W11	NA	925-1,230
Yw	W10	NA	1080-1315*
Xw	W9	NA	NA
Ww	W8	NA	7,235-7,815

* *contaminated age*

Composite Retrodeformation Sequence of Entire Trench

Figure 12 shows a composite retrodeformation of the entire trench, simplified such that fault zone F1 is a single fault, fault zone F2 is omitted, and on fault zone F4 all displacement postdates unit 7 (early Holocene alluvial fan). As previously mentioned, this last simplification is incorrect if unit 5 exists in an overthickened section beneath the trench floor, as suggested by the post-trenching geophysics.

CONCLUSIONS

Comparison With Previous Paleoearthquake Chronologies

The most detailed chronology of paleoearthquakes on the Salt Lake City segment prior to the megatrench was reported by Black and others (1996), who dated four events in the past 5 ka (table 7, figure 12) at the South Fork Dry Creek and Dry Gulch sites, roughly 5 km south of the megatrench site.

Table 7. Mean age estimates for paleoearthquakes on the Salt Lake City segment from Black and others (1996). All ages are in calibrated years BP.

Event	Min. Age	Preferred Age	Max. Age
Z	1,100	1,300	1,550
Y	2,100	2,450	2,800
X	3,500	3,950	4,500
W	4,950	5,300	5,750

The Black and others' (1996) estimates formed the main basis for the age estimates of McCalpin and Nishenko (1996) in their compilation of paleoearthquake ages in the central five segments of the WFZ. For the Salt Lake City segment, McCalpin and Nishenko (1996) extracted the closest maximum limiting dates (i.e., one-sided age constraints) on the latest four paleoearthquakes, mainly from the data set of Black and others (1996). Naturally, their results were very similar to Black and others (1996), resulting in a very regular recurrence of ca. 1,350 years among the latest four events.

By comparison to the Black and others (1996) chronology, the current age constraints on the latest four events in the megatrench are not as closely limiting (figure 12). This is partly due to the fact that organic matter in the megatrench could not always be found near paleoearthquake event horizons. On fault zone F1, the two latest events (Ze, Ye) overlap the age ranges cited by Black and others (1996), but the two older events (Xe, We) appear to be somewhat older than Black and others' events X and W. In fact, it could be argued that event Xe actually correlates with Black and others' event W. Part of the ambiguity on the ages of Events Xe and We stems from the fact that dated organics are from crack fills, rather than from soils buried by colluvial wedges. When a soil is buried by a colluvial wedge, the age of the soil constitutes a close maximum age on debris-facies colluvial deposition, and thus on the age of the event. In a crack fill, the origin of the organics is more ambiguous. The crack fill at the base of a free face is typically composed of intact blocks of material that fell off the scarp free face. These blocks could be parts of the surface soil, or parts of buried soils developed on previous colluvial wedges. Thus the age of organics could be older, even much older, than the age of the

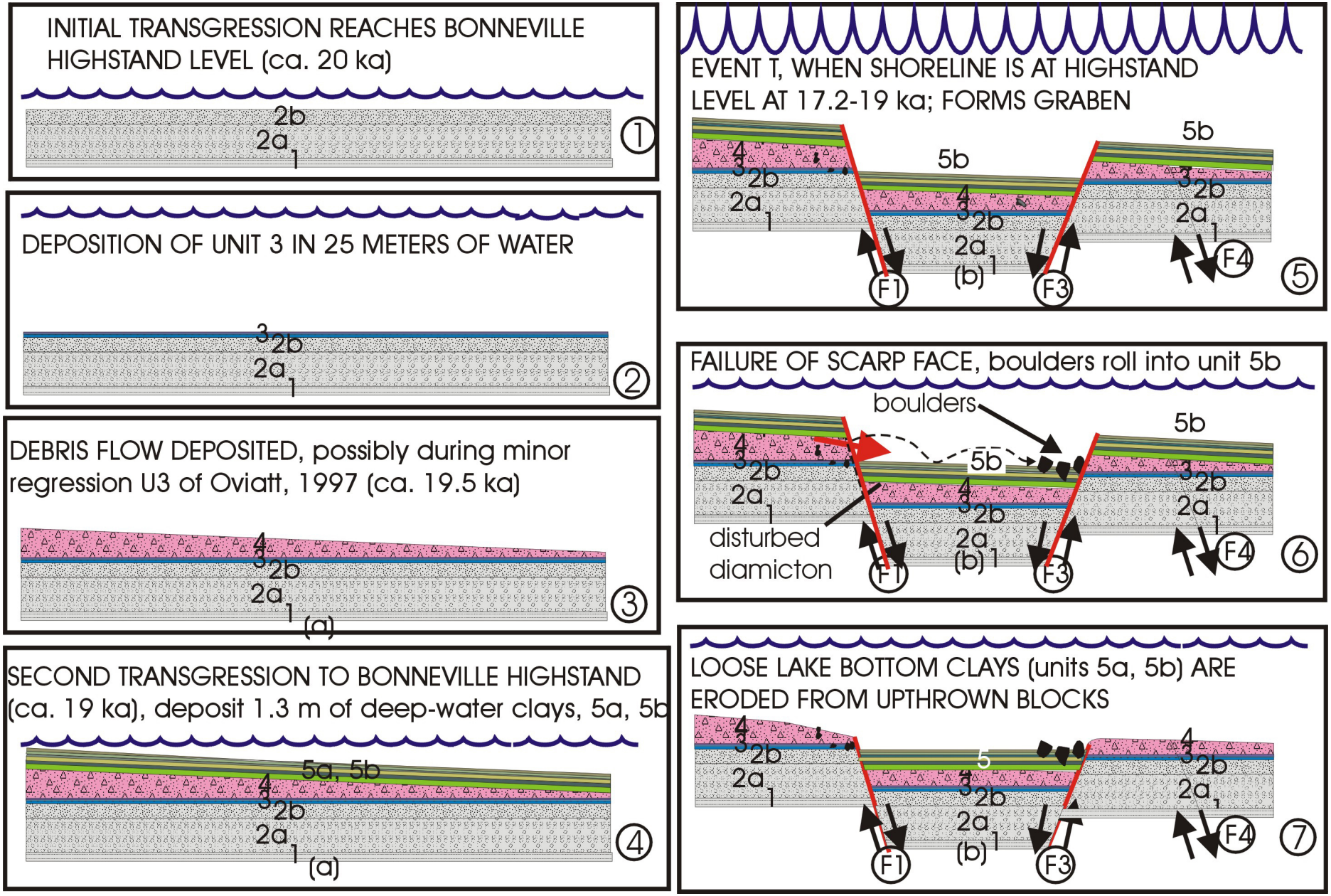


Figure 12(a). Simplified retro sequence for the entire megatrench, from ca. 17-20 ka.

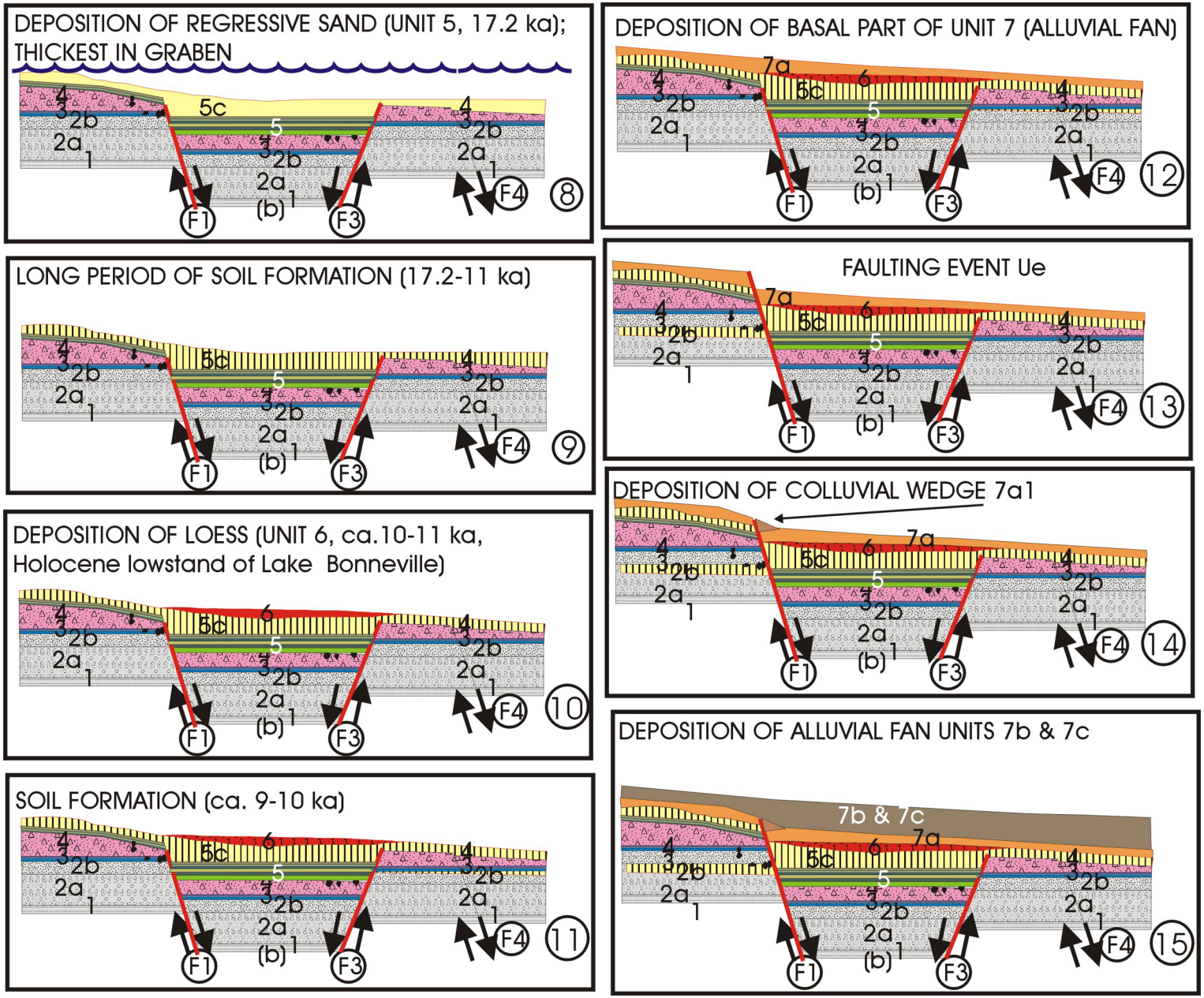


Figure 12 (b) Steps 8-15, 14.5 ka to ca. 7 ka.

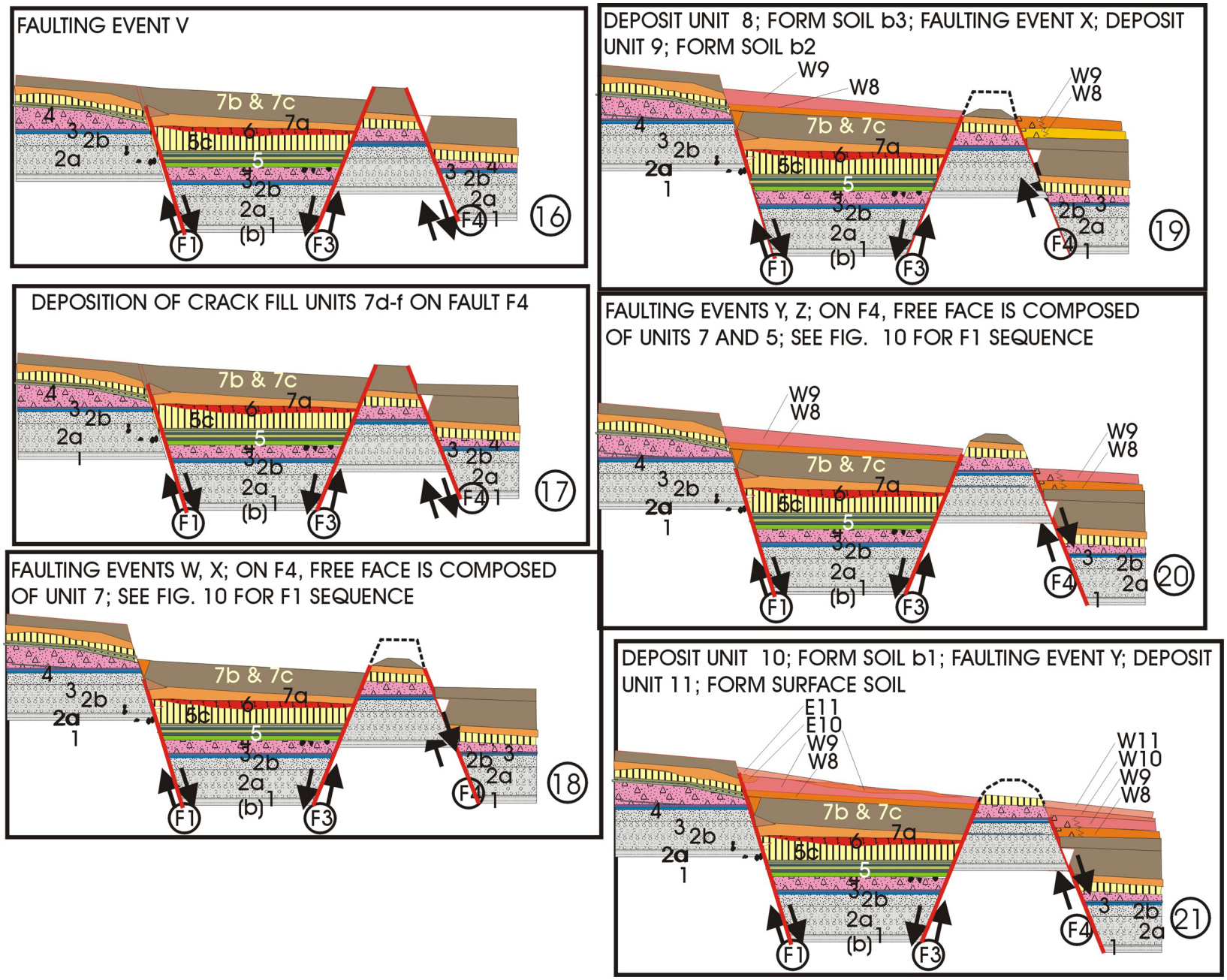


Figure 12 (c) Steps 16-21, ca. 7 ka to present. Stages 18 and 20 combine the displacements from two faulting events and omit the deposition between them. Those deposits appear in stages 19 and 21.

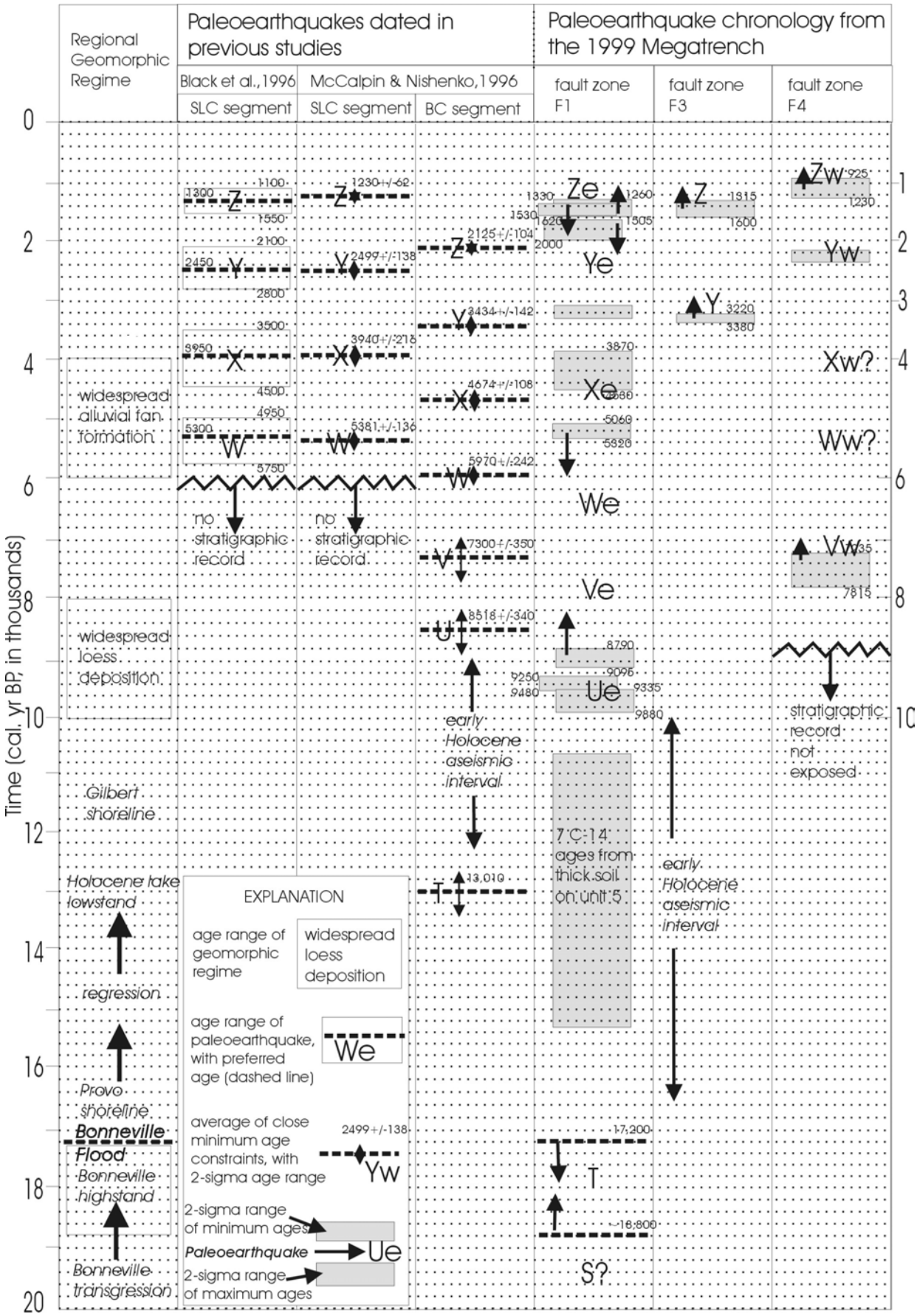


Figure 13. Space-time diagram of paleoearthquakes dated in previous studies, and in the Megatrench .

crack-forming event, even though the organics were deposited in the crack shortly after the cracking event

The ambiguity in correlating the latest four events in the megatrench does not affect the major goal of our investigation, that is, developing a chronology of paleoearthquakes between 6 ka and 17 ka. However, if our Event Xe actually correlates with event W of Black and others (1996), then there have been four paleoearthquakes on fault zone F1 between ca. 6 ka and 17 ka, rather than the three otherwise inferred.

Another ambiguity in correlation exists on fault zone F4, where there have been four faulting events since 7.2 ka (figure 12). If the radiocarbon age of 7,235-7,815 cal yr BP is closely limiting on Event Ww, then that event is roughly 2,000 years too old to correlate with Black and others' (1996) event W. That scenario then leaves only three recognizable faulting events on fault zone F4 in the past 6 ka, compared to the four recognized on the Salt Lake City segment by Black and others (1996). There are several possible explanations for this discrepancy: (1) one of Black and others four post-6 ka events did not rupture fault zone F4 (see discussion in Black and others, 1996, on event distribution), (2) rupture did occur in all four events, but the proportion of displacement on fault zone F4 was so small in relation to that on fault zone F1 that no colluvial signature was generated, and (3) the 7,235-7,815 cal yr BP age is incorrect. However, I have confidence in the 7,235-7815 cal yr BP age being correct, merely because it comes from strata deposited contemporaneously with the end of alluvial-fan deposition, which was dated farther east in the trench as somewhat younger than 8,790-9,095 cal yr BP.

In summary, the megatrench shows evidence for three paleoearthquakes in the same time period in which Black and others (1996) inferred four paleoearthquakes. Our event Z correlates well with their event Z. For the earlier events, our age control is not tight enough to state which of Black and others' events is missing from the megatrench, but the pattern suggests that I have only one event to correlate with their events X and Y. In fact, the date from the basal crack fill of fault zone F3 falls almost exactly between the age estimates for Black and others' events X and Y (but see previous discussion of the limitation of crack-fill dates).

The more important conclusion in relation to our goals is that there is stratigraphic evidence for only three paleoearthquakes (Events T, U, and V) in the period 6 ka-17 ka, rather than the 8 events that would have occurred if 1,350-year recurrence had continued throughout this 11,000 year-long interval. A critical question is whether the geologic record in the megatrench covering this time period is complete. For example, if the early Holocene alluvial fan eroded this site it may have removed evidence for pre-alluvial fan paleoearthquakes. For example, on the footwall of fault zone F1 unit 5 is only 0.6 meter thick, compared to 3.7 meter thick on the hanging wall; some of this difference must be attributed to alluvial-fan erosion. On the hanging wall of fault F1 the alluvial fan clearly eroded away unit 6 and the upper part of unit 5 between 34-40mH in the trench (figure 5). Although this 1.2 meters of erosion occurs in part of the trench that is not near a fault zone, the alluvial fan may have also eroded the fault zones and removed colluvial wedge or crack fill evidence. In fact, the retrodeformation sequence for fault zone F1 (figure 10) relies partly on such episodic erosion of domino blocks to identify pre-fan Events U and V. However, it is possible that some physical evidence of additional pre-fan paleoearthquakes (colluvial wedges, unconformities) was removed by alluvial-fan erosion ca. 9-10 ka and has been lost from the megatrench record. I consider this possibility unlikely but it cannot be disproven.

Physical Causes of Variable Earthquake Recurrence

I calculate a rough pattern of recurrence between the 7 paleoearthquakes inferred from the megatrench from the dates presented in figure 12. The mean recurrence between the latest four paleoearthquakes, based on Black and others (1996), ranges from 1,150 years to 1,500 years. The recurrence between events U and V, and V and W, is roughly 2,000 years in each case. However, the recurrence time between Events T and U ranges from 7,100 years to 9,600 years (2 sigma range), with a mean value of 8,350 years. This long period of landscape stability at the megatrench site is represented by the well-developed buried soils b4 and b5, formed on units 5 and 6, respectively, a time span during which no scarp-derived sediments or structures formed, even as close as 1 meter to the faults.

What would have caused such a long hiatus of faulting on the WFZ? The time window 9 ka to 17 ka coincides with the desiccation of Lake Bonneville, starting with the abrupt 100-meter drop from the Bonneville highstand to Provo shorelines at 17.2 ka, and continuing to the Holocene lowstand of the lake (below the present level of the Great Salt Lake) at ca. 13 ka. This desiccation removed an enormous weight of water from the hanging wall of the WFZ over a period of 4 ka. Could this desiccation have redistributed stress patterns on the hanging wall and footwall of the WFZ in a manner as to suppress fault movement? Conceptually, placing a load on the hanging wall of a normal fault and increasing the regional pore fluid pressure, such as would occur during a lake transgression, would tend to

encourage slip on a normal fault. Conversely, a lake regression should have the opposite effect, that of suppressing fault slip.

An early Holocene aseismic interval was inferred by McCalpin and Forman (in press) and McCalpin and Nishenko (1996), based on trenching results on the Brigham City segment of the WFZ. Their 1992-93 trenching campaign on the Provo delta surface at Brigham City was one of the few trench studies that exposed the paleoearthquake record prior to the mid-Holocene. They found stratigraphic and geochronologic evidence that no faulting events had occurred between the occupation of the Provo shoreline (ca. 16-17 ka) and about 8.5 ka. This quiescent period of 8 ka contrasts strongly with the subsequent 1,200-1,300 year recurrence between subsequent events (figure 12). Thus, the only two trench investigations (Brigham City and the megatrench) to deduce a detailed chronology of post-Bonneville paleoearthquakes both inferred an 8 ky early Holocene aseismic interval.

Implications of the Megatrench Results for Probability Estimates of Future Earthquakes on the Salt Lake City Segment

McCalpin and Nishenko (1996) calculated probabilities of M>7 earthquakes in the next 20, 50, and 100 years on the five central segments of the WFZ. They calculated probabilities for both memoryless (Poisson) models of recurrence and also conditional probabilities assuming various renewal models of recurrence (log normal and Weibull). For the Salt Lake City segment, Poisson probability in the next 100 years is 7 percent, compared to conditional probability estimates ranging from 6 percent to 56 percent (table 8).

What implications does the long paleoearthquake chronology from the megatrench have on the accuracy of these widely variable probability estimates? First, I have documented rather large departures in the latest Pleistocene/ early Holocene from the regular 1,300-1,400 year recurrence of the mid to late Holocene. However, I suspect that these longer recurrence times were strongly influenced by the unloading of the WFZ hanging wall during desiccation of Lake Bonneville. It appears that the unloading effect died out by the time of Event W, and that it has not affected the regular 1,300-1,400 year recurrence cycle since that time. Therefore, I do not propose to favor or disfavor any of McCalpin and Nishenko's (1996) recurrence models based on the long recurrence times observed while the lake was drying up.

However, I can apply the results of some more recent recurrence studies to the likelihood of the various recurrence models. For example, the highest 100-year conditional probability calculated by McCalpin and Nishenko (1996) was 57 percent, based on a Weibull model of recurrence with a mean of 1,328 years and a coefficient of variation (COV) of only 0.04. By comparison, conditional probabilities based on

Table 8. Probability estimates of M>7 earthquakes in the next 100 years for the Salt Lake City segment. From McCalpin and Nishenko, 1996, table 6.

Behavior Model	Recurrence Model	Mean Recurrence and Source[1] (years)	COV of Recurrence or Weibull shape parameter (â)	Probability of M>7 Earthquake in the Next 100 years[2]
memoryless	Poisson	NA	NA	7%
Renewal (memory)	Lognormal	1767, group	0.21	8%
Renewal (memory)	Lognormal	1767, group	0.5	8%
Renewal (memory)	Lognormal	1384, segment	0.21	22%
Renewal (memory)	Lognormal	1384, segment	0.5	11%
Renewal (memory)	Weibull	1775, group	â =3.36	6%
Renewal (memory)	Weibull	1328, short	â =17.8	57%

[1] *Source; "group" means derived from averaging all Holocene events on all five central segments; "segments" means derived just from the segment named; "short" refers to the group of short recurrences among the five central segments averaging, 1,328+/-104 years, as opposed to a separate group of "long" recurrences (dominantly observed on the Provo and Nephi segments) averaging, 2,346+/-448 years. See McCalpin and Nishenko, 1996, p. 6,248-6,250 for detailed discussion.*

[2] *All estimates assume an elapsed time of 1,230+/-62 years.*

Log normal models with COVs of 0.21 and 0.5 indicated probabilities of 22 percent and 11 percent, respectively (table 8). So, is the COV of long-term recurrence on the Salt Lake City segment closer to 0.04, 0.21, or 0.5?

McCalpin and Slemmons (1998) inventoried all published paleoseismic chronologies that contained 3 or more well-dated events. They found that, as a group, worldwide normal faults with a large span of slip rates and mean recurrences tended to have an average COV of recurrence of 0.35. The same data set for all fault types yielded an average COV of recurrence of 0.36. In addition, the more paleoearthquakes dated at a local trench site, the closer the COV of that local recurrence series approached 0.36. McCalpin and Slemmons (1998) argued that a relatively short recurrence series at a site (say, containing only 3-4 events, or 2-3 recurrence intervals) could yield a wide possible range of recurrence COVs, ranging from ca. 0.04 to 0.8. However, the site chronologies with successively more events tended to have COVs that converged on the value 0.36. They further argued that, for the purposes of making conditional probability estimates, it would be preferable to use the value COV=0.36 rather than use an "apparent" COV value from a short (3-4 event) recurrence series.

Their conclusions suggest that I should probably not lend much weight to the probability estimate of 57 percent in table 8, which is based on a COV=0.04 from only 4 events on the Salt Lake City segment. Instead, I should probably assume a long-term recurrence COV of 0.36 for the Salt Lake City segment. Note that 0.36 falls almost exactly halfway between the COVs of 0.21 and 0.5 cited in table 8, which resulted in probability estimates of 22 percent and 11 percent, respectively, for the next 100 years. If I assume that conditional probability varies linearly with COV over this relatively small range, then an assumed recurrence COV=0.36 would imply a conditional probability of 16.5 percent for M>7 earthquakes in the next 100 years.

Given the conclusion above, the megatrench study appears to have been a limited success. The goal of the study was to obtain a longer paleoearthquake record to assess the variability of recurrence times. However, I do not actually use the recurrence times between "newly identified" paleoearthquakes T, U, and V to recalculate conditional probabilities for future large earthquakes on the Salt Lake City segment. There are two main reasons for this: (1) I think that the abnormally long recurrence times between 17 ka and 9 ka were somehow influenced by the desiccation of Lake Bonneville, a process that does not affect the fault's behavior today, and (2) there is a small possibility that part of the latest Pleistocene-earliest Holocene stratigraphic record was removed by erosion at this site. If either of these inferences are true, then we should not average in those long recurrence times in calculations of conditional probability.

I would give a final caveat to future paleoseismic investigators on the WFZ, to be very careful about trench site selection. The U.S. Geological Survey specifically mapped the geology of the Salt Lake City segment at 1:50,000 scale to support detailed paleoseismic studies such as this one. However, their map (Personius and Scott, 1992, 1:10,000-scale insert) shows no alluvial-fan deposits on the footwall of fault F1, whereas the fan did deposit 1.5 meters of sediments there and eroded away an unknown thickness of lake deposits (unit 5). This seemingly trivial detail has major implications as to the completeness of the paleoseismic record, if alluvial-fan erosion removed stratigraphic evidence of pre-fan paleoearthquakes.

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APPENDIX 1: Unit Descriptions, Wasatch Fault Megatrench

Units in the eastern 45 meters of the trench; deposits (parent materials) are in bold, *soil horizons are in bold italics*

E11- Grayish brown (10YR5/2 d) gravelly silty sand; clasts average 2 cm diameter, max. 5-6 cm; moderately to poorly sorted; clasts are subangular; matrix is silty sand; matrix supported deposit; firm to hard; no bedding; downslope clast fabric; DEBRIS-FACIES COLLUVIAL WEDGE OF MOST RECENT EVENT (Event Ze) ON FAULT ZONE F1 (LATEST HOLOCENE)

E10cA- A horizon of surface soil developed on parent material E10c (see description below)

E10cAC- AC horizon of surface soil developed on parent material E10c (see description below)

E10cBt- Bt horizon of surface soil developed on parent material E10c (see description below)

E10c (parent material does not exist unaffected by soil horizons)- Dark yellowish brown (10YR4/6 d) sand; dominantly coarse sand, with clasts up to 10 cm diameter; moderately sorted, with lenses well sorted; clasts are subangular to subround; matrix is coarse sand, quite hard; matrix supported deposit; bedding is lenticular, with well-sorted lenses averaging 10 cm thick and 100 cm long; WASH-FACIES COLLUVIUM OF PENULTIMATE EVENT (Event Ye) ON FAULT ZONE F1 (LATEST HOLOCENE)

E10b- Brown (10YR5/3 d) gravelly sand; clasts average 1 cm diameter, max. 10 cm; moderately to poorly sorted; clasts are angular; matrix is sand; matrix-supported deposit; hard; no bedding; downslope clast fabric; upper half of DEBRIS-FACIES COLLUVIAL WEDGE OF PENULTIMATE EVENT (Event Ye) ON FAULT ZONE F1 (LATE HOLOCENE)

E10a- Dark brown (10YR3/3 d) gravelly sand; clasts average 1.5 cm diameter, max. 3 cm; moderately sorted; clasts subangular to subround; sand matrix; firm; downslope stratification, with beds 2-5 cm thick; downslope clast fabric; FLUVIAL CHANNEL ALONG BASE OF FAULT SCARP (LATE HOLOCENE)

E9bAb1- A horizon of buried soil 1 developed on parent material E9b (see description below)

E9bABb1- AB horizon of buried soil 1 developed on parent material E9b (see description below)

E9bBt1b1- Bt horizon of buried soil 1 developed on parent material E9b (see description below)

E9b- Dark grayish brown (10YR4/2 d) gravelly silty sand; dominantly pea gravel to coarse sand; clasts average 1-2 cm, max. 5 cm; poorly to moderately sorted; clasts are angular; matrix is silty sand; firm to loose; unstratified; weak downslope clast fabric; DEBRIS- and WASH-FACIES COLLUVIAL WEDGE OF THE ANTEPENULTIMATE EVENT (Event Xe) ON FAULT ZONE F1 (LATE HOLOCENE)

E8bAb2- A horizon of buried soil 2 developed on parent material E8b (see description below)

E8bACb2- AC horizon of buried soil 2 developed on parent material E8b (see description below)

E8aBtb2- Bt horizon of buried soil 2 developed on parent material E8a (see description below)

E8b- Brown (7.5YR5/4 d) gravelly silty sand; in crack fill and debris-facies colluvium, clasts average 2-3 cm diameter, max. 15 cm; poorly sorted; clasts are angular; matrix is silty sand; matrix supported deposit; hard to firm; unstratified; clasts generally have random orientation, slight downslope fabric; CRACK FILL AND DEBRIS-FACIES COLLUVIUM OF ANTE-ANTEPENULTIMATE EVENT (Event We) ON FAULT ZONE F1 (MIDDLE HOLOCENE)

E8a- Brown (10YR5/3 d) gravelly silty sand; fine to coarse sand (40-50%), silt (ca. 25%), and gravel (ca. 25%); very poorly sorted gravels; angular, average diameter 1-2 cm, max. 7 cm, dominantly green amphibolite, vein quartz, granodiorite; loose in upper 20 cm to moderately dense in lower part of unit; unstratified; lower 40 cm is darker brown (10YR4/3d), forms a slightly resistant bench below unit 9A; WASH-FACIES COLLUVIUM OF ANTE-ANTEPENULTIMATE EVENT (Event We) ON FAULT ZONE F1 (MIDDLE HOLOCENE)

7e- CRACK FILL AND STRATIFIED GRAVEL OF EVENT Ve?

E7d- coarse gravel lens in unit 7b

E7cA- A horizon of surface soil developed on parent material E7c (see description below)

E7cAB- AB horizon of surface soil developed on parent material E7c (see description below)

E7cBt1- Bt horizon of surface soil developed on parent material E7c (see description below)

E7c- Yellowish brown (10YR5/6 d) gravelly sand; clasts are pea gravel size, max. diameter 5 cm; poorly to moderately sorted, with some well-sorted stringers; clasts angular to subangular; matrix of silt to silty coarse sand; hard; matrix supported; no distinct bedding; weak downslope clast fabric; DISTAL FAN ALLUVIUM/ COLLUVIUM (HOLOCENE) ABOVE THE EASTERN (F1) SCARP

7b1- Similar to unit 7b except coarser-grained (sandy gravel rather than gravelly sand)

7b- Light yellow brown (10YR6/4 d) sandy gravel; gravel with few cobbles in medium-coarse sand matrix; gravel clasts are angular to subangular; lithologies = quartzite (max. diameter 16 cm), diorite, amphibolite (max. diameter 6 cm); dominantly matrix supported, poorly stratified; matrix is light yellow brown sand, subangular; GRABEN-FILL ALLUVIUM (HOLOCENE)

7a1- Poorly sorted gravelly sand at 23.5mH, 12mV, with wedge shape and strong downslope clast fabric; SUSPECTED COLLUVIAL WEDGE OF Event Ue

7aBtb1, 7bBtb1- Bt horizons of buried soil 1 developed on units 7a and 7b, as those units approach the ground surface near fault zone F2, due to pinchout of unit E8 and thinning of unit E9 (see parent material descriptions)

7a- Light yellow brown (10YR6/4 d) gravelly sand; fine-medium gravel in matrix of medium-coarse sand; gravels subangular to subround, max. diameter 2-3 cm, quartzite with a few (grussified) granitic clasts; sands are subround in undulating (scour) contact with underlying unit 7b; GRABEN-FILL ALLUVIUM (HOLOCENE).

6Btb4- Bt horizon of buried soil 4 developed on parent material 6 (see description below)

6Bkb4- Bk horizon of buried soil 4 developed on parent material 6 (see description below)

6- Yellowish brown (10YR5/4 d) silt; contains minor fine to medium sand; moderately dense; massive bedding ca. 75 cm thick; drapes underlying silty sand (unit 5c); LOESS (IMMEDIATELY POST-LAKE TO EARLY HOLOCENE)

5cAkb5- Ak horizon of buried soil 5 developed on parent material 5 (see description below)

5cAb5- A horizon of buried soil 5 developed on parent material 5 (see description below)

5cACb5- AC horizon of buried soil 5 developed on parent material 5 (see description below)

5cC1b5- Essentially unaltered parent material 5; Light yellowish brown (10YR6/4 d) silty sand; fine to coarse sand (fine 10%, medium 40%, coarse 20%); poorly sorted, subround, moderately loose and soft; massive beds ca. 20 cm thick; lower contact with 5cC2 is gradational over ca. 5 cm and undulatory; REGRESSIVE LACUSTRINE SAND OF BONNEVILLE FLOOD (ca. 17.2 ka)

5cC2b5- Essentially unaltered parent material 5; Yellow sand; medium to coarse grained, very clean, very loose; moderately sorted, subround; rare small gravel (granitic); poorly stratified with low angle foreset beds dipping 5-6 degrees west; REGRESSIVE LACUSTRINE SAND OF BONNEVILLE FLOOD (ca. 17.2 ka).

5b1- Light yellowish brown (2.5Y6/4 d) clayey silt; with occasional sand; moderately well sorted; massively bedded; contains large chunks of Unit 5a and 5b floating in it; most chunks congregate at the bottom of the unit; chunks range from 2x2cm, to 15x20 cm, to 30x50 cm; LACUSTRINE CLAY AND SILT SEVERELY DEFORMED BY SOFT-SEDIMENT DEFORMATION AND MECHANICALLY MIXED WITH ADJACENT UNITS. (Note: not in log explanation!)

5b- Olive yellow (2.5Y6/6 d) silt; sandy silt; well sorted; massively bedded; contains calcium carbonate tubes/nodules in irregular shapes; also contains occasional orange blobs; LACUSTRINE SILT (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

5a7- Pale olive (5Y6/4 d) silt and clay; alternating lenses of silt and silty clay; well sorted; breaks easily along bedding planes; dips 13-15 degrees east; LACUSTRINE SILT AND CLAY (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

5a6- Well-stratified fine sand and silt:(BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

Subunit **5a61**- Pale yellow (5Y7/4 d) coarsening-upward package of silt to very fine sand, very fine sand is dominant; well sorted; well stratified; beds 0.5-2 cm thick; dips 8-9 degrees east;

LACUSTRINE SILT AND SAND (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

Subunit **5a62**- Pale olive (5Y6/4 d) marker bed in unit 5a6; 2 cm thick bed of laminated silty clay; dips 8-9 degrees east; upper and lower contacts slightly irregular; LACUSTRINE CLAY (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

Subunit **5a63**- Pale yellow (5Y7/4 d) silty sand; dominantly very fine sand; well sorted; well bedded; beds 1.5 cm thick; banded with brown layers; brown turns orange toward top of unit; dips 9-12 degrees east; LACUSTRINE SILT AND SAND (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

5a5- Olive (5Y5/3 d) silty clay; finely laminated; slight orange- and brown-stained layers; beds typically <0.5 cm thick; dips 10-12 degrees east; LACUSTRINE CLAY (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

5a4- Pale yellow (5Y7/3 d) silty clay; hard, blocky, mottled clay; well sorted; very hard; orange mottling; well stratified with orange-stained layers; beds <0.5 cm thick; dips east at 15 degrees; breaks in a platy fashion; will not scrape to a smooth surface; LACUSTRINE CLAY (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

5a3- Pale olive (5Y6/3 d) clay; massive green silty clay; very firm; massive unit with no internal bedding; discontinuous vertical orange stringers of unknown origin; LACUSTRINE CLAY (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

5a2- Pale yellow (5Y7/4 d) to strong brown (7.5YR5/8 d) silt; sequence of interbedded silt and very fine sand beds of variable colors; very well stratified; average fining-upward sequence is 1.5 cm thick; some layers are very oxidized (orange); quite firm, breaks along bedding planes; dip is 15 degrees east, rotated toward fault zone F1; LACUSTRINE SILT AND SAND (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

5a1- Olive (5Y5/3 d) clayey silt; firm; contains stringers of silt to very fine sand, stringers are discontinuous and very sinuous, possible result of liquefaction; in places vague bedding is visible, but discontinuous; LACUSTRINE SILT (BONNEVILLE HIGHSTAND, ca. 17-20 ka?)

4b- White (5Y8/2 d) diamicton; upper half (unit 4b) contains clasts 10-50 cm on average, with max. diameter ca. 1 m; granitic; poorly sorted; clasts subangular to subrounded; matrix supported, with pale silt matrix (resembling Unit E9) between granite boulders; firm consistence; no bedding; DIAMICTON (DEBRIS FLOW DEPOSIT INTO LACUSTRINE SILT?)

4a- White (5Y8/2 d) diamicton; sandy gravel; poorly sorted; clasts subangular to subrounded; matrix-supported; contains some lenses of fine gravel 10-20 cm thick; carbonate rinds on clasts; DIAMICTON (DEBRIS FLOW DEPOSIT INTO LACUSTRINE SILT?)

3d- Light gray (5Y7/2 d) sand; coarse sand with minor pea gravel; moderately sorted; grains subround; loose; grain supported; well stratified, with beds 1-5 cm thick; LACUSTRINE SANDS, PROBABLY FROM BONNEVILLE TRANSGRESSION (ca. 20 ka)

3c- Olive (5Y5/3 d) silt; well sorted; firm; matrix-supported; well stratified, with beds 1-2 cm thick; iron oxidation on some bedding planes; LACUSTRINE SILT (ca. 20 ka)

3b- Reddish yellow (7.5YR6/8 d) sand; coarse sand; well sorted; subrounded grains; firm; well stratified, with beds 1-2 cm thick; iron oxidation throughout, strongest at top of unit; LACUSTRINE SANDS, PROBABLY FROM BONNEVILLE TRANSGRESSION (ca. 20 ka)

3a- Light olive brown (2.5Y5/4 d) fine silt; well sorted; firm; matrix supported; well stratified, bedding thickness of 1 cm; finer mm-scale horizontal laminations; some beds are oxidized; LACUSTRINE SILT

2b Gray (2.5Y6/0 d) to light gray (2.5Y5/0 d) sand; dominantly coarse sand, with rare clasts up to 20 cm; well sorted; clasts are subround to round; sand matrix, loose; matrix supported; well stratified, with beds averaging 2 cm thick; contains horizontal gravel beds throughout, 2-3 cm thick; some layers oxidized; LACUSTRINE SAND, PROBABLY FROM BONNEVILLE TRANSGRESSION (ca. 20 ka)

2a- Gray (5YR6/1 d) cobbly sandy gravel; cobbles average 10 cm in diameter, max. 18 cm; lithologies are quartzite, diorite, and metamorphic green amphibolite (Little Willow series, ca. 1.8 by); quartz-mica schist; clasts are subangular to subround; no apparent imbrication; no carbonate coats; sands are clean, poorly sorted, medium-coarse grained, subround-round, very loose; LACUSTRINE BEACH GRAVEL, PROBABLY FROM THE BONNEVILLE TRANSGRESSION (ca. 20 ka)

Additional units only in the western 15 meters of the trench (abbreviated descriptions)

W12A- A horizon of surface soil developed on parent material W12 (see description below)

W12AC- AC horizon of surface soil developed on parent material W12 (see description below)

W12- Gravelly sand, massive; matrix supported with rare small gravel clasts; POST-FAULTING GRABEN-FILL ALLUVIUM

W11- DEBRIS FACIES COLLUVIUM OF MOST RECENT EVENT (Event Zw)

W10Ab1- A horizon of buried soil 1 developed on parent material W10 (see description below)

W10ABb1- AB horizon of buried soil 1 developed on parent material W10 (see description below)

W10- DEBRIS-FACIES COLLUVIUM OF PENULTIMATE EVENT (Event Yw)

W9Ab2- A horizon of buried soil 2 developed on parent material W9 (see description below)

W9Btb2- Bt horizon of buried soil 2 developed on parent material W9 (see description below)

W9- WASH-FACIES COLLUVIUM OF ANTEPENULTIMATE EVENT (Event Xw)

W8bBtb3- Bt horizon of buried soil 3 developed on parent material W8b (see description below)

W8b- WASH-FACIES COLLUVIUM OF ANTE-ANTEPENULTIMATE EVENT (Event Ww)

W8a- DEBRIS-FACIES COLLUVIUM OF ANTE-ANTEPENULTIMATE EVENT (Event Ww)

W8c- LOESS OR FLUVIAL OVERBANK DEPOSIT

W7fAb4- A horizon of buried soil 4 developed on parent material W7f; parent material is a massive silt with no clasts (LOESS?)

W7e- Sandy gravel; very similar in color and texture to unit 7b; CRACK FILL OF EVENT Vw?

W7d- Sand; very similar in color and texture to unit 7a; CRACK FILL OF EVENT Vw?

7c, 7b—see previous descriptions

2a, 2b- see previous descriptions

1- Light brownish gray (10YR6/2 d) to light gray (5Y7/1) sand; fine to coarse, laminated to thinly bedded (up to 12 cm thick) with few crossbeds; well sorted, subangular (coarse sand) to round (fine sand); iron oxide staining; LACUSTRINE NEARSHORE SANDS, PROBABLY FROM THE BONNEVILLE TRANSGRESSION (ca. 20 ka)