Black, Giraud, Mayes

PALEOSEISMIC INVESTIGATION - WEST CACHE FAULT ZONE, CACHE COUNTY, UTAH

UGS Special Study 98

Paleoseismology of Utah, Volume 9

PALEOSEISMIC INVESTIGATION OF THE CLARKSTON, JUNCTION HILLS, AND WELLSVILLE FAULTS, WEST CACHE FAULT ZONE, CACHE COUNTY, UTAH

by

Bill D. Black, Richard E. Giraud, and Bea H. Mayes
Utah Geological Survey

SPECIAL STUDY 98
UTAH GEOLOGICAL SURVEY
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Utah Department of Natural Resources
2000

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Cover photograph

Lake Bonneville deposits displaced by Junction Hills fault at Roundy Farm stream-cut exposure, West Cache fault zone, Cache County, Utah.
Photo by Bill Black.

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FOREWORD

This Utah Geological Survey Special Study, Paleoseismic Investigation of the Clarkston, Junction Hills, and Wellsville faults, West Cache fault zone, Cache County, Utah, is the ninth report in the Paleoseismology of Utah Special Studies 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 earthquake timing, recurrence, displacement, slip rate, and fault geometry which can be used to characterize potential seismic sources and evaluate the long-term earthquake hazard presented by Utah's Quaternary faults.

Field work for this paleoseismic investigation was performed in 1997 at three sites (Winter Canyon, Roundy Farm, and Deep Canyon) on the Clarkston, Junction Hills, and Wellsville faults. These faults, along with several lesser associated faults nearby, comprise the West Cache fault zone on the west side of Cache Valley (Solomon, 1999). No previous paleoseismic studies had been conducted on these faults. Surficial geologic mapping of the fault zone and initial paleoseismic study results were presented by Black and Solomon (1998) to the 93rd Annual Meeting of the Seismological Society of America in Boulder, Colorado. Those results showed that recent movement on the faults was much younger than previously thought. The information reported here on the size, timing, and recurrence of surface-faulting earthquakes on the West Cache fault zone is critical to public officials, planners, and others making decisions regarding earthquake-hazard mitigation in Cache Valley and the northern Wasatch front.

William R. Lund, Series Editor
Utah Geological Survey

Other reports in the Paleoseismology of Utah series

Special Study 75. Paleoseismology of Utah, Volume 1: Fault behavior and earthquake recurrence on the Provo segment of the Wasatch fault zone at Mapleton, Utah County, Utah, by W.R. Lund, D.P. Schwartz, W.E. Mulvey, K.E. Budding, and B.D. Black, 41 p., 1991

Special Study 76. Paleoseismology of Utah, Volume 2: Paleoseismic analysis of the Wasatch fault zone at the Brigham City trench site, Brigham City, Utah and the Pole Patch trench site, Pleasant View, Utah, by S.F. Personius, 39 p., 1991

Special Study 78. Paleoseismology of Utah, Volume 3: The number and timing of paleoseismic events on the Nephi and Levan segments, Wasatch fault zone, Utah, by Michael Jackson, 23 p., 3 p., 1991

Special Study 82. Paleoseismology of Utah, Volume 4: Seismotectonics of north-central Utah and southwestern Wyoming, by Michael W. West, 93 p., 5 pl., 1:100,000, 1994

Special Study 83. Paleoseismology of Utah, Volume 5: Neotectonic deformation along the East Cache fault zone, Cache County, Utah, by J.P. McCalpin, 37 p., 1994

Special Study 88. Paleoseismology of Utah, Volume 6: The Oquirrh fault zone, Tooele County, Utah: surficial geology and paleoseismicity, W.R. Lund, editor, 64 p., 2 pl., 1:24,000, 1996

Special Study 92. Paleoseismology of Utah, Volume 7: Paleoseismic investigation on the Salt Lake City segment of the Wasatch fault zone at the South Fork Dry Creek and Dry Gulch sites, Salt Lake County, Utah, by B.D. Black, W.R. Lund, D.P. Schwartz, H.E. Gill, and B.H. Mayes, 22 p., 1 pl., 1996

Special Study 93. Paleoseismology of Utah, Volume 8: Paleoseismic investigation at Rock Canyon, Provo segment, Wasatch fault zone, Utah County, Utah, by W.R. Lund and B.D. Black, 21 p., 2 pl., 1998

Map 172 Surficial geologic map of the West Cache fault zone and nearby faults, Box Elder and Cache Counties, Utah, by B.J. Solomon, 1999, at a scale of 1:500,000 is another publication related to this study.

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PALEOSEISMIC INVESTIGATION OF THE CLARKSTON, JUNCTION HILLS, AND WELLSVILLE FAULTS, WEST CACHE FAULT ZONE, CACHE COUNTY, UTAH

by
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ABSTRACT

Three large, active fault zones in and adjacent to Cache Valley in northern Utah pose a significant earthquake risk: they are the Wasatch, East Cache, and West Cache fault zones. All of these fault zones show evidence of large surface-faulting earthquakes in late Quaternary time. Trenching to determine the size and timing of prehistoric surface-faulting earthquakes has been done for the Wasatch and East Cache fault zones, but prior to this study no trenching studies had been done for the West Cache fault zone. The West Cache fault zone is a series of three related east-dipping normal faults that extend 80 kilometers (50 mi) along the west side of Cache Valley from northern Utah into southern Idaho. Faults in the West Cache fault zone are, from north to south, the Clarkston, Junction Hills, and Wellsville faults. The purpose of this study is to determine the seismic-source potential of the West Cache fault zone and evaluate the earthquake hazard presented by the fault zone to Cache Valley and northern Utah.

We investigated three sites on the West Cache fault zone for this study. The investigations included interpreting aerial photographs and previous surficial-geologic mapping along the fault zone, profiling scarps and logging two trench exposures across the Clarkston and Wellsville faults, logging a natural stream-cut exposure of the Junction Hills fault, and radiocarbon dating. Our data show the most recent surface-faulting earthquake (MRE) on the faults occurred: 3,600 to 4,000 years ago on the Clarkston fault; 8,250 to 8,650 years ago on the Junction Hills fault; and 4,400 to 4,800 years ago on the Wellsville fault. The penultimate surface-faulting earthquake (PE) on the Wellsville fault occurred between 15,000 and 25,000 years ago, whereas the PE on the Junction Hills fault occurred some time prior to 22,500 years ago. We found no evidence of the PE on the Clarkston fault in our trenching, but a difference in elevation of the highest shoreline of Lake Bonneville along the Clarkston and Junction Hills faults suggests two or three surface-faulting earthquakes occurred on the Clarkston fault in the past 16,800 years. Three post-lake characteristic earthquakes of average vertical displacement similar to the MRE seem to best account for the elevation difference. Our paleoseismic data show a slip rate for the Wellsville fault of 0.11-0.21 millimeters/year (0.004-0.008 in/yr), and geologic evidence suggests a maximum long-term slip rate for this fault of 0.13 millimeters/year (0.005 in/yr) in the past 100,000 years. We could not determine slip rates for the Clarkston and Junction Hills faults, but stratigraphic and geomorphic evidence suggest that the faults have long-term slip rates less than 0.68 and 0.21 millimeters/year (0.027 and 0.008 in/yr), respectively, since the late Pleistocene. Differences in MRE timing and slip rates between the faults, as well as structural and geologic evidence, indicate that the Wellsville, Junction Hills, and Clarkston faults are separate fault segments of the West Cache fault zone, and may be earthquake segments. Estimated paleoearthquake magnitudes are M_w 6.9 - 7.4 for the Clarkston fault, M_w 6.8 - 7.3 for the Junction Hills fault, and M_w 6.6 - 7.2 for the Wellsville fault.

INTRODUCTION

This report summarizes the results of a project sponsored jointly by the Utah Geological Survey (UGS) and U.S. Geological Survey to investigate late Quaternary movement on the West Cache fault zone. From the Utah-Idaho border, the West Cache fault zone extends southward about 56 kilometers (35 mi) along the west side of Cache Valley to about 6 kilometers (4 mi) south of Wellsville, and northward 24 kilometers (15 mi) into southern Idaho. The fault zone consists of three normal faults that dip eastward beneath Cache Valley. The three faults are, from north to south, the Clarkston, Junction Hills, and Wellsville faults (CF, JHF, and WF, respectively; figure 1). Bedrock faults in three nearby areas also may be associated with the West Cache fault zone, but they lack both demonstrable continuity with the West Cache fault zone and evidence for late Quaternary activity. Solomon (1999) mapped and discussed these faults, but found no conclusive evidence to clarify their relationship to the West Cache fault zone. These faults include, from north to south, the Dayton and Hyrum faults and several faults in the Mantua area (DF, HF, and MF, respectively; figure 1).

The purpose of this study is to determine the seismic-source potential of the West Cache fault zone to aid evaluation of the earthquake hazard in Cache Valley and northern Utah. The study included interpreting aerial photographs and previous surficial-geologic mapping (Solomon, 1999), profiling scarps and logging two trench exposures across the Clarkston and Wellsville faults, logging a natural stream-cut exposure of the Junction Hills fault, and radiocarbon dating. Paleoseismic parameters determined from the study include displacement per event and slip rate, timing of past surface-faulting earthquakes and recurrence, and estimated maximum paleoearthquake magnitude. The results provide new information on which to base future land-use decisions and manage seismic risk.

GEOLOGIC SETTING

Cache Valley is a north-south-trending intermontane valley that is part of a structural transition zone between the extensional terrain of the Basin and Range Province and the uplifted Middle Rocky Mountains Province (Stokes, 1977, 1986). In Utah, the wide and rugged Bear River Range (maximum elevation 3,042 meters [9,981 ft]) bounds Cache Valley (average elevation 1,370 meters [4,495 ft]) on the east; the narrow and sharp-crested Malad Range and Wellsville Mountains (maximum elevation 2,860 meters [9,384 ft]) bound the valley on the west (figure 1). The valley is about 80 kilometers (50 mi) long and 13 to 20 kilometers (8-12 mi) wide. The Bear River, the largest tributary of Great Salt Lake, meanders south through Cache Valley and exits the valley near the Junction Hills, which are between the Malad Range and the Wellsville Mountains (figure 1). Several tributaries of the Bear River originate in the mountains surrounding Cache Valley, such as the Little Bear River, Logan River, Cub River, and Blacksmith Fork.

Cache Valley is near the center of the Intermountain seismic belt (Smith and Sbar, 1974; Smith and Arabasz, 1991), a north-south-trending zone of historical seismicity that extends from northern Arizona to central Montana (fig-

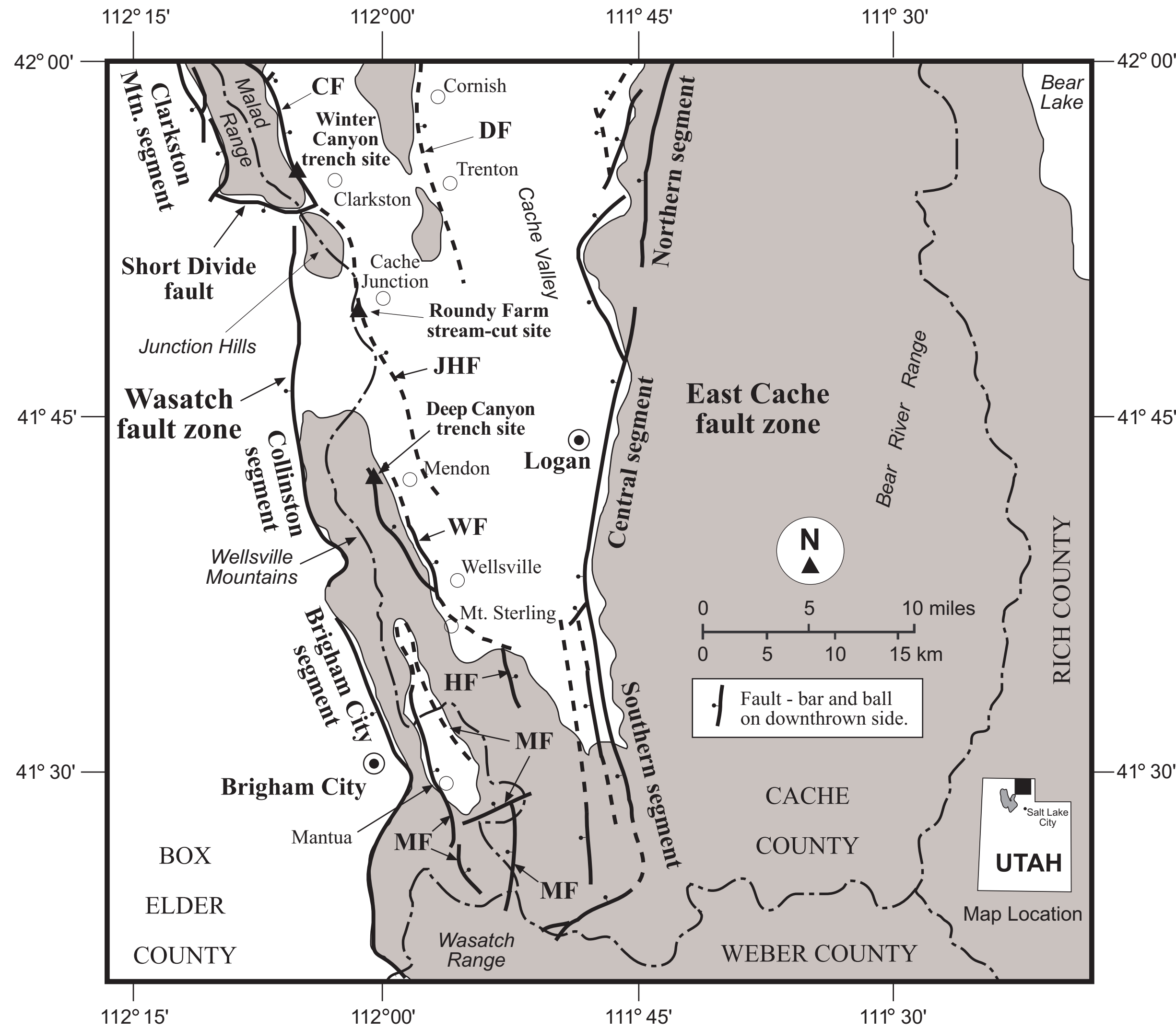


Figure 1. Simplified traces of the West Cache fault zone (WCFZ) and nearby faults in Utah (modified from Rember and Bennett, 1979; McCalpin, 1989; and Hecker, 1993). Faults in the WCFZ are: CF - Clarkston fault, JHF - Junction Hills fault, and WF - Wellsville fault. Nearby faults possibly associated with the WCFZ are: DF - Dayton fault, HF - Hyrum fault, and MF - faults in the Mantua area. Other nearby faults include the East Cache and Wasatch fault zones. Locations of our paleoseismic investigations are shown by solid triangles.

ure 2). Concentrated seismicity along this zone coincides with a belt of faulting that forms a right-stepping en-echelon pattern from the northern Wasatch Range in Utah to the Yellowstone area in northwestern Wyoming (Machette and others, 1991). Three major active fault zones in this belt are in or adjacent to Cache Valley. They are the Wasatch, East Cache, and West Cache fault zones (figure 1). The Wasatch and East Cache fault zones trend through Brigham City and Logan, respectively, Utah's nineteenth and twelfth largest cities (1994 populations of 16,618 and 36,078, respectively); the West Cache fault zone lies between the Wasatch and East Cache fault zones along the west side of Cache Valley (figure 1). All of these faults displace the ground surface and show evidence of large earthquakes in recent geologic time, and thus pose a significant seismic risk to the residents of northern Utah. Personius (1991) and McCalpin and Forman (1994) conducted trenching to identify the size and timing of prehistoric earthquakes on the Brigham City segment of the Wasatch fault zone, and McCalpin and Forman (1991) and McCalpin (1994) conducted similar studies on the East Cache fault zone. However, no trenching studies had been conducted on the West Cache fault zone prior to our investigation.

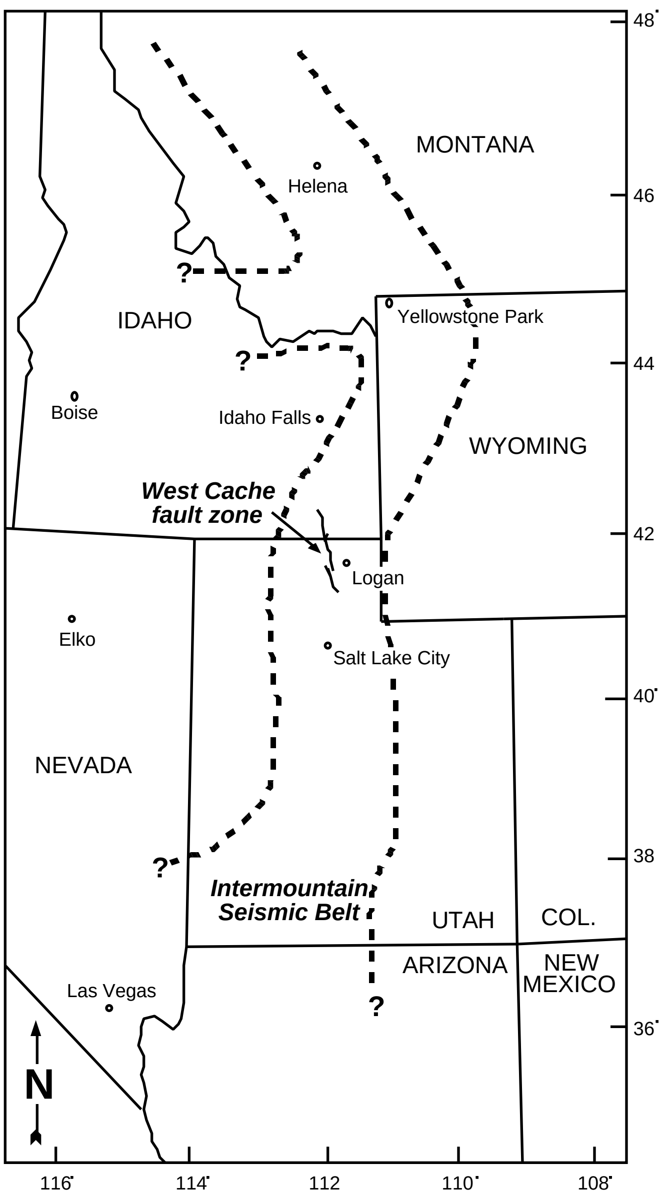


Figure 2. *West Cache fault zone with respect to the Intermountain seismic belt (modified from Smith and Arabasz, 1991).*

Structurally, Cache Valley is a narrow, elongate graben flanked by horst-block mountain ranges formed by movement on high-angle normal faults. The West Cache fault zone along the base of the uplifted Malad Range and Wellsville Mountains bounds the valley on the west; the East Cache fault zone along the base of the uplifted Bear River Range bounds the valley on the east. The mountains surrounding Cache Valley consist mainly of Precambrian to Permian sedimentary rocks, including limestone, dolomite, quartzite, sandstone, mudstone, siltstone, and shale. These rocks provided the detrital material that forms the younger deposits that fill Cache Valley. These younger deposits include the Tertiary Salt Lake Formation, consisting of conglomerate and tuffaceous sandstone, which overlies the Precambrian and Permian rocks and crops out in a nearly continuous belt in the foothills around the valley, and unconsolidated Quaternary deposits that are several hundred feet thick in the valley center (Williams, 1962; Kariya and others, 1994).

Cache Valley is also a geomorphic subbasin of the Bonneville basin, an area of internal drainage for much of the past 15 million years. Several successive lakes occupied the Bonneville basin during this time, but deposits of Pleistocene Lake Bonneville dominate the Quaternary geology of the West Cache fault zone (Solomon, 1999). To correlate ages related to Lake Bonneville with our paleoseismic data, we estimated calendar-calibrated ages rather than use radiocarbon ages (the most commonly used lake ages). Calibrated ages are herein designated "cal B.P.," or just "years ago." Details of our methods to estimate calendar ages related to the Bonneville lake cycle are outlined in the Radiocarbon Dating section.

The Bonneville lacustral cycle lasted from about 35,000 to 14,000 years ago, and coincides with the last global ice age of marine isotope stage 2 (Currey and Oviatt, 1985; Oviatt and others, 1992). The lake began gradually rising from levels close to modern-day Great Salt Lake about 35,000 years ago (Oviatt and others, 1992). The transgression from low to moderate lake levels apparently was very rapid, and by 30,700 years ago the lake transgressed to an elevation of 1,323 meters (4,341 ft) (Oviatt and others, 1992). Beginning about 25,500 years ago, the lake underwent a climatically induced stillstand and oscillation that produced the Stansbury shoreline (Oviatt and others, 1992). Brummer and McCalpin (1990) found no evidence of this shoreline in Cache Valley.

Between about 25,000 and 15,000 years ago, Lake Bonneville formed two shoreline complexes and deposited a thick sequence of sediments in Cache Valley (Solomon, 1999). Lake Bonneville continued rising after the Stansbury oscillation(s) and entered Cache Valley around 25,000 years ago (Solomon, 1999). The lake rise eventually slowed as water levels approached an external basin threshold in northern Cache Valley at Red Rock Pass (elevation of 1,552 meters [5,092 ft]) near Zenda, Idaho. Lake Bonneville reached the Red Rock Pass threshold and occupied its highest shoreline, named the Bonneville beach by

Gilbert (1890), after 18,000 years ago. The lake remained at this level until 16,800 years ago, when headward erosion of the Snake River-Bonneville basin drainage divide caused a catastrophic incision of the threshold and the lake level lowered by 108 meters (354 ft) in fewer than two months (Jarrett and Malde, 1987; O'Conner, 1993). Immediately after the Bonneville flood, the lake stabilized and formed the Provo shoreline (elevation of 1,444 meters [4,738 ft]). Oviatt (1986) reports that, during the flood, all of the water in the main lake body between the Bonneville and Provo shorelines discharged through three small passes in the Junction Hills into Cache Valley, and then out through Red Rock Pass into the Snake River. This rapid lake drawdown reduced the water-column weight on the earth's crust, which resulted in crustal rebound from isostatic compensation (Crittenden, 1963). Since the Bonneville highstand, isostatic rebound and regional tectonics uplifted the highest Bonneville shoreline in western Cache Valley as much as 27 meters (89 ft) to elevations of 1,567 to 1,579 meters (5,141-5,181 ft) (Currey, 1982; Solomon, 1999). The Provo shoreline in Cache Valley shows as much as 22 meters (72 ft) of uplift (elevations of 1,452 to 1,466 meters [4,764-4,810 ft]) (Currey, 1982; Solomon, 1999).

After about 16,200 years ago, the Bonneville basin once again became hydrologically closed and discharge ceased at the Red Rock Pass threshold. Climatic factors then caused Lake Bonneville to regress rapidly from the Provo shoreline, and the lake retreated from Cache Valley about 15,000 years ago. The lake eventually dropped below the present elevation of Great Salt Lake about 13,900 years ago. Oviatt and others (1992) deem this low stage the end of the Bonneville lake cycle. A subsequent transgression of Great Salt Lake between 13,900 and 11,600 years ago formed the Gilbert shoreline, but the lake did not rise high enough to re-enter Cache Valley.

Alluvial-fan deposition along the front of the Malad Range and the Wellsville Mountains also characterizes the Quaternary geology of the West Cache fault zone. Alluvial-fan deposits older than the Bonneville lake cycle are on remnants of extensive, dissected pediment surfaces cut into Tertiary deposits in the range-front foothills (Solomon, 1999). McCalpin (1989) estimates the age of similar deposits in eastern Cache Valley as 100,000 to 200,000 years old based on the amount of surface erosion and soil development. When Lake Bonneville transgressed into Cache Valley, the fan deposits were truncated by the highest shoreline (Bonneville) and covered by lake deposits at lower elevations. After the lake regressed, rapid and extensive downcutting eroded the lake shorelines, lake deposits, and old alluvial fans at canyon mouths. Much of this eroded material was deposited in younger alluvial fans along the range front (Solomon, 1999). Upper Holocene debris-flow deposits, possibly from a major fan-building episode about 4,000 to 5,000 years ago (Machette and others, 1992), constitute some of the alluvial-fan sediments. Stream alluvium was deposited in mountain drainages concurrently with the fan alluvium (Solomon, 1999).

Mass-movement deposits are found locally in the West Cache fault zone, including landslides and hillslope colluvium. The landslides are late Tertiary to late Pleistocene in age, and associated with failures of underlying Tertiary and Paleozoic sedimentary rocks and nearshore Lake Bonneville deposits (Solomon, 1999). Wave erosion of the Bonneville shoreline, rapid dewatering of oversteepened slopes during the Bonneville flood, or earthquakes caused most of the landslides (Solomon, 1999). Colluvial deposits are commonly found on mountain slopes and above stream channels in canyons. Solomon (1999) mapped undifferentiated colluvium and alluvium where colluvium-mantled hillsides grade imperceptibly into alluvium-filled ephemeral stream channels.

PALEOSEISMIC INVESTIGATIONS AND DATA

To establish the timing of past surface-faulting earthquakes on the Clarkston, Junction Hills, and Wellsville faults, we excavated and logged two trenches and cleaned and logged a natural stream-cut exposure. One trench was near the mouth of Winter Canyon west of Clarkston, Utah (figures 1 and 3), where Solomon (1999) indicates that the Clarkston fault may displace upper Holocene alluvial-fan deposits. The natural stream-cut exposure was on the Junction Hills fault at Roundy Farm west of Cache Junction, Utah (figures 1 and 4), where Oviatt (1986) reports observing displacement in transgressive Lake Bonneville deposits. The other trench was near the mouth of Deep Canyon west of Mendon, Utah (figures 1 and 5), where Solomon (1999) indicates that the Wellsville fault displaces upper to middle Pleistocene alluvial-fan deposits. The surficial geology at each site, sequence of deposition and faulting in the exposures, and results of our investigations are discussed below. Detailed logs of the fault zones in these exposures are shown on plates 1A through 1C.

Radiocarbon Dating

The Wasatch, East Cache, and West Cache fault zones all consist of normal faults (faults having mostly vertical and downward movement in the direction of dip). Surface displacement from a large earthquake on a normal fault typically produces a near-vertical scarp in unconsolidated sediments, which subsequently erodes back to a stable slope. Wallace (1977) and Swan and others (1980) first recognized deposits produced by fault-scarp degradation and described the erosional and depositional sequence. Erosion of the scarp forms a wedge-shaped deposit of colluvium (colluvial wedge) along the scarp base, burying the soil that was forming at the ground surface prior to the earthquake. Soil development then ceases on the buried soil (paleosol), but initiates on the colluvial wedge and degraded scarp. Each subsequent surface-faulting earthquake forms another colluvial wedge that stacks on top of the previous colluvial wedge. Radiocarbon dating of organic-rich material in these paleosols and colluvial wedges can estimate their age, and therefore, the approximate timing for the earthquake that formed them (for example, Swan and others, 1981; Schwartz and Coppersmith, 1984; Lund and others, 1991; Personius, 1991; Black and others, 1996; Lund and Black, 1998).

Radiocarbon age estimates from this study come from organic-rich material in paleosol A horizons and fault-scarp-

Figure 3. *West view of the Winter Canyon trench.*

Figure 4. *North view of the Roundy Farm stream cut.*

Figure 5. *West view of the Deep Canyon trench, Wellsville fault.*

derived colluvium, except for a sample of detrital charcoal entrained in a debris-flood deposit exposed in the Deep Canyon trench. The age of the detrital charcoal was obtained using an accelerator mass spectrometer; conventional gas-proportional methods provided the remaining ages. One sample from the Winter Canyon trench was not analyzed; it was taken as a backup to be used if we determined that one of the other samples was possibly contaminated by animal burrowing.

Table 1 shows radiocarbon laboratory results and calendar-calibrated age estimates for all samples taken from the Winter and Deep Canyon trenches, and the Roundy Farm stream cut. We calibrated the laboratory results using the computer program CALIB 3.0.3C (Stuiver and Reimer, 1993), which is based on studies of tree rings of known ages (Stuiver and Quay, 1979; Stuiver and Kra, 1986). We used an error multiplier of one and a uniform carbon age span (CAS) of 200 years for all the samples. Carbon age span is used by the calibration program to smooth fluctuations in the calibration curve (Machette and others, 1992; Stuiver and Reimer, 1993). The radiocarbon calibration curve of Stuiver and Reimer (1993) is based on studies of tree rings of known ages to about 11,500 years ago, and mass spectrometry of marine (coral) samples for older ages. All Lake Bonneville ages fall in the marine portion of the curve, which is generally linear and lacks the cyclic age variability of the tree-ring portion. Dr. Donald R. Currey (University of Utah Department of Geography, written communication, 1995) multiplies radiocarbon ages by the slope (1.16) of a best-fit line to the marine portion of the calibration curve (rounding to the nearest century). This method provides the best estimate of calendar ages of events related to the lake cycle (Donald R. Currey, verbal communication, 1998; David Madsen, Utah Geological Survey, verbal communication, 1998).

Radiocarbon ages from soil organics and organic-rich colluvium are termed apparent-mean-residence-time (AMRT) ages, and are a measure of total ^{14}C carbon activity. Although we used the calibration procedure to improve accuracy of the AMRT ages, the corrected ages are not sufficiently accurate to be termed dates and thus represent intervals of time. Machette and others (1992) indicate soils serve as a "carbon bank," accumulating a range of carbon of different ages having a distribution dependent on the carbon turnover rate in the soil. Modern soils thus typically yield AMRT ages of a few tens to a few hundreds of years. Careful sampling of the uppermost 5-10 centimeters (2-4 in) of a paleosol typically yields ages having the least variation, best reflecting the time of soil burial (Machette and others, 1992). The AMRT age of a soil before burial is termed the mean residence correction (MRC); we estimated MRC for the samples using methods in Machette and others (1992) and subtracted it from the radiocarbon age prior to calibration (Minze Stuiver, University of Washington, personal communication to W.R. Lund, 1992). Table 1 shows radiocarbon ages after MRC subtraction. Because of the uncertainties in these age estimates, we rounded our calendar-calibrated ages to the nearest half century. Two-sigma (2σ) error limits are shown for the age estimates (table 1), and are similarly rounded.

Clarkston Fault

Geology

The Clarkston fault is 35 kilometers (22 mi) long (11 kilometers [7 mi] in Utah, 24 kilometers [15 mi] in Idaho) and for most of its length consists of a single, sinuous fault trace with discontinuous east-dipping normal fault scarps. The fault is at elevations above the highest shoreline of Lake Bonneville, and generally separates unconsolidated

Table 1. *Radiocarbon results and calendar-calibrated age estimates taken from the Winter and Deep Canyon trenches, and Roundy Farm stream cut.*

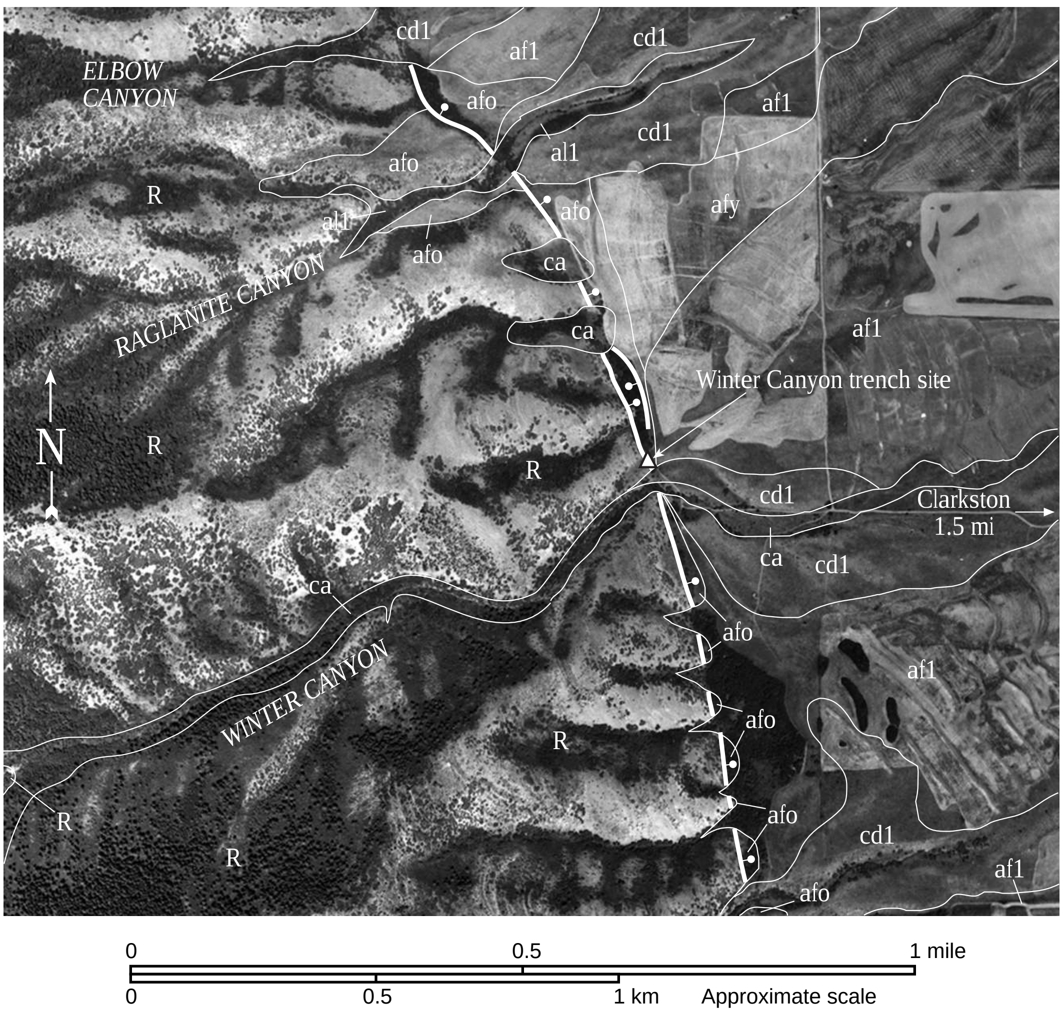
Laboratory sample number (Field sample number)	Material sampled	Radiocarbon age in ^{14}C yr B.P.	AMRT age estimate in ^{14}C cal B.P. (two-sigma error)	MRC (in yr)	CAS (in yr)	Notes
Winter Canyon trench, Clarkston fault, WCFZ						
Beta-110958 (WCT-RC1)	Upper 5-10 cm of paleosol S1	3,420 ± 50	3,650 (3,550-3,800)	150	200	UHC of paleosol S1 beneath MRE colluvial wedge.
(WCT-RC2)	Upper 5-10 cm of paleosol S1	—	—	—	—	Backup sample for WCT-RC1 not submitted to lab.
Beta-110959 (WCT-RC3)	Fault-scarp colluvium	2,200 ± 50	2,200 (2,050-2,300)	300	200	Distal part of MRE colluvial wedge.
Beta-110960 (WCT-RC4)	Fault-zone colluvium	3,530 ± 80	3,800 (3,600-4,000)	300	200	Heel of MRE colluvial wedge in fault zone.
Roundy Farm stream cut, Junction Hills fault, WCFZ						
Beta-110961 (RF-RC1)	Fault-scarp colluvium	7,690 ± 110	8,450 (8,250-8,650)	300	200	MRE colluvial wedge near UHC of paleosol S1.
Deep Canyon trench, Wellsville fault, WCFZ						
Beta-110953 (DCT-RC1)	Degraded charcoal	21,530 ± 160	—	—	—	Radiocarbon age too old to be calibrated. Limiting age for PE.
Beta-110954 (DCT-RC2)	Lower 5-10 cm of paleosol S1	4,540 ± 50	5,250 (5,000-5,350)	300	200	LHC of paleosol S1.
Beta-110955 (DCT-RC3)	Upper 5-10 cm of paleosol S1	4,020 ± 50	4,500 (4,350-4,600)	150	200	UHC of paleosol S1 beneath MRE colluvial wedge.
Beta-110956 (DCT-RC4)	Fault-scarp colluvium	3,010 ± 40	3,200 (3,050-3,300)	300	200	Distal part of MRE colluvial wedge.
Beta-110957 (DCT-RC5)	Lower 5-10 cm of soil S2	1,790 ± 60	1,700 (1,550-1,850)	300	200	LHC of soil S2 above MRE colluvial wedge.

Abbreviations used above:

MRE - most recent surface-faulting earthquake
PE - penultimate surface-faulting earthquake
MRC - mean residence correction
CAS - carbon age span
LHC - lower horizon contact
UHC - upper horizon contact
WCFZ - West Cache fault zone
AMRT - Apparent mean residence time

deposits in the hanging wall from bedrock in the footwall (Solomon, 1999). At the south end of the Clarkston fault, Hanson (1949) mapped a transverse fault (Short Divide fault, figure 1) that separates distinctly different geologic terranes to the north and south and shows a total estimated 3,000 meters (9,800 ft) of down-to-the-south stratigraphic throw. The concealed projection of the Short Divide fault obliquely intersects the Clarkston and Junction Hills faults. The elevation of the Bonneville shoreline near the south end of the Clarkston fault, north of Short Divide, is distinctly lower than the shoreline elevation to the south on the Junction Hills fault. Solomon (1999) reports that north of Short Divide the Bonneville shoreline is at an elevation of about 1,570 meters (5,151 ft), but south of the divide the shoreline is at an elevation of about 1,579 meters (5,181 ft).

Two areas of potentially displaced Holocene deposits exist on the Clarkston fault (Solomon, 1999). The first area is at the mouth of Winter Canyon, roughly 3 kilometers (2 mi) west of Clarkston, and the second is at the mouth of Raglanite Canyon, 0.8 kilometers (0.5 mi) north of Winter Canyon. Surficial deposits in these areas consist of upper Holocene to middle Pleistocene alluvium and colluvium (figure 6; Solomon, 1999). The fault at Winter and Raglanite Canyons consists of a single, discontinuous fault trace



DESCRIPTION OF MAP UNITS AND SYMBOLS

af1	Fan alluvium, unit 1 (upper Holocene)
cd1	Debris flows, unit 1 (upper Holocene)
al1	Stream alluvium, unit 1 (upper Holocene)
afy	Younger fan alluvium (Holocene to uppermost Pleistocene)
ca	Colluvium and alluvium, undivided (Holocene to middle Pleistocene)
afo	Older fan alluvium (upper to middle Pleistocene)
R	Bedrock, undivided

Normal fault, bar and ball on downthrown side.

Contact

Δ Trench site

Figure 6. *Aerial-photo geologic map of the Winter Canyon trench site vicinity (modified from Solomon, 1999).*

buried at the canyon mouths by stream alluvium, debris flows, and undivided colluvium and alluvium. The canyon mouths are separated from each other by steep, faceted, range-front spurs. Between Winter and Raglanite Canyons, the fault displaces upper to middle Pleistocene fan alluvium. South of Winter Canyon, the fault marks a contact between alluvium and bedrock.

Sequence of Deposition and Faulting in the Winter Canyon Trench

We excavated the Winter Canyon trench slightly north of the mouth of Winter Canyon across a roughly 4-meter-high (13 ft) scarp of the Clarkston fault. The trench exposed a single main fault trace (figure 7) and evidence of one surface-faulting earthquake. The oldest unit exposed in the Winter Canyon trench is a calcium-carbonate-cemented alluvial-fan deposit (unit 1, plate 1A). The alluvial-fan deposit is overlain by loess (unit 2). A soil A horizon (paleosol S1) formed on top of unit 2. The most recent surface-faulting earthquake (MRE) on the Clarkston fault displaced these units down to the east. A colluvial wedge (unit 3b) roughly 1.3 meters (4.3 ft) thick lies on top of unit 2 and paleosol S1. Unit 3a is a sheared zone in unit 2 along the fault. The modern soil (S2) is forming on top of unit 3; soil formation continued on top of unit 2 in the footwall. Unit 2, paleosol S1, and soil S2 showed considerable animal burrowing. Evidence in the trench also indicates that the degraded scarp free face continues to the surface and is not buried by colluvium. Colluvial deposits (generally with a modern soil A horizon) typically overlie the degraded scarp free face in trenches along the Wasatch fault zone (for instance, Black and others, 1996; Lund and Black, 1998). Therefore, we believe degradation of the scarp has been gradual and may still be continuing.

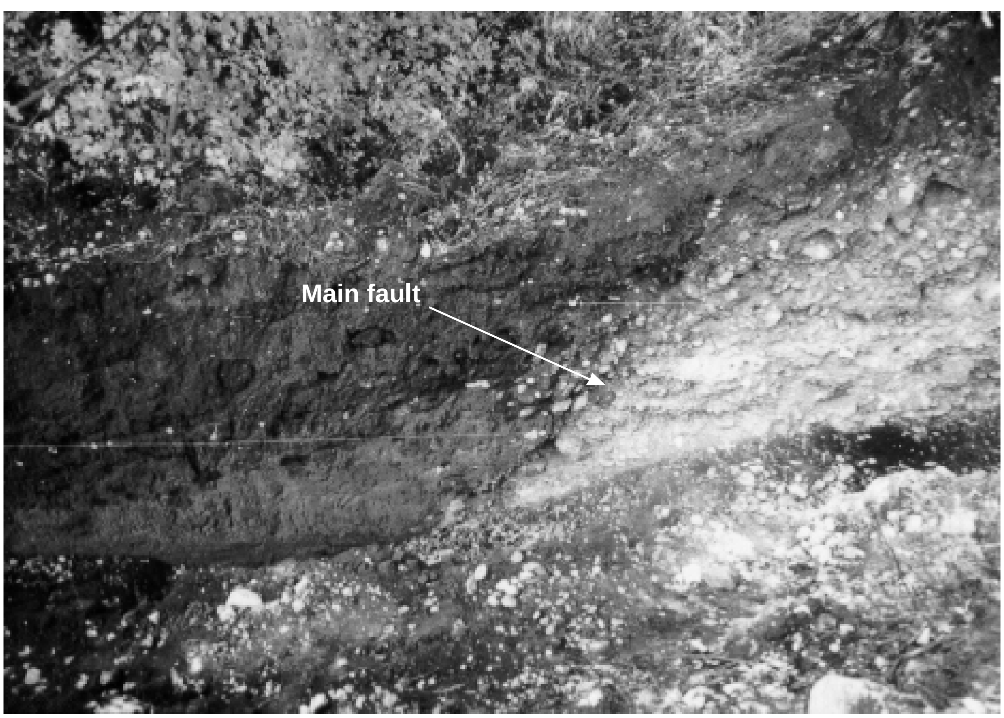


Figure 7. *South view of fault zone exposed in the Winter Canyon trench, Clarkston fault.*

Earthquake Timing and Recurrence

We collected four samples of organic material from the Winter Canyon trench for radiocarbon dating. We did not send WCT-RC2 for analysis (because it was a backup sample) and therefore no lab result is recorded on plate 1A and table 1. WCT-RC1 and WCT-RC4 show similar age estimates, and results from WCT-RC1, RC3, and RC4 are in proper chronostratigraphic order.

Formation of paleosol S1 predates the MRE on the Clarkston fault. Scarp colluvium buried the soil some time after this event and formed the colluvial wedge. Organic-rich sediment from the upper horizon contact of paleosol S1 beneath the MRE colluvial wedge (WCT-RC1, plate 1A) gave an age estimate of 3,650 +150/-100 cal B.P., which indicates soil burial was around 3,550 to 3,800 years ago. Organic-rich sediment from the middle of the colluvial wedge (WCT-RC3) gave an age estimate of 2,200 +100/-150 cal B.P., which supports our belief that formation of the colluvial wedge was gradual. Thus, we believe a few tens to hundreds of years passed before paleosol S1 was buried at the location of WCT-RC1. Radiocarbon analysis of organic-rich sediment from the heel of the colluvial wedge (WCT-RC4) gave an age estimate of 3,800 +/-200 cal B.P. This material would have been shed from the scarp free face very rapidly, possibly immediately after the event. Therefore, our best estimate for timing of the MRE on the Clarkston fault is 3,600 to 4,000 years ago.

We could not determine timing of the penultimate surface-faulting earthquake (PE) on the Clarkston fault because our trench only exposed evidence for the MRE. However, the shoreline-elevation difference (9 meters [30 ft]) across Short Divide suggests multiple post-Bonneville surface-faulting earthquakes on the Clarkston fault. Possible vertical displacement on the Short Divide fault does not explain the difference, because this fault is a south-dipping normal fault and displacement would produce a higher shoreline elevation (rather than lower) on the Clarkston side. Solomon (1999) also found no evidence for Quaternary displacement on the Short Divide fault. Isostasy accounts for about 0.3 meters (1.0 ft) of the difference, since the gradient of the Bonneville shoreline in this area is about -0.5 meters/kilometer (2.6 ft/mi) northward and the distance across Short Divide is 0.6 kilometers (0.4 mi). The remainder is due to movement on the Clarkston fault, Junction Hills fault, or Wasatch fault zone, or to a combination of events on these faults which differentially lowered the shoreline on the hanging wall of the Clarkston fault and/or raised the shoreline on the footwall of the Junction Hills fault (Solomon, 1999).

The Collinston segment of the Wasatch fault zone west of Short Divide (figure 1) shows no evidence of surface faulting since Lake Bonneville and a decrease in total vertical displacement northward (Machette and others, 1992). Our paleoseismic data from Roundy Farm (discussed below) indicate one post-lake event on the Junction Hills fault that could account for some of the difference. Stein and Barrientos (1985) observed that footwall uplift accounted for about 20 percent of the total vertical displacement from the 1983 Borah Peak earthquake (on a similar Basin and Range fault); similar displacement from the MRE on the Junction Hills fault would produce 0.6 meters (2.0 ft) of footwall uplift in 2.9 meters (9.5 ft) of total vertical displacement. Thus, isostasy and footwall uplift on the Junction Hills fault probably accounts for about 0.9 meters (3.0 ft) of the elevation difference; the remaining 8.1 meters (26.6 ft) must be due to hanging-wall subsidence from vertical displacement on the Clarkston fault. Based on this and the vertical displacement we measured from our scarp profiles, and assuming a characteristic earthquake model (Schwartz and Coppersmith, 1984), two or three surface-faulting earthquakes are necessary on the Clarkston fault since lake retreat to account for the remainder.

Using Stein and Barrietos'(1985) displacement ratio (20 percent footwall uplift, 80 percent hanging wall subsidence), three characteristic post-lake earthquakes on the Clarkston fault would produce 8.1 meters (26.6 ft) of total subsidence (equal to our above remainder) if each event averages 2.7 meters (8.9 ft) of hanging-wall subsidence and 3.4 meters (11.2 ft) of total vertical displacement (see Displacement and Slip Rate section below). Thus, we believe the Clarkston fault probably produced three post-lake events, though inaccuracies in elevation measurements and/or displacement variations could alter our interpretation. Such a scenario also fits the characteristic earthquake model better than two post-lake events, because the latter would require a PE having uncharacteristically large displacement compared to the MRE. Assuming three events occurred since Lake Bonneville instead of two (an MRE, a PE, and an antepenultimate event near Bonneville shoreline time), the average recurrence interval between surface-faulting earthquakes on the Clarkston fault is a maximum of 6,600 years. If we assume two post-lake events (an MRE and a PE near Bonneville shoreline time), the maximum recurrence interval would be 13,200 years.

Displacement and Slip Rate

We could not directly measure displacement in the Winter Canyon trench. Although unit 2 is traceable across the fault, the upper contact of this unit is an erosional surface in the footwall and we could not expose the lower contact in the hanging wall. Ongoing formation of the degraded scarp free face has removed the upper part of unit 2 in the footwall, and no slope colluvium overlies it. Topographic profiles across the fault near the trench site and at the mouth of Raglanite Canyon to the north in similar-age deposits indicated 3.1 to 3.7 meters (10.2 - 12.1 ft) of net vertical displacement. Scarp morphology suggests this displacement likely resulted from one earthquake. Symmetric scarp degradation models predict the maximum thickness of scarp-derived colluvium is roughly one-half the height of the free face from which it was shed (McCalpin, 1991). The MRE colluvial wedge in the Winter Canyon trench has a thickness of 1.3 meters (4.3 ft). This suggests an MRE scarp roughly 2.6 meters (8.5 ft) high, which is lower than our measured vertical displacement from the scarp profile at the trench site (3.1 meters [10.2 ft]). However, wedges deposited on sloping surfaces (such as the Winter Canyon site) have lower maximum thicknesses than those on horizontal or nearly horizontal surfaces (Ostenaa, 1984; McCalpin, 1991).

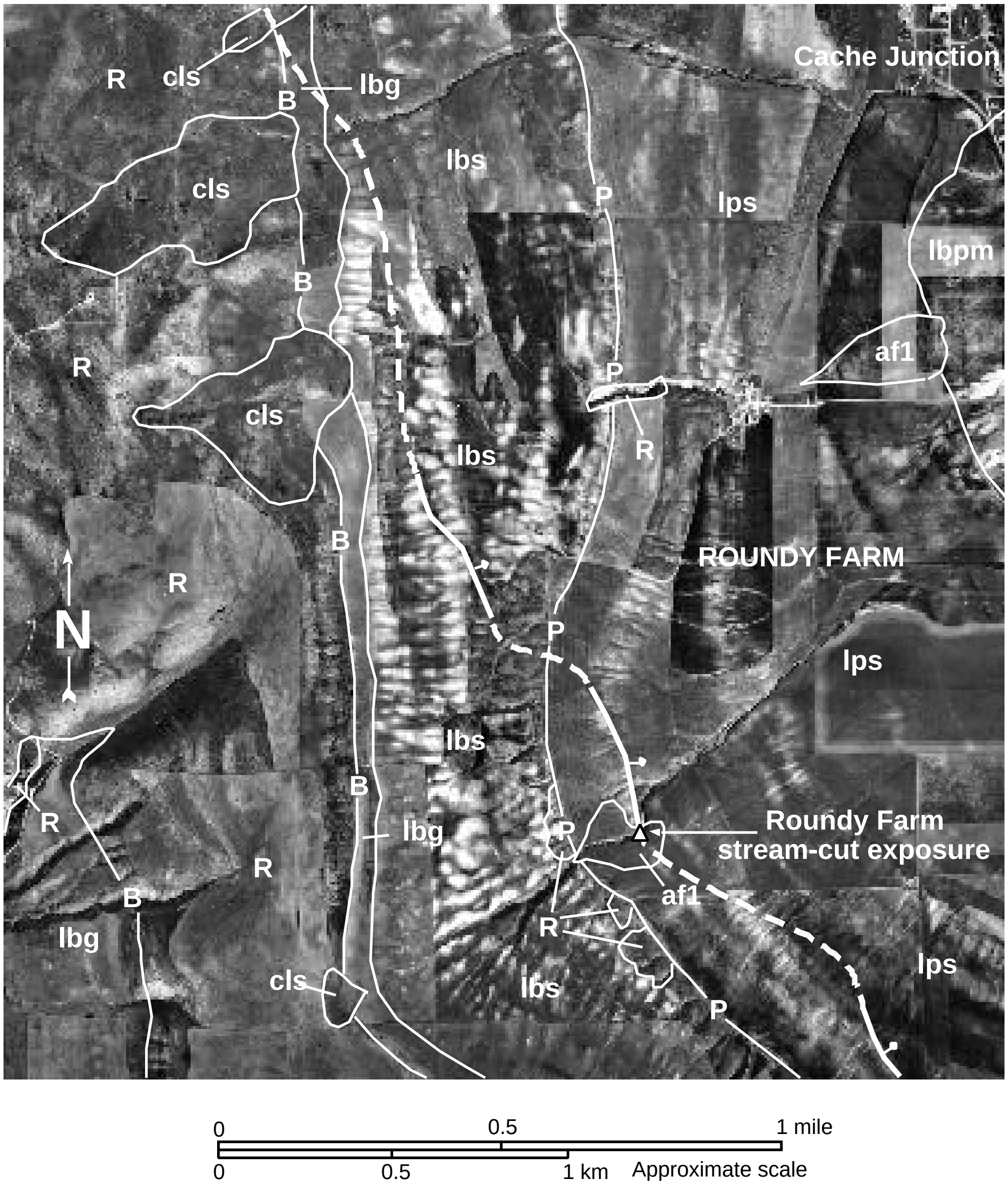
Due to a lack of evidence for the PE, we could not determine a slip rate based on a closed seismic cycle on the Clarkston fault. However, the shoreline-elevation difference (9 meters [30 ft]) across Short Divide and our paleoseismic data provide information to estimate a long-term slip rate. These data indicate a maximum long-term slip rate of 0.68 millimeters/year (0.027 in/yr), based on 9 meters (30 ft) of displacement in 13,200 years (age of the shoreline minus the MRE age). This estimated maximum slip rate is the highest of any of the faults in the West Cache fault zone, though the true slip rate is likely much lower and may be similar to the slip rate of the northern segment of the East Cache fault zone of 0.25 to 0.50 millimeters/year (0.010-0.020 in/yr) since the early Pleistocene (table 2; McCalpin, 1994). McCalpin (1994) suggests the slip rate for the northern segment of the East Cache fault zone may be overestimated and could also be lower, because this segment shows no evidence of post-lake faulting (unlike the Clarkston fault). Machette and others (1992) indicate scarps and steep topography on the eastern side of the Malad Range suggest the northern part (Clarkston fault) of the West Cache fault zone is the most active.

Junction Hills Fault

Geology

The Junction Hills fault is 25 kilometers (16 mi) long and consists of a single, discontinuous, east-dipping fault trace locally buried by landslide debris and fan alluvium. At its north end east of Short Divide, the fault displaces Tertiary sedimentary rock, but to the south the fault leaves bedrock and displaces Pleistocene Lake Bonneville deposits (Solomon, 1999). The fault parallels the Bonneville shoreline to the south, but the fault diverges near Cutler Reservoir once again into bedrock (Solomon, 1999).

Surficial evidence of the Junction Hills fault is poorly preserved. Solomon (1999) states that the only conclusive evidence of late Quaternary displacement on the Junction Hills fault exists near Roundy Farm, about 2 kilometers (1 mi) southwest of Cache Junction. Surficial geology there consists of deposits related to the Bonneville and Provo stages of Lake Bonneville, and local deposits of alluvium and colluvium (figure 8). Three 460 to 610-meter-long (1,509 -2,001 ft) east-facing normal fault scarps displace the lake deposits at this site. The central and southern scarps are below the Provo shoreline, the northern scarp is be-tween the Bonneville and Provo shorelines (Solomon, 1999). A natural stream cut exposes the fault at the southern end of the central scarp. The stream cut crosses the fault obliquely, yielding a low apparent fault dip in exposures. The site is on the edge of a plowed field; consequently, little surface expression of the scarp remains. Oviatt (1986) reports 2.4 meters (7.9 ft) of vertical dis-



DESCRIPTION OF MAP UNITS AND SYMBOLS

af1	Fan alluvium, unit 1 (upper Holocene)
cls	Landslide deposits (Holocene to middle Pleistocene)
lps	Provo regressive sand and silt (uppermost Pleistocene)
lbpm	Undivided Lake Bonneville deposits (upper Pleistocene)
lbg	Bonneville transgressive gravel and sand (upper Pleistocene)
lbs	Bonneville transgressive sand and silt (upper Pleistocene)
R	Bedrock, undivided

	Normal fault, bar and ball on downthrown side, dashed where approximately located.
	Contact
—B—	Highest shoreline of the Bonneville level
—P—	Highest shoreline of the Provo level
Δ	Steam-cut exposure

Figure 8. *Aerial-photo geologic map of the Roundy Farm stream cut vicinity (modified from Solomon, 1999).*

placement in the basal transgressive gravel of Lake Bonneville and evidence for additional pre-Bonneville surface-faulting earthquakes. Solomon (1999) reports finding no fault exposures at the other two scarps, but he assumes they are also of tectonic origin.

Sequence of Deposition and Faulting in the Roundy Farm Stream Cut

The stream cut exposes a single main fault trace (figure 9), an antithetic fault trace bounding a 4.3-meter-wide (14.1 ft) graben, and evidence for two surface-faulting earthquakes. The oldest unit in the stream cut exposure is a pre-Lake Bonneville alluvial-fan deposit (unit 1, plate 1B) consisting of clay and grusified cobbles, possibly highly weathered bedrock of the Tertiary Salt Lake Formation. Unit 1 is truncated by a degraded-scarp free face related to the penultimate surface-faulting earthquake (PE), but we observed no evidence of a colluvial wedge from the PE and believe it is buried beneath material sloughing off the stream-cut wall. The PE free face is overlain by a pre-Lake Bonneville alluvial-fan deposit consisting of silty sand with gravel forming crudely bedded channels (unit 2). Unit 2 is thin in the footwall, but thickens eastward in the hanging wall and extends well away from the fault zone, and it contains at least one interbedded paleosol A horizon east of the logged part of the exposure. No soil was evident on top of unit 2; the upper part of this unit may have been eroded when Lake Bonneville transgressed over the site. Unit 2 may also comprise paleochannel deposits along the base of the scarp, which would account for its thinness in the footwall.

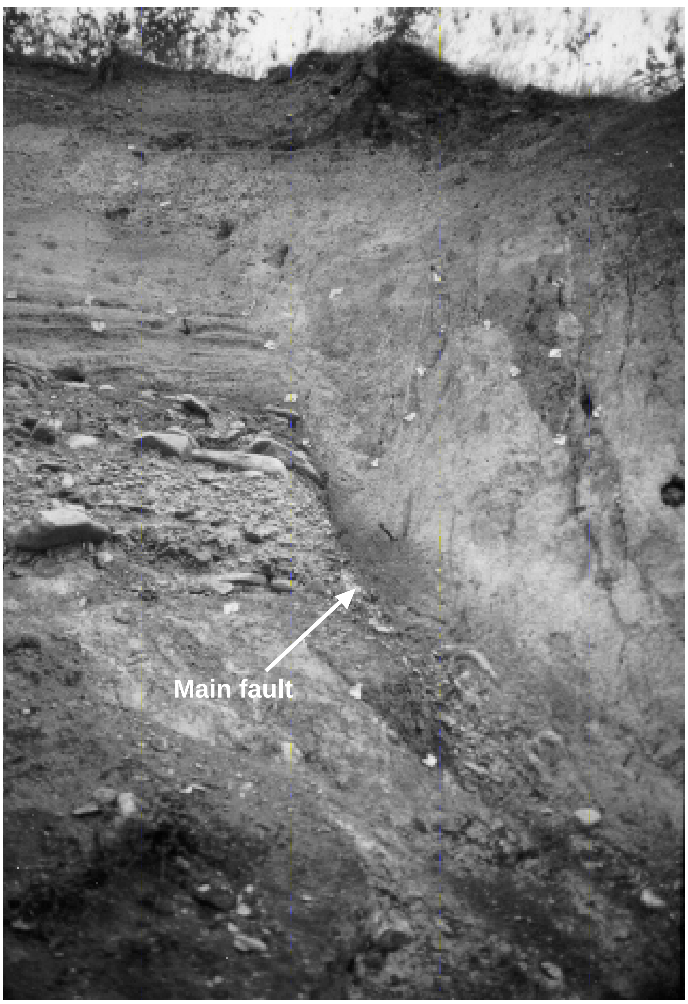


Figure 9. *North view of fault zone exposed in the Roundy Farm stream cut, Junction Hills fault.*

Units 1 and 2 are overlain by a transgressive sequence of Lake Bonneville deposits. The basal part of these deposits is a well-bedded gravel with sand (unit 3, plate 1B). Unit 3 is overlain by silty sand with gravel (unit 4) and silt having interbedded sand layers (unit 5). A weakly developed soil A horizon formed on top of unit 5 (paleosol S1). The MRE displaced all these units down to the east. The MRE also formed a graben (bounded by a west-dipping antithetic fault) showing considerable deformation (small faults and cracks), and a sheared zone along the main fault from upward drag in units 3 through 5 and paleosol S1 (unit 6a). A colluvial wedge roughly 1.3 meters (4.3 ft) thick lies on top of paleosol S1 (unit 6b). Unit 6c is fissure fill derived from paleosol S1. The upper parts of units 5, S1, 6b, and 6c have been removed by agricultural activity, and are overlain by a plowed zone in which a modern soil is forming (unit 7S).

Earthquake Timing and Recurrence

We collected one sample of organic material from the Roundy Farm stream-cut exposure for radiocarbon dating. Radiocarbon analysis of this sample, which consisted of slightly organic sediment collected from unit 6b and the top of paleosol S1 (RF-RC1, plate 1B), gave an age estimate of 8,450 +/- 200 cal B.P. This suggests that the MRE on the Junction Hills fault occurred around 8,250 to 8,650 years ago. We found no material to determine timing for the PE on the Junction Hills fault, but lake sediments exposed at Roundy Farm postdate the PE. The basal part of these sediments (unit 3) was likely deposited about 22,500 years ago (19,500 yr B.P.) as Lake Bonneville transgressed over the site (Oviatt and others, 1992; Donald R. Currey, written communication to J.W. Gwynn, 1995). Thus, a minimum of 13,850 years passed between the PE and MRE.

Displacement and Slip Rate

Due to agricultural activities, the scarp at Roundy Farm has been altered. Therefore, we measured no topographic profiles at this site. The remaining surficial expressions of the Junction Hills fault are subdued, rendering profiles inconclusive. However, correlative transgressive lake deposits are in both the footwall and hanging wall in the stream-cut exposure, and therefore we could directly measure their vertical displacement. Units 3 and 4 show evidence of drape on a pre-existing scarp or possible drag. Unit 5 is mostly horizontal on both sides of the fault zone. Therefore, we measured displacement in the basal contact of unit 5, between the fault zone and meter mark 7.5. This contact shows 2.9 meters (9.5 ft) of net vertical displacement from the MRE. No correlative stratigraphy was evident in the stream-cut exposure to indicate displacement from the PE.

Because of a lack of paleoseismic and geologic evidence, we were unable to determine a slip rate for the Junction Hills fault. However, vertical displacement from the MRE (2.9 meters [9.5 ft]) and the minimum elapsed time between the MRE and PE (13,850 years) suggest a maximum slip rate during post-Bonneville time of 0.21 millimeters/year (0.008 in/yr). This maximum rate is lower than the average slip rate of the central segment of the East Cache fault zone of 0.28 millimeters/year (0.01 in/yr) (table 2; McCalpin, 1994). Evans (1991) estimates net slip of 600 to 1,200 meters (2,000 - 3,900 ft) on the West Cache fault zone in the vicinity of the Junction Hills fault since Miocene extension of Cache Valley began, resulting in an average slip rate of 0.04 to 0.06 millimeters/year (0.0016 - 0.0024 in/yr). This rate is also lower than for the central segment of the East Cache fault zone since Miocene time of 0.29 to 0.54 millimeters/year (0.011 - 0.021 in/yr) (Evans, 1991).

Wellsville Fault

Geology

The Wellsville fault is 20 kilometers (12 mi) long and consists of an east-dipping normal fault that branches northward into two subparallel fault traces (figure 1). The eastern fault extends about 16 kilometers (10 mi) and separates Tertiary sedimentary rock in the hanging wall from Paleozoic sedimentary rock in the footwall. Quaternary deposits cover the eastern fault between bedrock outcrops; Pleistocene alluvial fans conceal the fault at its northern end, whereas Lake Bonneville and younger deposits conceal the fault at its southern end. The western fault extends about 13 kilometers (8 mi) and for much of its length marks a sharp boundary between Paleozoic bedrock and Tertiary and Quaternary deposits.

Solomon (1999) reports evidence of Quaternary displacement in two areas along the Wellsville fault. The first area is on the western fault branch at the mouth of Deep Canyon, where Oviatt (1986) notes 15 meters (49 ft) of vertical displacement in middle to upper Pleistocene alluvial-fan deposits. However, Solomon (1999) indicates that upper Holocene fan alluvium in the canyon is apparently not displaced. The second area is at the mouth of Pine Canyon, 7 kilometers (4 mi) south of Deep Canyon. At Pine Canyon, Solomon (1999) found several small faults and tilted beds exposed in the wall of a gravel pit excavated on the edge of prograding spit deposits near the Bonneville shoreline. Cumulative vertical displacement across these faults is at least 2 meters (7 ft) (Solomon, 1999). However, Solomon (1999) believes deformation in the gravel pit is probably the result of landsliding, rather than displacement on the Wellsville fault.

Table 2. *Comparison between ages of faulting and slip rates for the West Cache and East Cache fault zones.*

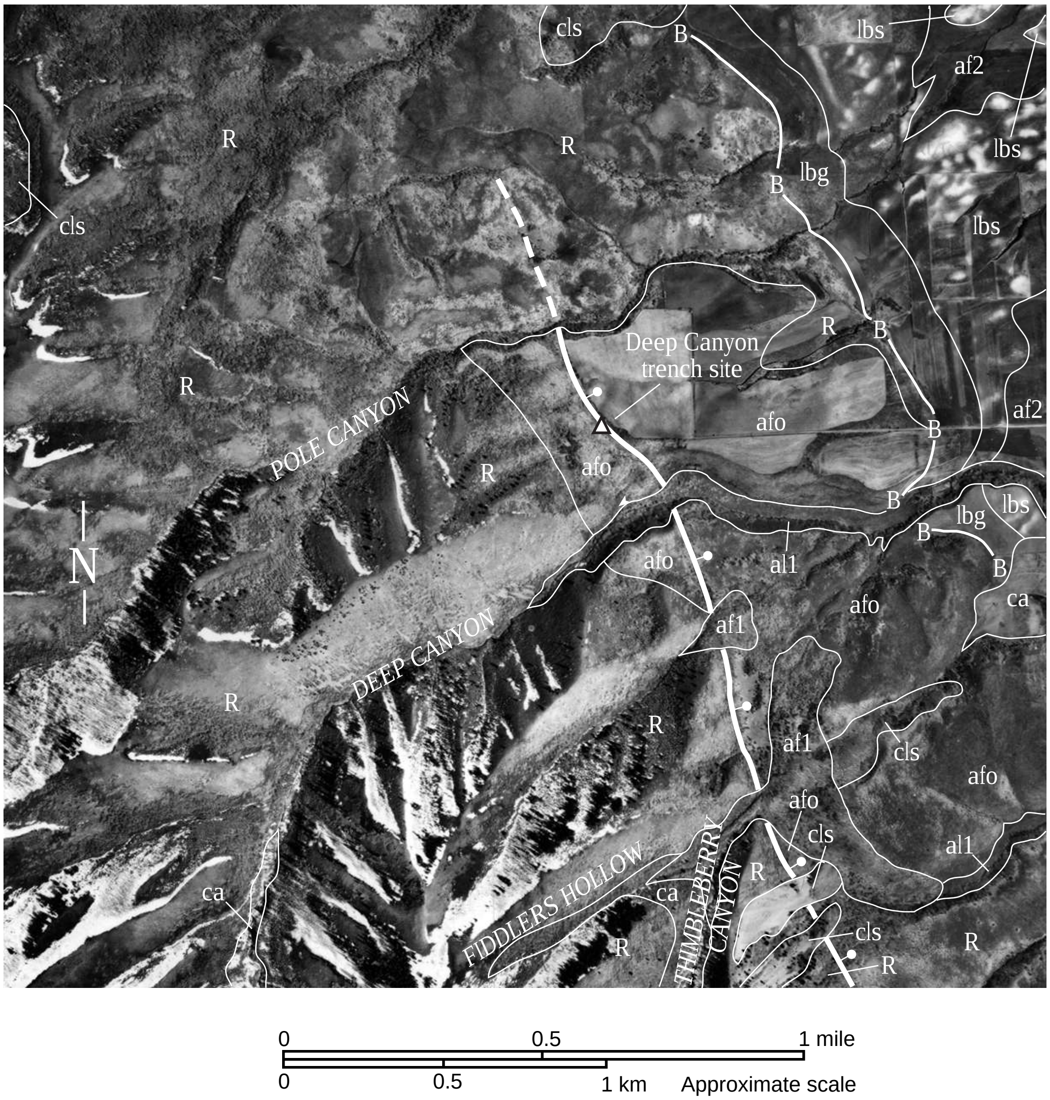
	Timing of most recent surface-faulting earthquake	Timing of penultimate surface-faulting earthquake	Slip rate (time frame)
WEST CACHE FAULT ZONE			
Clarkston fault	3,600-4,000 years ago	Post-Bonneville (<16,800 years ago)	<0.68 millimeters/year (late Pleistocene to middle Holocene)
Junction Hills fault	8,250-8,650 years ago	Pre-Bonneville (>16,800 years ago)	<0.21 millimeters/year (late Pleistocene to early Holocene)
Wellsville fault	4,400-4,800 years ago	15,000-25,000 years ago	0.11-0.22 millimeters/year (late Pleistocene to middle Holocene)
EAST CACHE FAULT ZONE[1]			
Northern segment	Pre-Bonneville (>16,800 years ago)		0.25-0.5 millimeters/year (early Pleistocene)
Central segment	4,300-4,800 years ago	15,000-18,000 years ago	0.28 millimeters/year (late Pleistocene to middle Holocene)
Southern segment	Pre-Bonneville (>16,800 years ago)		0.01-0.07 millimeters/year (early Pleistocene)

[1] East Cache fault zone data are from McCalpin (1994). Ages reported in McCalpin (1994) are uncalibrated and are calibrated here for comparison only. We determined calibrated age of the most recent surface-faulting earthquake on the central segment using methods described in the Radiocarbon Dating section, based on a lab age of 4,240 ± 80 yr B.P., MRC of 200, and a CAS of 200. We estimated the age of the penultimate surface-faulting earthquake on the central segment by multiplying by 1.16, as per the method used to calibrate lake-cycle ages. Slip rates for the Clarkston and Junction Hills faults are maximums and the true slip rates are uncertain and likely lower. McCalpin (1994) indicates that the northern-segment slip rate may be overestimated.

Surficial deposits in the vicinity of Deep Canyon include upper Holocene to middle Pleistocene fan alluvium, landslide deposits, and undivided alluvium and colluvium; and upper Pleistocene Bonneville transgressive gravel, sand, and silt (figure 10; Solomon, 1999). Unit afo is mostly an old alluvial fan above the Bonneville shoreline at the mouth of Deep Canyon, similar to the dissected alluvial fans in eastern Cache Valley estimated by McCalpin (1989) to be 100,000 to 200,000 years old. Downcutting along the drainage from Deep Canyon has dissected the alluvial fan at the canyon mouth by more than 30 meters (100 ft).

Sequence of Deposition and Faulting in the Deep Canyon Trench

We excavated the Deep Canyon trench north of the mouth of Deep Canyon across a 7-meter-high (23 ft) multiple-event scarp of the Wellsville fault. The trench exposed



DESCRIPTION OF MAP UNITS AND SYMBOLS

al1	Stream alluvium (upper Holocene)
af1	Fan alluvium, unit 1 (upper Holocene)
af2	Fan alluvium, unit 2 (middle Holocene to uppermost Pleistocene)
cls	Landslide deposits (Holocene to upper Pleistocene)
ca	Colluvium and alluvium, undivided (Holocene to middle Pleistocene)
lbg	Bonneville transgressive gravel and sand (upper Pleistocene)
lbs	Bonneville transgressive sand and silt (upper Pleistocene)
afo	Pre-Lake Bonneville fan alluvium (upper to middle Pleistocene)
R	Bedrock, undivided

- Normal fault, bar and ball on downthrown side, dashed where approximately located.
- Contact
- B — Highest shoreline of the Bonneville level
- △ Trench site

Figure 10. *Aerial-photo geologic map of the Deep Canyon trench site vicinity (modified from Solomon, 1999).*

two main faults (figure 11), smaller subsidiary faults, and evidence for two surface-faulting earthquakes. The oldest units in the trench are a series of interbedded, coarse- to fine-grained alluvial-fan deposits consisting of clay, silt, sand, and gravel (units 1-3, plate 1C). The PE on the Wellsville fault displaced these units an unknown amount down to the east (below the trench floor). The PE formed a wide fissure that filled with material likely derived from units 1 and 2 (unit 4a), and a colluvial wedge (unit 4b) formed on top of units 2, 3, and 4a after the event. Units 3 and 4b are overlain by additional alluvium (unit 5).

The trench exposes no alluvial units younger than unit 5. We believe that after the retreat of Lake Bonneville the alluvial fan at Deep Canyon became inactive as it was entrenched and deposition moved eastward into the valley. Units 4b and 5 are overlain by loess deposited after the lake retreat (unit 6, plate 1C), similar to the stratigraphic sequence found in the Winter Canyon trench (plate 1A). However, unit 6 is only evident in the hanging wall. A 2-meter-deep (7 ft) test pit west of the trench above the fault scarp also did not expose unit 6, and thus the loess either accumulated only along the base of the fault scarp at this site or was eroded from the top and front of the scarp. A soil A horizon formed on top of units 5 and 6 (paleosol S1). The MRE displaced all these units down to the east across the main fault and a smaller subsidiary fault (near meter mark 3); the MRE also displaced a wedge of units 4b through 6 up to the west along a small thrust fault in the fault zone (meter mark 7). A colluvial wedge roughly 1.2 meters (3.9 ft) thick formed on top of unit 6 and paleosol S1 following the MRE (unit 7). Unit 7 is overlain by slope colluvium (unit 8) on which the modern soil (soil S2) is forming.

Earthquake Timing and Recurrence

We collected five samples of organic material from the Deep Canyon trench for radiocarbon dating. Radiocarbon analysis of degraded charcoal taken from the base of unit 2 (DCT-RC1, plate 1C) gave an age estimate of 21,530 ± 160 yr B.P. Organic-rich sediment from the lower horizon contact of paleosol S1 (DCT-RC2) gave an age estimate of 5,250 +100/-250 cal B.P.; material from the upper horizon contact of paleosol S1 (DCT-RC3) gave an age estimate of 4,500 +100/-150 cal B.P. Organic-rich sediment from the center of the colluvial wedge unit 7 (DCT-RC4) above DCT-RC3 gave an age estimate of 3,200 +100/-150 cal B.P.; material from the lower horizon contact of soil S2 (DCT-RC5) above DCT-RC4 gave an age estimate of 1,700 +/-150 cal B.P. All these samples are in a proper chrono-stratigraphic sequence.

Formation of paleosol S1 predates the MRE on the Wellsville fault. Scarp colluvium (unit 7, plate 1C) buried the soil sometime after this event. Based on the age of the top of paleosol S1, the soil was buried around 4,350 to 4,600 years ago. However, this age comes from beneath the distal part of the colluvial wedge; we were unable to sample the wedge heel or paleosol upper horizon contact at the main fault (due to possible contamination from animal burrowing). Thus, as in the Winter Canyon trench on the Clarkston fault, time passed between the MRE and soil bur-

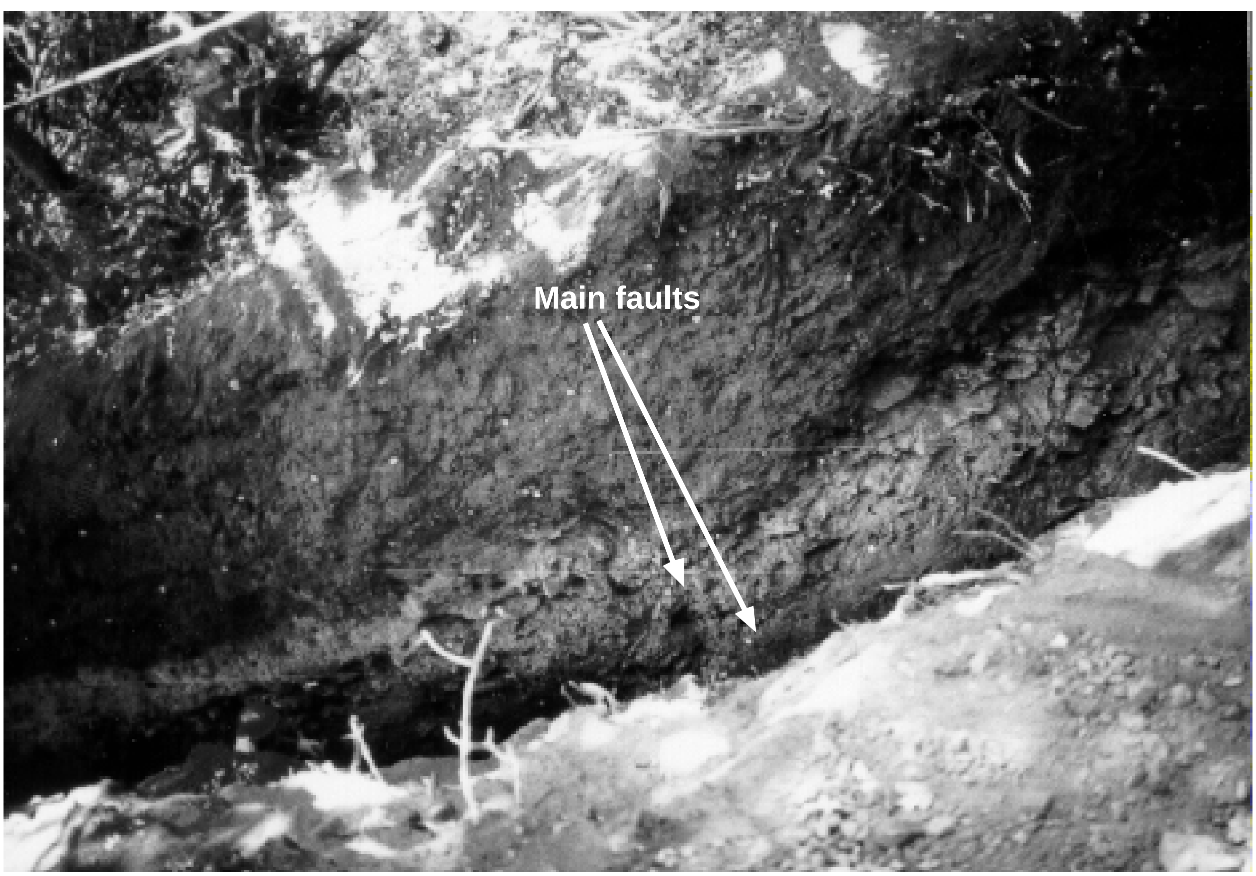


Figure 11. *South view of complex fault zone exposed in the Deep Canyon trench, Wellsville fault.*

ial. The age difference between DCT-RC3 and RC4 suggests that the rate of scarp degradation at Deep Canyon was slow, similar to that at Winter Canyon. At Winter Canyon, about 50 to 200 years passed between the MRE on the Clarkston fault and soil burial by scarp colluvium. Therefore, we believe the MRE on the Wellsville fault likely occurred between 4,400 and 4,800 years ago.

Units 1 through 3 in the Deep Canyon trench are alluvial-fan sediments deposited by debris flows and debris floods. These units predate the PE on the Wellsville fault. We found small pieces of degraded detrital charcoal along the base of unit 2 that yielded an age of 21,530 ± 160 yr B.P. Although this age is too old to calibrate directly, the method we use for correlating Lake Bonneville ages (radiocarbon age times 1.16) yields an approximate age of 25,000 years. This age is a maximum limiting age for the PE on the Wellsville fault. The PE predates deposition of unit 6 (plate 1C), which consists of windblown silt and fine sand (loess). Loess was commonly deposited in valley basins throughout the Basin and Range around 15,000 years ago (13,000 yr B.P.) after dessication of pluvial lakes in the region and retreat of glaciers and soil ice (Donald R. Currey, verbal communication, 1998). Based on this, we believe the PE occurred sometime between 15,000 and 25,000 years ago. This suggests a minimum of 10,200 and a maximum of 20,600 years passed between the PE and MRE on the Wellsville fault.

Displacement and Slip Rate

The absence of correlative stratigraphy in the Deep Canyon trench prevented calculation of displacement from the PE. However, unit 5 is traceable across the fault and provides evidence for the MRE displacement (unit 5 postdates the PE). Linear projection of the basal contact of this unit across the fault zone shows 1.9 meters (6.2 ft) of displacement down to the east from the MRE. Topographic profiling of the scarp at the trench site shows 6.6 meters (21.7 ft) of net vertical displacement from multiple surface-faulting earthquakes. A compound scarp often contains multiple breaks in slope, each evidencing a separate rupture event; a histogram of slope angle versus total distance (Haller, 1988) can often point out subtle inflections (gradient changes) in a compound scarp (McCalpin, 1996). A histogram of the profile at the Deep Canyon trench site shows three gradient changes that we believe represent three past surface-faulting earthquakes (figure 12). Average vertical displacement per event would therefore be 2.2 meters (7.2 ft), which is similar to the displacement measured in the trench from the MRE.

The average vertical displacement per event (2.2 meters [7.2 ft]) and elapsed time between the MRE and PE (10,200 - 20,600 years) indicate a slip rate of 0.11 - 0.22 millimeters/year (0.004 - 0.008 in/yr) for the Wellsville fault. This rate is less than the post-Bonneville slip rate for the central segment of the East Cache fault zone of 0.28 millimeters/year (0.011 in/yr), but is higher than the average slip rate for the southern segment of the East Cache fault zone of 0.01 to 0.07 millimeters/year (0.0004 - 0.0026 in/yr) since the early Pleistocene (table 2; McCalpin, 1994). South of Deep Canyon, the fault displaces an alluvial fan similar to those in eastern Cache Valley estimated by McCalpin (1989) to be 100,000 to 200,000 years old. Topographic profiling of this scarp showed 13.2 meters (43.3 ft) of net vertical displacement. Based on this displacement and the estimated age for the faulted alluvial-fan deposits, the maximum long-term slip rate for the Wellsville

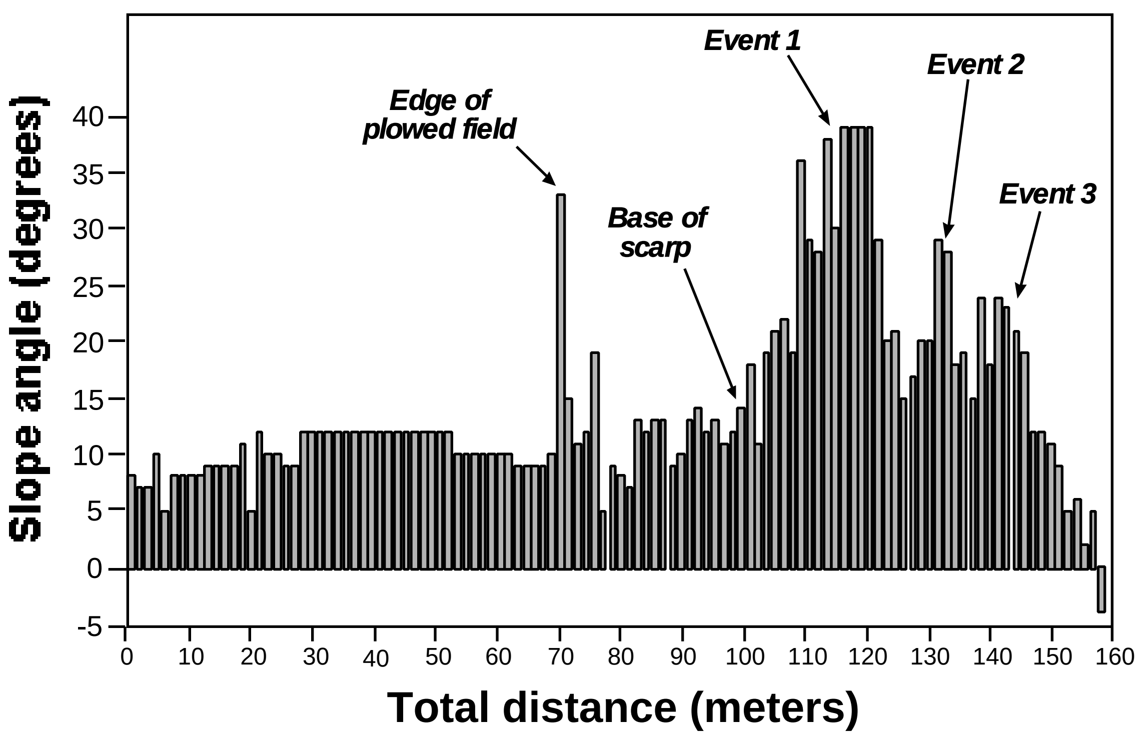


Figure 12. *Histogram of slope angle versus total distance for scarp profile 1, Deep Canyon, Wellsville fault. The scarp shows three gradient changes (spikes) possibly representing three surface-faulting earthquakes.*

fault since middle Pleistocene time is 0.13 millimeters/year (0.005 in/yr).

Fault Segmentation and Comparison

Behavioral, structural, and geomorphic evidence suggest that the Clarkston, Junction Hills, and Wellsville faults are separate segments of the West Cache fault zone. Based on this evidence and criteria in McCalpin (1996), the faults have a moderate likelihood of being earthquake segments (discrete portions of faults that have ruptured the surface two or more times; dePolo and others, 1989, 1991). Our paleoseismic data show timing for the MRE on all three faults differs, which indicates that each fault generated a separate MRE. The Clarkston fault shows the highest degree of independence and is the most active fault segment, having generated probably two additional surface-faulting earthquakes since Lake Bonneville (compared to the Junction Hills and Wellsville faults) and showing a higher slip rate (more than twice their maximum rate). However, because we could not determine timing for the PE on the Junction Hills segment, we are uncertain if the Junction Hills and Wellsville segments always rupture independently (such as in the MRE).

The Short Divide fault appears to mark a structural boundary between the Clarkston and Junction Hills faults, based on the elevation difference of the Bonneville shoreline across Short Divide. The relationship between the Junction Hills and Wellsville faults is less clear. The south end of the Junction Hills fault is poorly expressed at the surface. Solomon (1999) maps a concealed trace of the Junction Hills fault trending south out into the valley and dying out. The Wellsville fault begins farther west near the range front, about 3 kilometers (2 mi) north of the southern end of the Junction Hills fault. The overlap between the Junction Hills and Wellsville faults is the segment boundary. This boundary may not be persistent; surface faulting from a large-magnitude earthquake on one fault may step over and propagate onto the adjacent fault. However, the MREs on the Junction Hills and Wellsville faults show no evidence of cross-boundary propagation either at the surface or in the fault exposures.

Table 2 shows a possible correlation between earthquake timing for the Wellsville fault and the central segment of the East Cache fault zone. The MRE and PE on both faults have similar ages. The earthquake timing similarity suggests a large earthquake on one of the faults may have triggered a corresponding event on the opposing basin-bounding fault, or one of the faults is antithetic to the opposing fault and ruptured co-seismically, or both. However, no earthquake-timing correlations are evident between the East Cache fault zone and the Clarkston and Junction Hills faults.

Earthquake Magnitude

Various empirical relations exist to estimate paleoearthquake magnitudes from fault parameters. Table 3 compares magnitude estimates for the Clarkston, Junction Hills, and Wellsville faults based on surface-rupture length (L_S), displacement (D), and slip rate (S) (Bonilla and others, 1984; Mason, 1992; Mason and Smith, 1993; Wells and Coppersmith, 1994; Anderson and others, 1996). We assume fault displacements are near mean values for moment-magnitude calculations. Moment magnitude (M_w) is generally considered a better estimate of earthquake magnitude than surface-wave magnitude (M_s) (Hanks and Kanamori, 1979; Machette, 1986), and thus our estimates do not consider surface-wave magnitude (though results are still shown on table 3). Based on the various rupture parameters, table 3 shows moment magnitudes for surface-faulting earthquakes are M_w 6.9 - 7.4 for the Clarkston fault, M_w 6.8-7.3 for the Junction Hills fault, and M_w 6.6 - 7.2 for the Wellsville fault.

Table 3 also shows that magnitude estimates based on displacement are consistently higher than those based on surface-rupture length for all the faults. Zollweg (1998) indicates that regressions based solely on rupture length can underestimate paleoearthquake magnitudes, probably from a failure to recognize all fault traces that ruptured in an event (such as small-displacement scarps removed by erosion, or incomplete surface ruptures). Faults having aspect ratios (displacement divided by surface-rupture length, D/L_s) of 10^{-4} or more may have a longer rupture length than is evident, and thus earthquake magnitudes may be underestimated (Zollweg, 1998). The Wellsville fault has an aspect ratio above 10^{-4}, the Clarkston and Junction Hills faults are slightly below 10^{-4} (table 3). The latter two faults also lack true slip-rate data. Observations of historical surface-faulting earthquakes show a discrepancy between predicted and observed values of M_w based on rupture length, and Anderson and others (1996) indicate that including fault slip rate in relations based on rupture length can reduce this discrepancy and yield more accurate predictions of future earthquake magnitudes on active faults. Because the Clarkston and Junction Hills faults lack slip-rate data (and have aspect ratios below 10^{-4}), we applied Anderson and others' (1996) regression only to the Wellsville fault. Results show a moment magnitude estimate (M_w 6.8, table 3) roughly midway between estimates based on displacement and rupture length (M_w 6.6 - 7.2, table 3).

SUMMARY

To determine the paleoseismic history of the West Cache fault zone, we excavated and mapped two trenches at Winter and Deep Canyons across the Clarkston and Wellsville faults (respectively), and mapped a natural stream-cut exposure of the Junction Hills fault at Roundy Farm. Evidence from these exposures suggests that the MRE on the faults occurred: 3,600 to 4,000 years ago on the Clarkston fault, 8,250 to 8,650 years ago on the Junction Hills fault, and 4,400 to 4,800 years ago on the Wellsville fault. The Deep Canyon trench exposed evidence for the PE on the Wellsville fault, but timing for this event is poorly constrained to between 15,000 to 25,000 years ago. The Roundy Farm stream cut exposed indirect evidence for the PE on the Junction Hills fault; although we could not determine timing for this event, younger undisplaced Lake Bonneville deposits in the exposure show the PE occurred prior to the transgression of the lake across the site 22,500 years ago. The Winter Canyon trench did not expose evidence for the PE on the Clarkston fault, but the difference in

Table 3. *Magnitude estimates for surface-faulting earthquakes on the Clarkston, Junction Hills, and Wellsville faults.*

FAULT PARAMETERS

	Surface-trace distance (L_S, in kilometers)	**Displacement (D, in meters)**	**Aspect ratio (D/L_S)**	**Slip rate (S, in millimeters/year)**
Clarkston fault	37	3.4	9.19×10^{-5}	< 0.68
Junction Hills fault	33	2.9	8.79×10^{-5}	< 0.21
Wellsville fault	20	2.2	1.1×10^{-4}	0.11-0.22

MAGNITUDE ESTIMATES

	Moment Magnitude (M_w)		**Surface-Wave Magnitude(M_s)**	
	Wells and Coppersmith (1994)[1]	Anderson and others (1996)[2]	Bonilla and others (1984)[3]	Mason (1992); Mason and Smith (1993)[4]
Based on rupture length (L_s)				
Clarkston fault	6.9		7.1	
Junction Hills fault	6.8		7.0	
Wellsville fault	6.6		6.8	
Based on rupture length (L_s) and slip rate (S)				
Clarkston fault		—*		
Junction Hills fault		—*		
Wellsville fault		6.8		
Based on displacement (D)				
Clarkston fault	7.4		7.4	
Junction Hills fault	7.3		7.3	
Wellsville fault	7.2		7.2	
Based on rupture length (L_s) and displacement (D)				
Clarkston fault				7.1
Junction Hills fault				7.0
Wellsville fault				6.9

* *Not calculated due to a lack of slip-rate data and low aspect ratios ($<10^{-4}$).*

[1] *Regression for all types of slip;* $M_w = 5.08 + 1.16 \log L_s$; $M_w = 6.93 + 0.82 \log D$.

[2] $M_w = 5.12 + 1.16 \log L_s - 0.20 \log S$.

[3] *Ordinary least-squares relations for western North America;* $M_s = 5.17 + 1.237 \log L_s$, $M_s = 6.98 + 0.742 \log D$.

[4] $M_s = 6.1 + 0.47 \log(D \times L_s)$

shoreline elevations between the Junction Hills and Clarkston faults suggests that two or three events occurred on the Clarkston fault since the Lake Bonneville highstand. Three post-lake characteristic earthquakes of average vertical displacement similar to the MRE seem to best account for the elevation difference.

Trenching, scarp profiling, and geologic mapping from the Winter Canyon, Roundy Farm, and Deep Canyon sites also provide information on fault displacement and slip rate for the Clarkston, Junction Hills, and Wellsville faults. For the Clarkston fault, the data show 3.1 to 3.7 meters (10.2-12.1 ft) of net vertical displacement from the MRE and a maximum slip rate of 0.68 millimeters/year (0.018 - 0.027 in/yr) since late Pleistocene time. For the Junction Hills fault, the data show 2.9 meters (9.5 ft) of net vertical displacement from the MRE and a maximum slip rate during late Pleistocene time of 0.21 millimeters/year (0.008 in/yr). For the Wellsville fault, the data show 6.6 meters (21.7 ft) of net vertical displacement from the last three surface-faulting earthquakes, including 1.9 meters (6.2 ft) of MRE displacement; slip rate for the Wellsville fault since late Pleistocene time is 0.11 - 0.22 millimeters/year (0.004 - 0.008 in/yr). The data and paleoseismic history suggest that the faults in the West Cache fault zone behave independently and are probably earthquake segments, with the Clarkston fault having the highest degree of independence and activity rate. Earthquake timing is similar for the Wellsville fault and central segment of the East Cache fault zone and suggests a possible correlation between these faults, but no timing correlation is evident between the East Cache fault zone and other faults in the West Cache fault zone. Empirical relations to estimate paleoearthquake magnitudes from fault parameters such as rupture length, displacement, and slip rate indicate a moment magnitude of M_w 6.9 - 7.4 for the Clarkston fault, M_w 6.8 - 7.3 for the Junction Hills faults, and M_w 6.6 - 7.2 for the Wellsville fault.

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APPENDIX

DESCRIPTION OF GEOLOGIC UNITS EXPOSED IN THE WINTER CANYON AND DEEP CANYON TRENCHES AND THE ROUNDY FARM STREAM CUT

Classification of soil follows the Unified Soil Classification System (USCS) as per American Society for Testing and Materials (ASTM) Standard D2488-93 (Visual-Manual Procedure); for coarse-grained units characteristics apply to the matrix (fine-grained portion). Size ranges are: gravel, 4.75-75 millimeters; sand, 0.075-4.75 millimeters; and fines (clay and silt), less than 0.075 millimeters. Soil characteristics were estimated in the field. All colors are for dry soils.

WINTER CANYON TRENCH (PLATE 1A), CLARKSTON FAULT

UNIT 1 — **ALLUVIAL-FAN DEPOSIT** (matrix to clast supported) - Well-graded gravel with clay and sand (GW-GC); yellowish brown (10YR 5/4); 65 percent gravel, 25 percent sand, 10 percent fines; maximum clast size 35 cm, clasts subangular to rounded; medium toughness; slow dilatancy; predominantly low dry strength, high dry strength in $CaCO_3$-cemented layers; crudely bedded with cross-cutting channels; reacts strongly to HCl, stage I-III pedogenic carbonate; upper contact distinct; truncated by degraded-scarp free face.

UNIT 2 — **LOESS** - Clayey sand (SC); brown (7.5YR 5/4); 10 percent gravel, 50 percent sand, 40 percent fines; maximum clast size 10 cm, clasts subangular to subrounded; medium toughness; no to slow dilatancy; medium dry strength; nonstratified; weak reaction to HCl in hanging wall, moderate reaction to HCl in footwall; few roots and abundant animal burrows; paleosol S1 formed on top of unit in hanging wall, soil S2 formed on top of unit in footwall.

PALEOSOL S1 — **SOIL A HORIZON FORMED ON UNIT 2** - Clayey sand (SC); dark brown (10YR 3/3); 10 percent gravel, 50 percent sand, 40 percent fines; maximum clast size 10 cm, clasts subangular to subrounded; medium toughness; no to slow dilatancy; medium dry strength; nonstratified; very weak reaction to HCl; upper contact gradational; organic rich, few roots, and abundant animal burrows.

UNIT 3 (a and b) — **FAULT-ZONE MATERIALAND FAULT-SCARP COLLUVIUM**

3a Shear - Clayey gravel with sand to clayey sand with gravel (GC, SC); brown (10YR 5/3); 40 percent gravel, 40 percent sand, 20 percent fines; maximum clast size 30 cm, clasts subangular to subrounded; low to medium toughness; no to slow dilatancy; low to medium dry strength; crudely bedded, clasts aligned vertically parallel to fault zone; weak reaction to HCl.

3b Colluvial wedge - Clayey sand with gravel (SC); dark grayish brown (10YR 4/2); 15 percent gravel, 55 percent sand, 30 percent fines; maximum clast size 20 cm, clasts subangular; medium toughness, seems more plastic than unit 2; no to slow dilatancy; low to medium dry strength; nonstratified to crudely bedded, most clasts oriented along the degraded-scarp free face; no reaction to HCl; organic rich, few roots and animal burrows; soil S2 formed on top of unit.

SOIL S2 — **SOIL A HORIZON FORMING ON UNITS 2 AND 3** - Clayey sand with gravel (SC); dark grayish brown (10YR 4/2); 15 percent gravel, 50 percent sand, 35 percent fines; maximum clast size 10 cm, clasts subangular to subrounded; medium toughness; no to slow dilatancy; low to medium dry strength; nonstratified; no reaction to HCl; organic rich, abundant roots and few animal burrows.

ROUNDY FARM STREAM-CUT EXPOSURE (PLATE 1B), JUNCTION HILLS FAULT

UNIT 1 — **PRE-LAKE BONNEVILLE ALLUVIAL-FAN DEPOSIT** (matrix supported) - Lean clay with sand and gravel (CL); white (10YR 8/2); 10 percent gravel, 10 percent sand, 80 percent fines; clasts appear to have grusified into clay, maximum size and angularity uncertain; medium toughness; no dilatancy; medium dry strength; crudely bedded; reacts moderately with HCl; upper contact distinct, truncated by a degraded-scarp free face and unit 3 in footwall, may be highly weathered bedrock of the Tertiary Salt Lake Formation.

UNIT 2 — **PRE-LAKE BONNEVILLE ALLUVIAL-FAN DEPOSIT** (matrix supported) - Composition varies, but predominantly silty sand with gravel (SM); pale brown (10YR 6/3); 15 percent gravel, 50 percent sand, 35 percent fines, gravel and sand percentages higher in channels; maximum clast size 19 cm, clasts subrounded to rounded; low toughness; rapid dilatancy; low dry strength; crudely bedded with channels, mantles a degraded-scarp free face formed in unit 1, possibly occupied a paleochannel along the base of the scarp;

no reaction to HCl; upper contact distinct; truncated by unit 3 in footwall; contains an interbedded weakly developed paleosol A horizon east of the logged part of the exposure.

UNIT 3 **LAKE BONNEVILLE TRANSGRESSIVE GRAVEL DEPOSIT** - Well- graded gravel with sand (GW); light brownish gray (10YR 6/2); 65 percent gravel, 30 percent sand, 5 percent fines; maximum clast size 30 cm, clasts subrounded to rounded; low toughness; rapid dilatancy; no dry strength; well bedded; reacts strongly with HCl; upper contact distinct.

UNIT 4 **LAKE BONNEVILLE TRANSGRESSIVE SAND DEPOSIT** - Well-graded sand with gravel (SW); light yellowish brown (10YR 6/4); 15 percent gravel, 80 percent sand, 5 percent fines; maximum clast size 2 cm, clasts rounded; low toughness; rapid dilatancy; no dry strength; well bedded; reacts strongly with HCl; upper contact distinct.

UNIT 5 **LAKE BONNEVILLE NEARSHORE DEPOSITS** - Composition varies, interbedded silt, sand, and gravel; lower part is silt with sand (ML) to silty sand with gravel (SM), 5-15 percent gravel, 15-50 percent sand, 35-80 percent fines, low toughness, rapid dilatancy, low dry strength; upper part is silt (ML), 5 percent gravel, 10 percent sand, 85 percent fines, low toughness, slow dilatancy, low dry strength; light gray (10YR 7/2); maximum clast size 6 cm, clasts rounded; well bedded; reacts strongly with HCl; contains ostracodes and few animal burrows, paleosol S1 formed on top of unit, upper part truncated by plowed-horizon soil (unit 7S).

PALEOSOL S1 **WEAKLY DEVELOPED SOIL A HORIZON FORMED ON UNIT 5** - Silt (ML); light brownish gray (2.5Y 6/2); 5 percent gravel, 10 percent sand, 85 percent fines; maximum clast size 2 cm, clasts subrounded to rounded; low toughness; slow dilatancy; low dry strength; nonstratified; reacts strongly with HCl; upper contact distinct; few roots and animal burrows, truncated to west by plowed-horizon soil (unit 7S).

UNIT 6 (a, b, and c) **FAULT-ZONE MATERIALAND FAULT-SCARP COLLUVIUM**

6a Sheared material from units 1 through 5.

6b Colluvial wedge - Sandy elastic silt with gravel (MH); brown (10YR 5/3); 15 percent gravel, 30 percent sand, 55 percent fines; medium toughness; slow dilatancy; low dry strength; maximum clast size 2 cm, clasts subangular to subrounded; nonstratified; reacts strongly with HCl; upper contact distinct to gradational; few roots and animal burrows, upper part truncated by plowed-horizon soil (unit 7S).

6c Fissure fill - Same description as unit 6b.

UNIT 7S **PLOWED ZONE AND SOIL A HORIZON** - Sandy silt with gravel (ML); dark grayish brown (10YR 4/2); 20 percent gravel, 30 percent sand, 50 percent fines; low to medium toughness; slow dilatancy; no dry strength; maximum clast size 20 cm, clasts angular to subrounded; nonstratified; reacts moderately with HCl; organic-rich plowed soil for a wheat field, abundant roots.

DEEP CANYON TRENCH (PLATE 1C), WELLSVILLE FAULT

UNIT 1 **ALLUVIAL-FAN DEPOSIT** (matrix supported) - Sandy lean clay with gravel (CL); light yellowish brown (10YR 6/4); maximum clast size 30 cm, clasts angular to subrounded; medium toughness; no to slow dilatancy; medium dry strength; nonstratified; no reaction to HCl; upper contact sharp to gradational.

UNIT 2 **ALLUVIAL-FAN DEPOSIT** (matrix supported) - Sandy elastic silt (MH); brownish yellow (10YR 6/6); 10 percent gravel, 30 percent sand, 60 percent fines; maximum clast size 18 cm, clasts subangular to subrounded; low toughness; no to slow dilatancy; medium dry strength; nonstratified; no reaction to HCl; upper contact gradational; contains charcoal near base of unit.

UNIT 3 **ALLUVIAL-FAN DEPOSIT** (matrix supported) - Clayey gravel with sand (GC) to gravelly lean clay with sand (CL); yellow (10YR 7/6); 40 percent gravel, 20 percent sand, 40 percent fines; maximum clast size 28 cm, clasts subangular to subrounded; medium toughness; no to slow dilatancy; medium dry strength; nonstratified; no reaction to HCl; upper contact gradational to indistinct.

UNIT 4 (a and b) **FAULT-ZONE MATERIALAND FAULT-SCARP COLLUVIUM**

4a Fissure Fill - Clayey gravel with sand (GC); brownish yellow (10YR 6/6); 40 percent gravel, 30 percent sand, 30 percent fines; maximum clast size 24 cm, clasts subangular to subrounded; medium toughness; no to slow dilatancy; medium dry strength; nonstratified, some vertical clast-alignment fabric; no reaction to HCL; upper contact gradational.

4b Colluvial Wedge - Sandy lean clay with gravel (CL); very pale brown (10YR 7/4); 25 percent gravel, 35 percent sand, 40 percent fines; maximum clast size 19 cm, clasts subangular to subrounded; medium toughness; no to slow dilatancy; medium dry strength; nonstratified; no reaction to HCl; upper contact sharp in hanging wall, gradational contact along degraded-scarp free face.

UNIT 5 **ALLUVIAL-FAN DEPOSIT** (matrix supported) - Gravelly elastic silt with sand (MH); very pale brown (10YR 8/3); 40 percent gravel, 15 percent sand, 45 percent fines; maximum clast size 25 cm, clasts sub-

	angular to subrounded; medium toughness; slow dilatancy; medium dry strength; nonstratified; no reaction to HCl; upper contact sharp; paleosol S1 formed on top of unit but mostly removed by scarp erosion.
UNIT 6	**LOESS** - Elastic silt (MH); very pale brown (10YR 8/4); 5 percent gravel, 5 percent sand, 90 percent fines; maximum clast size 7 cm, clasts subrounded; low toughness; slow dilatancy; medium dry strength; nonstratified; no reaction to HCl; paleosol S1 formed on top of unit; not evident in footwall.
PALEOSOL S1	**SOIL A HORIZON FORMED ON UNITS 5 AND 6** - Elastic silt (MH); brown (10YR 3/3); 5 percent gravel, 5 percent sand, 90 percent fines; maximum clast size 7 cm, clasts subrounded; low toughness; slow dilatancy; medium dry strength; nonstratified; no reaction to HCl; upper contact gradational, incorporated in soil S2 forming on unit 5 in footwall; organic rich, few roots.
UNIT 7	**COLLUVIALWEDGE** - Sandy silt (ML); dark grayish brown (10YR 4/2); 10 percent gravel, 40 percent sand, 50 percent fines; maximum clast size 28 cm, clasts subangular to subrounded; low toughness; slow to rapid dilatancy; no to low dry strength; nonstratified, but fining eastward; no reaction to HCl; upper contact gradational; organic rich, few roots and animal burrows; most clasts oriented along the degraded-scarp free face.
UNIT 8	**SLOPE COLLUVIUM** - Silty sand (SM); dark grayish brown (10YR 4/2); 10 percent gravel, 50 percent sand, 40 percent fines; maximum clast size 15 cm, clasts subangular to subrounded; low toughness; slow to rapid dilatancy; low dry strength; nonstratified; no reaction to HCl; organic rich, abundant roots and few animal burrows; soil S2 formed on top of unit.
SOIL S2	**SOIL A HORIZON FORMING ON UNIT 8** - Silty sand (SM); dark grayish brown (10YR 4/2); 10 percent gravel, 50 percent sand, 40 percent fines; maximum clast size 15 cm, clasts subangular to subrounded; low toughness; slow to rapid dilatancy; low dry strength; nonstratified; no reaction to HCl; organic rich, abundant roots and few animal burrows.

PLATE 1
TRENCH LOGS

A. Log of the south wall of the Winter Canyon trench Clarkston fault, West Cache fault zone, Utah.

Mapped by Bill D. Black and Richard E. Giraud.

EXPLANATION

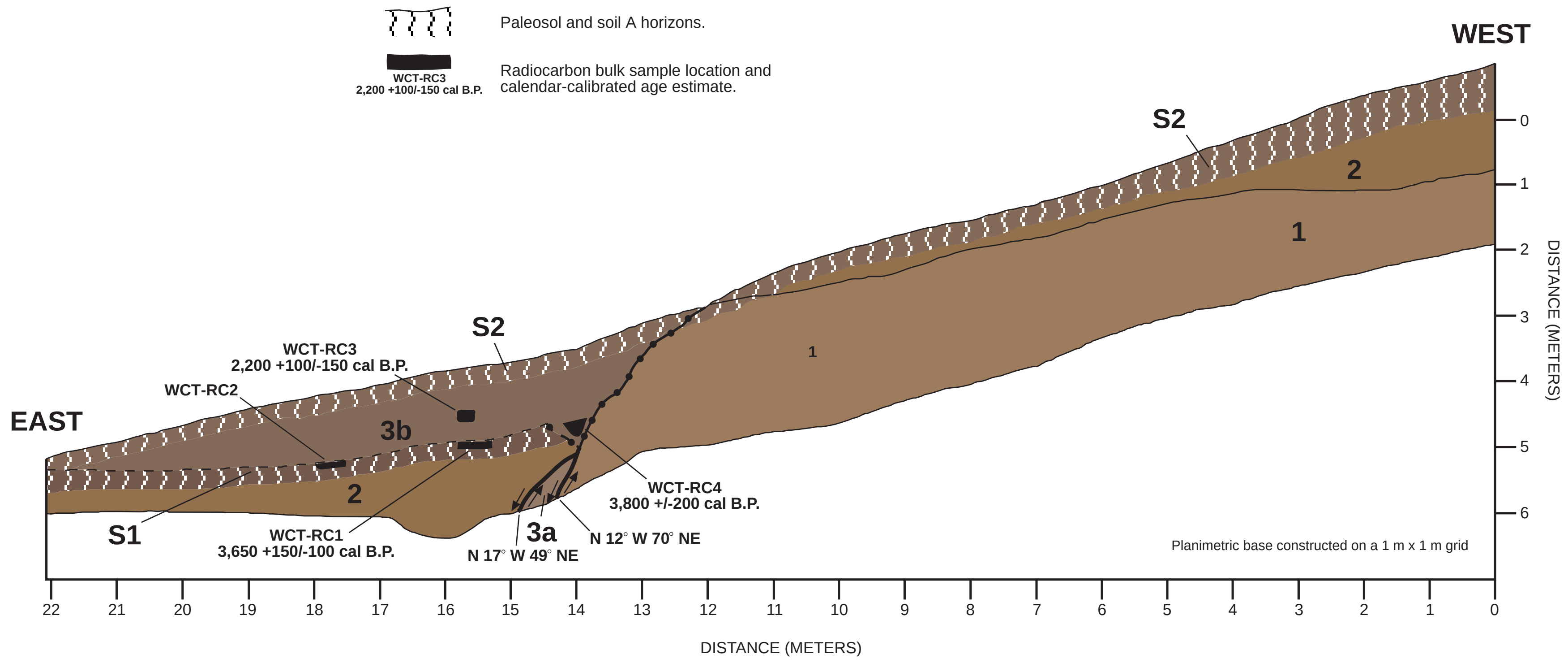
SYMBOLS

- Contact, dashed where indistinct.
- Fault, dashed where indistinct (arrows indicate relative movement).
- Degraded free face, dashed where indistinct.
- Paleosol and soil A horizons.
- WCT-RC3 2,200 +100/-150 cal B.P. — Radiocarbon bulk sample location and calendar-calibrated age estimate.

UNIT DESCRIPTIONS

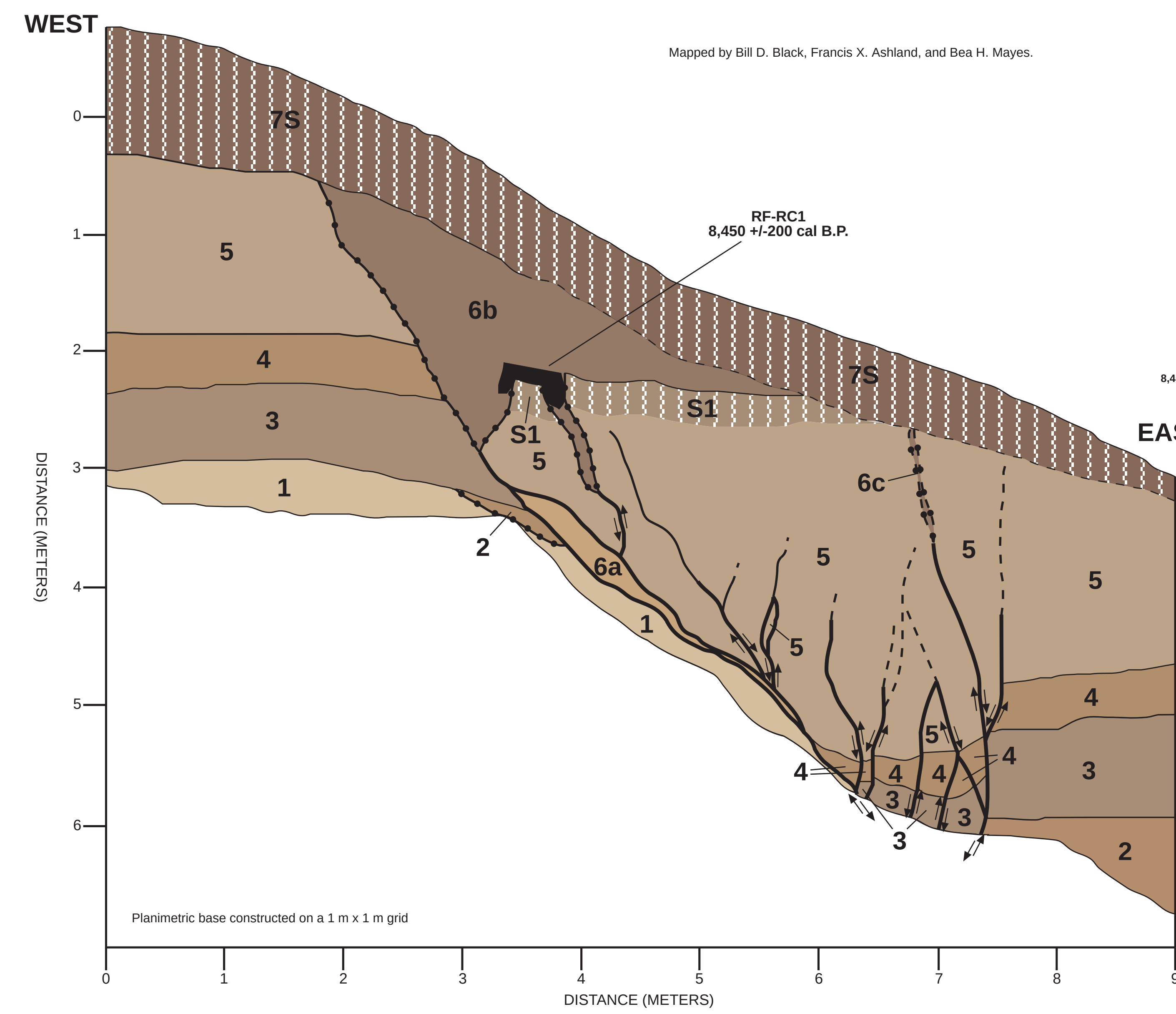
See appendix for detailed unit descriptions.

1. Alluvial-fan deposit.
2. Loess.
S1. Soil A horizon formed on unit 2.
3. Fault-zone material and fault-scarp colluvium.
   3a. Shear.
   3b. Colluvial wedge.
S2. Soil A horizon formed on units 2 and 3.



B. Log of the north wall of the Roundy Farm stream-cut exposure, Junction Hills fault, West Cache fault zone, Utah.

Mapped by Bill D. Black, Francis X. Ashland, and Bea H. Mayes.



EXPLANATION

SYMBOLS

- Contact, dashed where indistinct.
- Fault, dashed where indistinct (arrows indicate relative movement).
- Crack, dashed where indistinct.
- Degraded free face, dashed where indistinct.
- Paleosol and soil A horizons.
- RF-RC1 8,450 +/-200 cal B.P. — Radiocarbon bulk sample location and calendar-calibrated age estimate.

UNIT DESCRIPTIONS

See appendix for detailed unit descriptions.

1. Pre-Lake Bonneville alluvial-fan deposit.
2. Pre-Lake Bonneville alluvial-fan deposit mantling a degraded-scarp free face formed in unit 1.
3. Lake Bonneville transgressive gravel deposit.
4. Lake Bonneville transgressive sand deposit.
5. Lake Bonneville nearshore deposits.
S1. Weakly developed soil A horizon formed on unit 5.
6. Fault-zone material and fault-scarp colluvium.
   6a. Shear.
   6b. Colluvial wedge.
   6c. Fissure fill.
7S. Plowed zone and soil A horizon.

C. Log of the south wall of the Deep Canyon trench, Wellsville fault, West Cache fault zone, Utah.

Mapped by Bill D. Black, Richard E. Giraud, Bea H. Mayes, Barry J. Solomon, Gary E. Christenson, and William R. Lund.

EXPLANATION

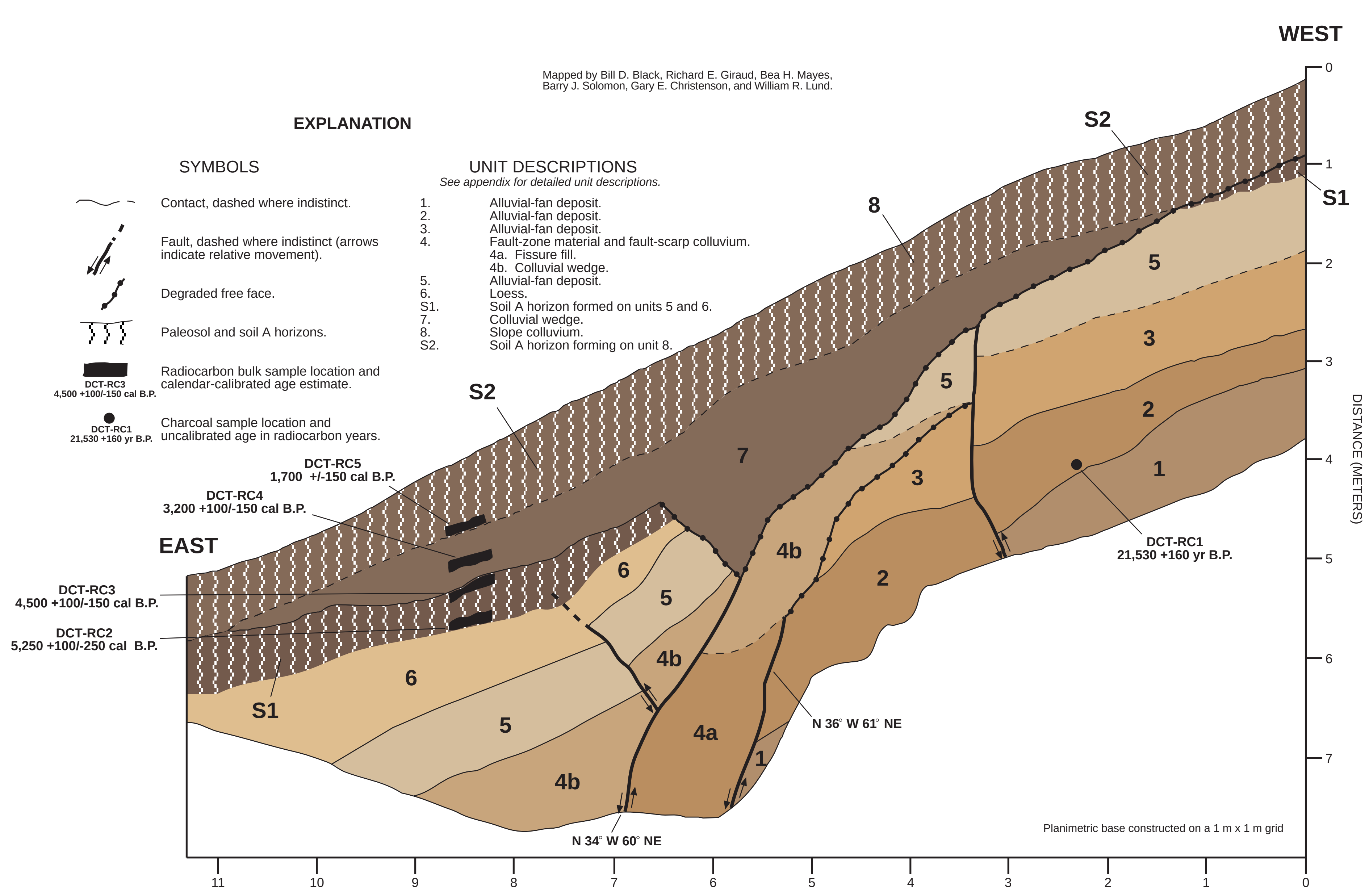
SYMBOLS

- Contact, dashed where indistinct.
- Fault, dashed where indistinct (arrows indicate relative movement).
- Degraded free face.
- Paleosol and soil A horizons.
- DCT-RC3 4,500 +100/-150 cal B.P. — Radiocarbon bulk sample location and calendar-calibrated age estimate.
- DCT-RC1 21,530 +160 yr B.P. — Charcoal sample location and uncalibrated age in radiocarbon years.

UNIT DESCRIPTIONS

See appendix for detailed unit descriptions.

1. Alluvial-fan deposit.
2. Alluvial-fan deposit.
3. Alluvial-fan deposit.
4. Fault-zone material and fault-scarp colluvium.
   4a. Fissure fill.
   4b. Colluvial wedge.
5. Alluvial-fan deposit.
6. Loess.
S1. Soil A horizon formed on units 5 and 6.
7. Colluvial wedge.
8. Slope colluvium.
S2. Soil A horizon forming on unit 8.



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