SEISMIC-SOURCE EVALUATION OF THE WEST CACHE FAULT ZONE, CACHE COUNTY, UTAH

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ABSTRACT

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. Three large active fault zones are in and adjacent to Cache Valley that pose a significant risk: the Wasatch, East Cache, and West Cache fault zones. All of these fault zones displace the surface and show evidence of large earthquakes in recent geologic time. Trenching to identify the size and timing of prehistoric surface-faulting earthquakes has been done for the Wasatch and East Cache fault zones, but no such studies have been previously done for the West Cache fault zone. The purpose of this study is to determine the seismic-source potential of the West Cache fault zone, to help evaluate the earthquake hazard presented by the fault zone to Cache Valley and northern Utah.

To determine the seismic-source potential of the West Cache fault zone, the Utah Geological Survey investigated three sites on the Clarkston, Junction Hills, and Wellsville faults. The investigation included interpreting aerial photographs and previous surficial-geologic mapping along the fault zone, profiling scarps and mapping two trench exposures across the Clarkston and Wellsville faults, mapping 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 probably occurred between 15,100 to 25,000 years ago, whereas the PE on the Junction Hills fault occurred some time prior to 22,500 years ago. No evidence of the PE on the Clarkston fault was found 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 events may have occurred on the Clarkston fault since 16,800 years ago. Timing for the MRE on the faults suggests they behave independently. The paleoseismic data also indicate maximum slip rates of the faults are 0.54 millimeters/year (0.021 in/yr) for the Clarkston fault, 0.13 millimeters/year (0.005 in/yr) for the Junction Hills fault, and 0.18-0.29 millimeters/year (0.007-0.011 in/yr) for the Wellsville fault. Estimated paleoearthquake magnitudes are M_w 7.0-7.1 for the Clarkston and Junction Hills faults, and M_w 6.8-6.9 for the Wellsville fault.

INTRODUCTION

This report summarizes results of a Utah Geological Survey (UGS) project, partially funded by the U.S. Geological Survey National Earthquake Hazards Reduction Program (contract no. 1434-HQ-97-03055), to investigate prehistoric earthquakes on the West Cache fault zone. The West Cache fault zone extends about 56 kilometers (35 mi) along the west side of Cache Valley in northern Utah from the Utah-Idaho border, and another 24 kilometers (15 mi) into southern Idaho, to about 6 kilometers (4 mi) south of Wellsville. The fault zone consists of three normal faults that dip eastward beneath Cache Valley, from north to south: the Clarkston, Junction Hills, and Wellsville faults (CF, JHF, and WF respectively; figure 1). Faults in three nearby areas may also be associated with the West Cache fault zone, but they have not been previously included because of a lack of demonstrable continuity with the fault zone and evidence for late Quaternary activity. Solomon (1997) mapped and discussed these faults, but did not find any conclusive evidence to clarify their relationship to the West Cache fault zone. The 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). These faults are in bedrock, and Solomon (1997) found no evidence of displaced late Quaternary deposits.

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 (figure 2). Concentrated seismicity along this zone is coincident 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 and adjacent to Cache Valley: 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 is between these cities (figure 1). All of these faults displace the surface and show evidence of large earthquakes in recent geologic time, and thus they pose a significant seismic risk to citizens living in Cache Valley and northern Utah. Trenching to identify the size and timing of prehistoric earthquakes has been conducted on the Brigham City segment of the Wasatch fault zone (Personius, 1991; McCalpin and Forman, 1994) and East Cache fault zone (McCalpin and Forman, 1991; McCalpin, 1994), but no such studies have been previously conducted on the West Cache fault zone.

The Wasatch, East Cache, and West Cache fault zones all contain normal faults having mostly vertical and downward movement in the direction of fault dip. Surface displacement from a large earthquake on these faults may produce a near-vertical scarp (free face) in unconsolidated sediments, which rapidly erodes to a stable slope. Wallace (1977) and Swan and others (1980) recognized deposits produced by fault-scarp erosion and described the sequence of erosion and deposition. Erosion of the scarp forms a wedge-shaped deposit of colluvium (colluvial wedge) along the scarp base, burying the soil forming at the ground surface prior to the earthquake. Soil development ceases on the buried soil but continues on the colluvial wedge and degraded scarp. Each subsequent surface-faulting earthquake forms another colluvial wedge stacked on top of the downdropped surface soil, older wedge, and buried soil (paleosol). Earthquake timing can be constrained by determining the age of the paleosols and colluvial wedges. Paleoseismic studies along the Wasatch fault zone have used radiocarbon dating of organic-rich material in paleosols and colluvial wedges to define timing of past surface-faulting earthquakes (for example, Swan and others, 1981; Schwartz and Coppersmith, 1984; Lund and others, 1991; Personius, 1991; Black and others, 1996; and Lund and Black, 1998).

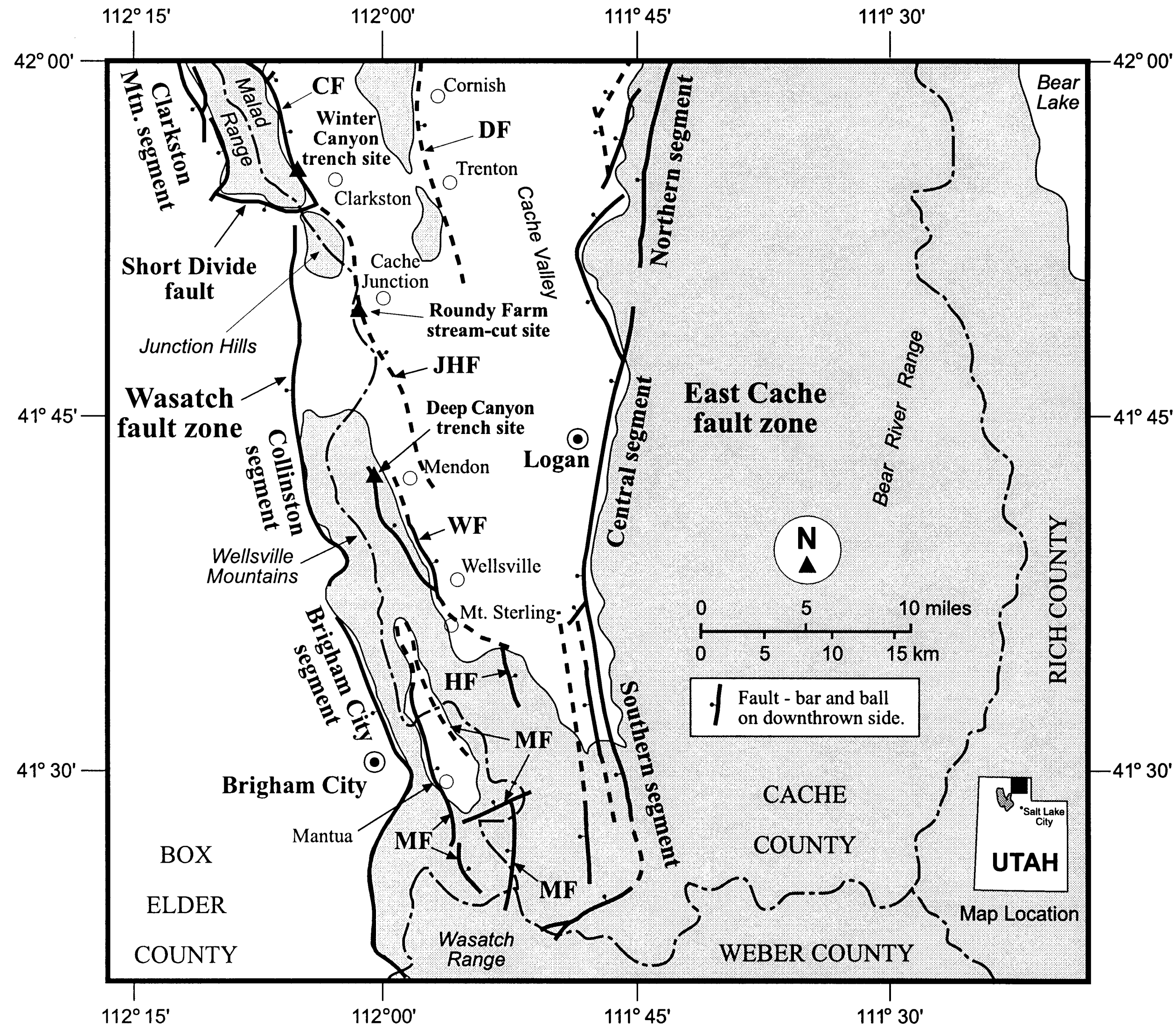


Figure 1. Location map showing simplified traces of the West Cache fault zone (WCFZ) and nearby faults (modified from Rember and Bennett, 1979; McCalpin, 1989; and Hecker, 1993). Faults in the WCFZ are: CF - Clarkston fault, JHF - Junction Hills fault, and WF - Wellsville fault. Nearby faults possibly 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.

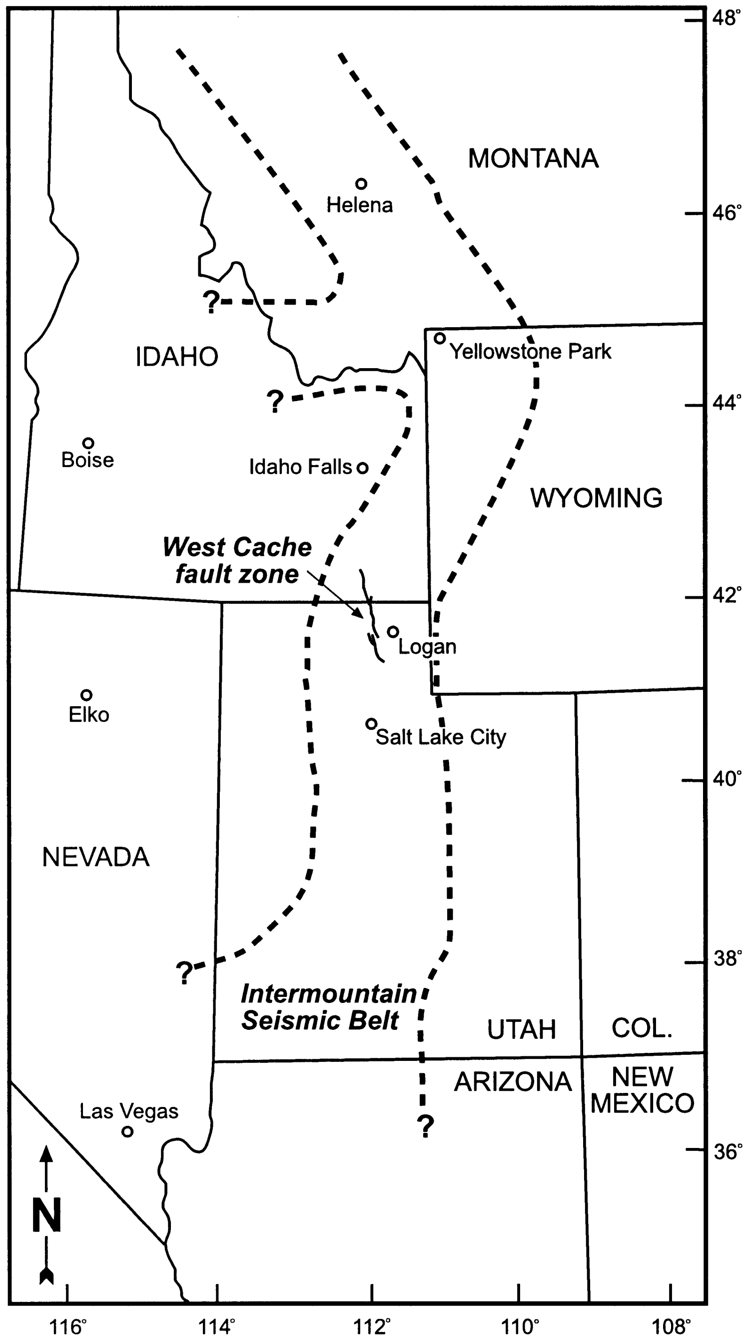


Figure 2. West Cache fault zone with respect to the Intermountain seismic belt (modified from Smith and Arabasz, 1991).

Late Quaternary geology of Cache Valley is dominated by deposits of Pleistocene Lake Bonneville. To correlate ages of events related to Lake Bonneville with our paleoseismic data, we estimated calendar-calibrated ages rather than use the radiocarbon ages commonly reported in the references. Calibrated ages are designated "cal B.P.", or just "years ago." 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 thereafter. Most 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. Don Currey (University of Utah Department of Geography, written communication, 1995) estimated various lake-cycle ages by multiplying the radiocarbon age 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 a best estimate of ages of events related to the lake cycle (Don Currey, verbal communication, 1998; David Madsen, Utah Geological Survey, verbal communication, 1998).

The purpose of this study is to determine the West Cache fault zone seismic-source potential to aid evaluation of the earthquake hazard it presents to Cache Valley and northern Utah. The study included interpreting aerial photographs and previous surficial-geologic mapping (Solomon, 1997), profiling scarps and mapping two trench exposures across the Clarkston and Wellsville faults, mapping a natural stream-cut exposure of the Junction Hills fault, and radiocarbon dating. Paleoseismic parameters determined from the data 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 valley (average elevation 1,370 meters [4,495 ft]) is bounded on the east by the wide and rugged Bear River Range (maximum elevation 3,042 meters [9,981 ft]) and on the west by the narrow and sharp-crested Malad Range and Wellsville Mountains (maximum elevation 2,860 meters [9,384 ft]) (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 found between the Malad Range and the Wellsville Mountains (figure 1). Several tributaries of the Bear River originate from the mountains surrounding Cache Valley, such as the Little Bear River, Logan River, Cub River, and Blacksmith Fork.

Structurally, Cache Valley is a narrow, elongate graben flanked by horst-block mountain ranges formed by movement on high-angle normal faults. To the west, the valley is bounded by the West Cache fault zone along the base of the uplifted Malad Range and Wellsville Mountains;

to the east, the valley is bounded by the East Cache fault zone along the base of the uplifted Bear River Range. The mountains surrounding Cache Valley are comprised mainly of Precambrian to Permian sedimentary rocks, including limestone, dolomite, quartzite, sandstone, mudstone, siltstone, and shale. These rocks have provided detrital material to form the younger deposits that fill Cache Valley. Younger deposits in the valley include the Tertiary Salt Lake Formation, a conglomerate and tuffaceous sandstone that overlies the Precambrian and Permian rocks and crops out in a nearly continuous belt in the foothills around the valley, and unconsolidated Quaternary deposits which 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, 1997). The Bonneville lacustral cycle is coincident with the last global ice age of marine isotope stage 2 and lasted from about 34,800 to 13,900 years ago (Currey and Oviatt, 1985; Oviatt and others, 1992). Between about 25,000 and 15,000 years ago, the lake occupied Cache Valley and deposited a thick sequence of sediments and formed two shoreline complexes (Solomon, 1997). The shorelines are useful datums for evaluating Holocene and late Pleistocene structure and stratigraphy.

Lake Bonneville began gradually rising from levels close to modern-day Great Salt Lake about 34,800 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 had 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 still-stand and oscillation that produced the Stansbury shoreline (Oviatt and others, 1992). Brummer and McCalpin (1990) found no evidence of this shoreline in Cache Valley. Lake Bonneville continued rising during the Stansbury oscillation(s) and entered Cache Valley around 25,000 years ago (Solomon, 1997).

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 17,400 to 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) found evidence that during the Bonneville flood, all of the water in the main body of Lake Bonneville 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. The rapid drawdown of the lake reduced the water-column weight on the earth's crust, which resulted in crustal rebound from isostatic compensation (Crittenden, 1963). In western Cache Valley, isostatic rebound and regional tectonics have uplifted the highest Bonneville shoreline as much as 27 meters (89 ft) to elevations of 1,567 to 1,579 meters (5,141-5,181 ft) (Currey, 1982; Solomon, 1997). Similarly, the Provo shoreline has been uplifted as much as 22 meters (72 ft) to elevations of 1,452 to 1,466 meters (4,764-4,810 ft) (Currey, 1982; Solomon, 1997).

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

Quaternary geology of the West Cache fault zone is also characterized by deposition of alluvium in alluvial fans along the front of the Malad Range and the Wellsville Mountains. Alluvial-fan deposits older than the Bonneville lake cycle are preserved on remnants of extensive, dissected pediment surfaces cut into Tertiary deposits in the range-front foothills (Solomon, 1997). 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 material was deposited in younger alluvial fans along the range front (Solomon, 1997). Upper Holocene debris-flow deposits constitute some of the alluvial-fan sediments, and may have been deposited during a major fan-building episode from about 4,000 to 5,000 years ago (Machette and others, 1992). Stream alluvium was deposited in mountain drainages concurrently with the fan alluvium (Solomon, 1997).

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 are associated with failures of underlying Tertiary and Paleozoic sedimentary rocks and nearshore Lake Bonneville deposits (Solomon, 1997). Most landslides were caused either by wave erosion of the Bonneville shoreline, rapid dewatering of oversteepened slopes during the Bonneville flood, or earthquakes (Solomon, 1997). Colluvial deposits are commonly found on mountain slopes and above stream channels in canyons. Solomon (1997) mapped undifferentiated colluvium and alluvium where colluvium-mantled hillsides grade imperceptibly into alluvium-filled ephemeral stream channels.

PALEOSEISMIC INVESTIGATIONS AND DATA

To establish timing for past surface-faulting earthquakes on the Clarkston, Junction Hills, and Wellsville faults, we investigated two trenches and a natural stream-cut exposure. One trench was excavated near the mouth of Winter Canyon west of Clarkston, Utah (figures 1 and 3). At this location, Solomon (1997) noted the Clarkston fault may displace upper Holocene alluvial-fan deposits. We also mapped a natural stream-cut exposure of the Junction Hills fault at Roundy Farm west of Cache Junction, Utah (figures 1 and 4), where Oviatt (1986) noted displacement in transgressive Lake Bonneville deposits. A second trench was excavated near the mouth of Deep Canyon west of Mendon, Utah (figures 1 and 5). At this location, Solomon (1997) indicated 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

Radiocarbon age estimates from this study come from organic-rich material in paleosol A horizons and fault-scarp-derived colluvium, except for a sample in the Deep Canyon trench that was detrital charcoal entrained in a debris-flood deposit. The age from the detrital charcoal was obtained from accelerator-mass-spectrometer methods; the remaining ages were obtained from conventional gas-proportional methods. One sample from the Winter Canyon trench was not analyzed and was taken as a backup in case the first sample was contaminated by animal burrowing.

Table 1 shows radiocarbon laboratory results and calendar-calibrated age estimates for all

Figure 3. West view of the Winter Canyon trench.

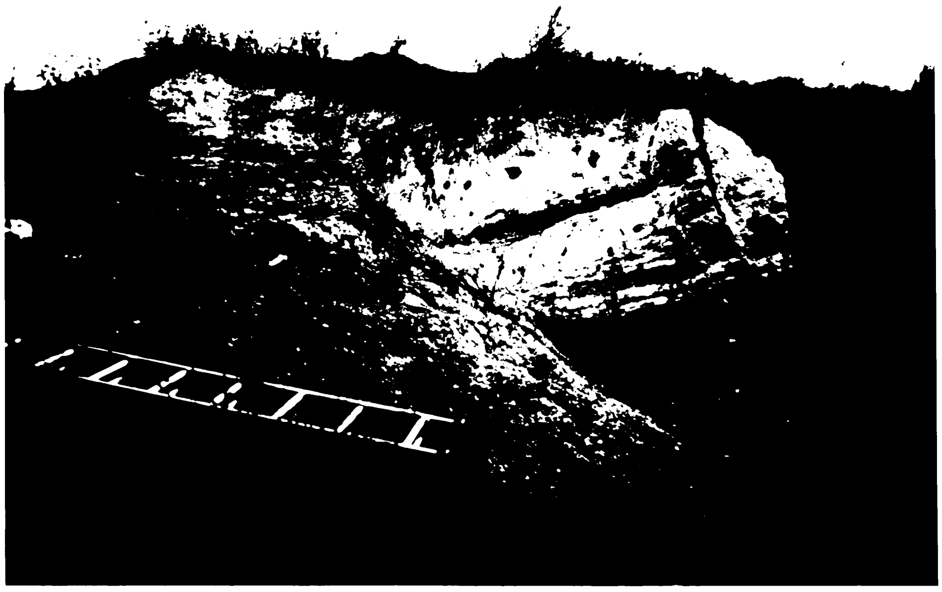


Figure 4. North view of the Roundy Farm stream cut.

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. CAS is used by the calibration program to smooth fluctuations in the calibration curve (Machette and others, 1992; Stuiver and Reimer, 1993).

Radiocarbon ages obtained 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 accurate enough 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) typically yields ages with 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). The MRC was subtracted from the radiocarbon age prior to calibration (Minze Stuiver, University of Washington, personal communication to W.R. Lund, 1992); table 1 shows modified radiocarbon ages. Because of the uncertainties in

Figure 5. West view of the Deep Canyon trench.

these age estimates, we rounded the calendar 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

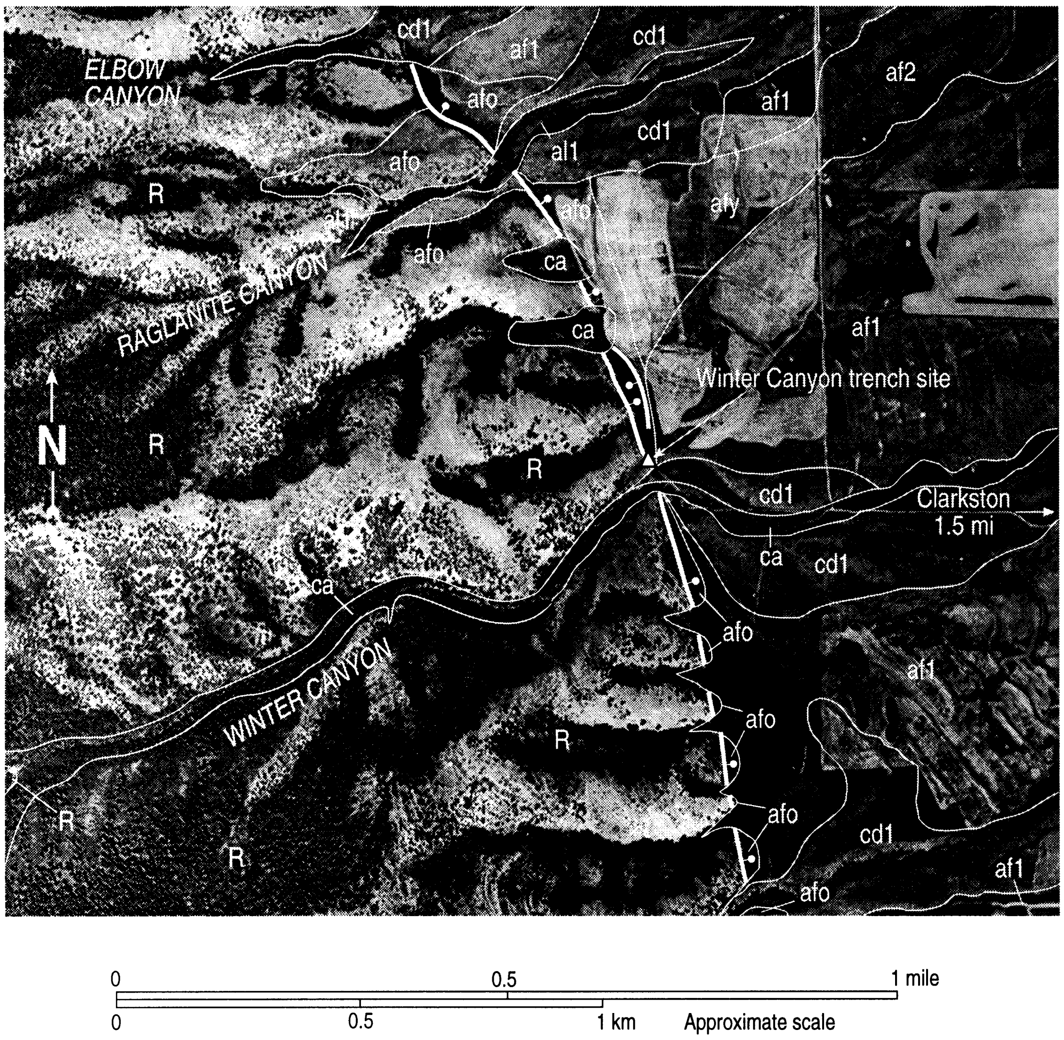
Geology

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 lies at elevations above the highest shoreline of Lake Bonneville and generally separates unconsolidated deposits in the hanging wall from bedrock in the footwall (Solomon, 1997). 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, 1997). 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). Hanson (1949) mapped a transverse fault in Short Divide 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.

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

Laboratory sample number (Field sample number)	*Material sampled*	*Radiocarbon age in 14C yr B.P.*	*AMRT age estimate in 14C 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 portion 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	21,500 ± 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 portion 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.

Two areas of potential displaced Holocene deposits exist on the Clarkston fault (Solomon, 1997). 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 at these areas consist of upper Holocene to middle Pleistocene alluvium and colluvium (figure 6; Solomon, 1997). The fault at Winter and Raglanite Canyons consists of a single, discontinuous fault trace buried at the canyon mouths by stream alluvium, debris flows, and undivided colluvium and alluvium (figure 6). The canyon mouths are separated from each other by steep, faceted, range-front spurs (Solomon, 1997). South of Winter Canyon, the fault marks a contact between upper to middle Pleistocene fan alluvium and bedrock (figure 6). Directly north of Winter Canyon, the fault displaces a narrow apex of an upper Holocene alluvial fan (figure 6). At Raglanite Canyon, the fault displaces upper



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, dashed where approximately located.

Contact

Trench site

Figure 6. Air-photo geologic map of the Winter Canyon trench site vicinity (modified from Solomon, 1997).

to middle Pleistocene fan alluvium (Solomon, 1997). Between Winter and Raglanite Canyons, the fault also marks the contact between upper to middle Pleistocene fan alluvium and bedrock (figure 6).

Sequence of Deposition and Faulting in the Winter Canyon Trench

The Winter Canyon trench was excavated slightly north of the mouth of Winter Canyon across a roughly 4-meter- (13-ft-) high scarp of the Clarkston fault. The trench exposed a single main fault trace (figure 7) and evidence for 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, plate 1A). A soil A horizon (paleosol S1, plate 1A) formed on top of unit 2. These units are displaced down to the east by the most recent surface-faulting earthquake (MRE) on the Clarkston fault. A colluvial wedge (unit 3, plate 1A) roughly 1.3 meters (4.3 ft) thick lies on top of unit 2 and paleosol S1. A modern soil (S2, plate 1A) is forming on top of units 2 and 3. Unit 2, paleosol S1, and soil S2 showed considerable animal burrowing. Evidence in the trench exposure 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; and Lund and Black, 1998). Therefore, we believe degradation of the scarp was very gradual and is still 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. One sample (WCT-RC2) was not analyzed and therefore no date is recorded on plate 1A. WCT-RC1 and 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. The soil was buried some time after this event by scarp colluvium which formed the colluvial wedge. Organic-rich sediment collected from the upper horizon contact (UHC) 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 the soil was buried around 3,550 to 3,800 years ago. Organic-rich sediment collected from the middle of the colluvial wedge (WCT-RC3, plate 1A) 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 collected from the heel of the colluvial wedge (WCT-RC4; plate 1A) 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. Based on this, our best estimate for timing of the MRE on the Clarkston fault is 3,600 to 4,000 years ago.

Limited data exist regarding timing for the penultimate surface-faulting earthquake (PE) on the Clarkston fault because we only exposed evidence for the MRE in the trench. However, Solomon (1997) noted that the Bonneville shoreline across Short Divide is 9 meters (30-ft) lower near the Clarkston fault than to the south on the Junction Hills fault. Isostasy cannot solely account for the difference, since the gradient of the Bonneville shoreline in this area is about 0.5 meters/kilometer (2.6 ft/mi) and the distance across Short Divide is only 0.6 kilometers (0.4 mi). Furthermore, the Short Divide fault is a south-dipping normal fault and displacement on this fault would produce a higher shoreline elevation (rather than lower) on the Clarkston side. Therefore, most of the difference must be 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, 1997). 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 displacement northward (Machette and others, 1992). Our paleoseismic data from Roundy Farm (discussed below) indicates only one post-lake event on the Junction Hills fault. Based on this and the displacement we measured from our scarp profiles, and assuming a characteristic earthquake model (Schwartz and Coppersmith, 1984), we believe two or three surface-faulting earthquakes occurred on the Clarkston fault since lake retreat to account for the elevation difference. Assuming one other event at Bonneville shoreline time, the recurrence interval (time between surface-faulting earthquakes) on the Clarkston fault is a maximum of

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 visible only in the hanging wall and the lower contact is visible only in the footwall. Ongoing formation of the degraded-scarp free face has also removed the upper portion of unit 2 in the footwall, and no slope colluvium overlies it. However, we observed evidence for the contact between units 1 and 2 (calcium-carbonate coated cobbles and pieces of carbonate matrix) in hand excavations near meter mark 16, which suggests the contact is near the trench floor. Based on this evidence, we estimate unit 1 was displaced at least 3.5 meters (11.5 ft) down to the east by the MRE on the Clarkston fault. Topographic profiles across the fault near the trench site and at the mouth of Raglanite Canyon to the north indicated 3.1 to 3.7 meters (10.2-12.1 ft) of displacement, which is similar to the amount estimated from the trench exposure.

Material suggestive of the contact between units 1 and 2 in the hanging wall may also be part of an older colluvial wedge derived from unit 1. However, because no stratigraphic sequence below unit 2 was exposed in the hanging wall, we are uncertain whether an older wedge exists between units 1 and 2. McCalpin (1991) indicates symmetric scarp degradation models predict the maximum thickness of scarp-derived colluvium is one-half the height of the free face from which it was shed. The MRE colluvial wedge in the Winter Canyon trench has a maximum thickness of 1.3 meters (4.3 ft). This suggests the MRE scarp should have been at least 2.6 meters (8.5 ft) high, which is slightly lower than the estimated displacement. 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). Therefore, we believe the displacement is probably the result of only one surface-faulting earthquake. A multiple-event scarp with the measured displacement at the Winter Canyon site should show multiple, thinner colluvial wedges.

Because evidence for only one event was exposed at Winter Canyon, we were unable to determine a long-term slip rate for the Clarkston fault. For this, the difference in shoreline elevations across Short Divide provides the best information. Based on this difference and the shoreline age, Solomon (1997) determined a maximum slip rate of 0.54 millimeters/year (0.021 in/yr) for the Clarkston fault since latest Pleistocene time (9 meters [30 ft] of displacement in the past 16,800 years). This rate is higher than for 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), and is the highest of any of the faults in the West Cache fault zone. 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. East of Short Divide, at its north end, the fault displaces Tertiary sedimentary rock, but to the south the fault exits bedrock and displaces deposits of Pleistocene Lake Bonneville (Solomon, 1997). The fault parallels the Bonneville shoreline to the south of Cutler Reservoir, where it diverges and once again enters bedrock (Solomon, 1997).

Surficial evidence of the Junction Hills fault is poorly preserved. Solomon (1997) indicates the only conclusive evidence of late Quaternary displacement on the Junction Hills fault is found near Roundy Farm about 2 kilometers (1 mi) southwest of Cache Junction. Surficial geology in the vicinity of Roundy Farm consists of deposits related to the Bonneville and Provo stages of Lake Bonneville, and local deposits of alluvium and colluvium (figure 8). Three short (460- to 610-meter- [1,509-2,001-ft] long) east-facing normal fault scarps displace the lake deposits at this site. Two of the scarps are below the Provo shoreline, the third is between the Bonneville and Provo shorelines (figure 8). The fault is exposed in a natural stream cut at the southern end of the central scarp. At this exposure, Oviatt (1986) reported 2.4 meters (7.9 ft) of displacement in the basal transgressive gravel of Lake Bonneville and evidence for additional pre-Bonneville surface-faulting earthquakes. Solomon (1997) indicates 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 Roundy Farm stream cut is at the southern end of the central scarp mapped by Solomon (1997). The stream cut crosses the fault obliquely, yielding a low apparent fault dip in exposures. The site is also on the edge of a plowed field, and little surface expression of the scarp remains. The stream cut exposes a single main fault trace (figure 9), an antithetic fault trace bounding a 4.3-meter- (14.1-ft-) wide 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) comprised 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 from the penultimate surface-faulting earthquake (PE) on the Junction Hills fault, but we observed no evidence of a colluvial wedge from the PE and believe it is likely buried beneath material sloughing off the stream-cut wall. The PE free face is mantled by a pre-Lake Bonneville alluvial-fan deposit comprised of silty sand with gravel forming crudely bedded channels (unit 2, plate 1B). 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 exposure. No soil was evident on top of unit 2; the upper portion of this unit may have been

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

△ Steam-cut exposure

Figure 8. Air-photo geologic map of the Roundy Farm stream cut vicinity (modified from Solomon, 1997).

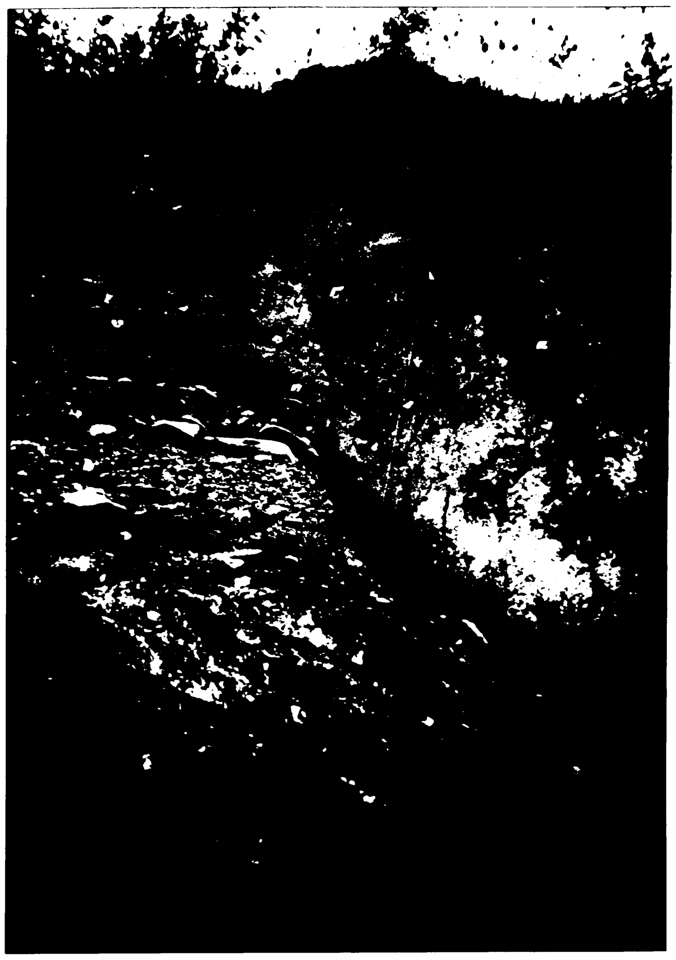


Figure 9. North view of fault zone exposed in the Roundy Farm stream cut, Junction Hills fault.

eroded when Lake Bonneville transgressed over the site. Unit 2 may also be paleochannel deposits along the base of the scarp, which would account for its thinness in the footwall.

Units 1 and 2 are overlain by a transgressive sequence of Lake Bonneville deposits. The basal portion 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, plate 1B). A weakly developed soil A horizon formed on top of unit 5 (paleosol S1, plate 1B). All these units were downdropped to the east by the MRE. The MRE also formed a graben (bounded by a west-dipping antithetic fault) showing considerable deformation (small faults and cracks), and a shear zone along the main fault comprised of units 2 through 5 and paleosol S1 (unit 6a, plate 1B). A colluvial wedge roughly 1.3 meters (4.3 ft) thick lies on top of paleosol S1 (unit 6b, plate 1B). Unit 6c (plate 1B) is a crack that likely filled with material derived from paleosol S1.

The upper portion of units 5, S1, 6b, and 6c have been removed, and they are overlain by a plowed horizon in which a modern soil is forming (unit 7S, plate 1B).

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 the MRE on the Junction Hills fault occurred around 8,250 to 8,650 years ago. No material was found to determine timing for the PE on the Junction Hills fault, but lake sediments exposed at Roundy Farm postdate the PE. The basal portion of these sediments 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, 1995). Thus, a minimum of 13,850 years passed between the PE and MRE.

Displacement and Slip Rate

Due to agriculture, the scarp at Roundy Farm has been altered. Therefore, we measured no topographic profiles at this site. The remaining surficial expression of the Junction Hills fault is 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 the amount they were displaced. 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 displacement from the MRE. No correlative stratigraphy was evident in the stream-cut exposure to indicate displacement from the PE.

Assuming the lake beds in the stream cut are displaced 2.9 meters (9.5 ft) and were deposited since 22,500 years ago, the maximum slip rate for the Junction Hills fault during post-Bonneville time is 0.13 millimeters/year (0.005 in/yr). This rate is lower than the average slip rate for 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 rocks in the footwall. The eastern fault is covered by Quaternary deposits between bedrock outcrops; at its northern end the fault is concealed by Pleistocene alluvial fans, whereas at its southern end the fault is concealed by Lake Bonneville and younger deposits. 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 (1997) indicates evidence of Quaternary displacement exists 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 displacement in middle to upper Pleistocene alluvial-fan deposits. However, Solomon (1997) indicates 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) to the south of Deep Canyon. At the mouth of Pine Canyon, Solomon (1997) found several small faults and tilted beds exposed in the wall of a gravel pit excavated on the edge of prograding spits near the Bonneville shoreline. Cumulative displacement across these faults is at least 2 meters (7 ft) (Solomon, 1997). However, Solomon (1997) believes deformation in the gravel pit is probably the result of landsliding, rather than displacement on the Wellsville fault.

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, 1997). Unit afo mostly comprises an old alluvial fan above the Bonneville shoreline at the mouth of Deep Canyon, similar to the dissected alluvial fans estimated by McCalpin (1989) to be 100,000 to 200,000 years old. Downcutting along the drainage issuing 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

The Deep Canyon trench was excavated north of the mouth of Deep Canyon across a 7-meter- (23-ft-) high multiple-event scarp of the Wellsville fault. The trench exposed two main faults (figure 11), smaller subsidiary faults, and evidence for two surface-faulting earthquakes. The oldest units exposed in the trench are a series of interbedded coarse- to fine-grained alluvial-fan deposits comprised of clay, silt, sand, and gravel (units 1-3, plate 1C). These units were displaced down to the east (below the trench floor) by the PE on the Wellsville fault. 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 (plate 1C). Units 3 and 4b are overlain by additional alluvium (unit 5, plate 1C).

No younger alluvial-fan units are evident in the trench exposure. We believe after the retreat of Lake Bonneville, the alluvial fan at the Deep Canyon trench site became inactive as it was downcut and deposition moved farther eastward in the valley. Units 4b and 5 are overlain by

DESCRIPTION OF MAP UNITS AND SYMBOLS

al1	Stream alluvium (upper Holocene)	afo	Pre-Lake Bonneville fan alluvium (upper to middle Pleistocene)
af1	Fan alluvium, unit 1 (upper Holocene)	R	Bedrock, undivided
af2	Fan alluvium, unit 2 (middle Holocene to uppermost Pleistocene)		
cls	Landslide deposits (Holocene to upper Pleistocene)		Normal fault, bar and ball on downthrown side, dashed where approximately located.
ca	Colluvium and alluvium, undivided (Holocene to middle Pleistocene)		Contact
lbg	Bonneville transgressional gravel and sand (upper Pleistocene)	—B—	Highest shoreline of the Bonneville level
lbs	Bonneville transgressional sand and silt (upper Pleistocene)	Δ	Trench site

Figure 10. Air-photo geologic map of the Deep Canyon trench site vicinity (modified from Solomon, 1997).

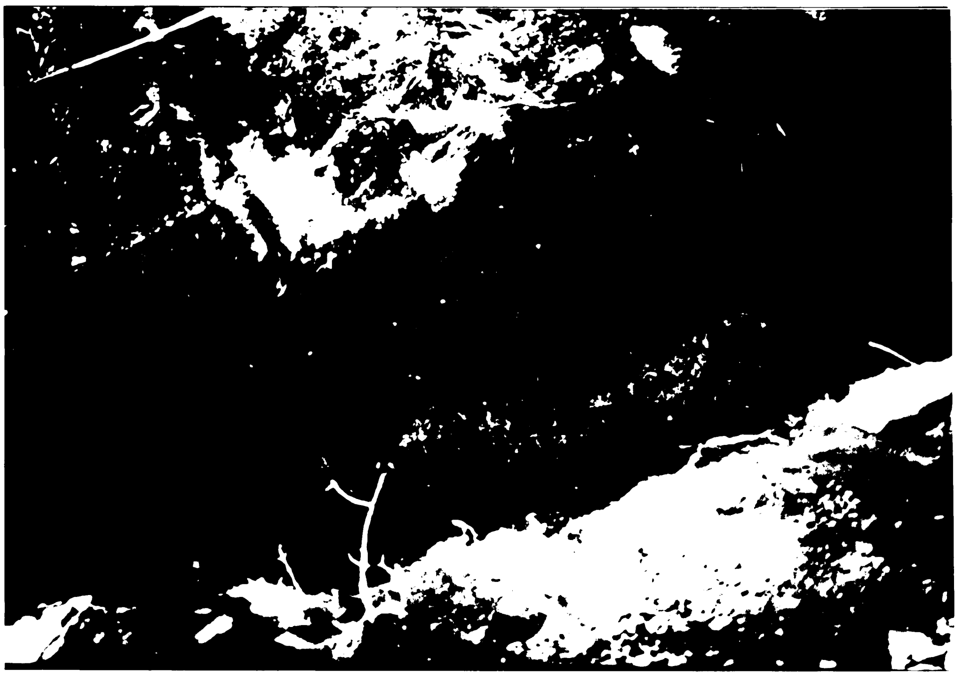


Figure 11. South view of fault zone exposed in the Deep Canyon trench, Wellsville fault.

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- (7-ft-) deep test pit west of the trench above the fault scarp also did not expose unit 6, and thus the loess was either only deposited along the base of the fault scarp at this site or it has been eroded from the top and front of the scarp. A soil A horizon formed on top of units 5 and 6 (paleosol S1, plate 1C). All these units were displaced down to the east by the MRE across the main fault and a smaller subsidiary fault (near meter station 3, plate 1C); 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, plate 1C). 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 (plate 1C).

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 collected from the lower horizon contact (LHC) of paleosol S1 (DCT-RC2, plate 1C) gave an age estimate of 5,250 +100/-250 cal B.P.; material from the UHC of paleosol S1 (DCT-RC3, plate 1C) gave an age estimate of 4,500 +100/-150 cal B.P. Organic-rich sediment collected from the center of the colluvial wedge unit 7 (DCT-RC4, plate 1C) above DCT-RC3 gave an age estimate of 3,200 +100/-150 cal B.P.; material collected from the LHC of soil S2 (DCT-RC5, plate 1C) above DCT-RC4 gave an age estimate of 1,700 +/-150 cal B.P. All these samples appear to be in a proper chronostratigraphic sequence.

Formation of paleosol S1 predates the MRE on the Wellsville fault. The soil was buried sometime after this event by scarp colluvium which formed unit 7. Based on the age of the UHC contact of paleosol S1, the soil was buried around 4,350 to 4,600 years ago. However, this age comes from beneath the distal portion of the colluvial wedge; we were unable to sample the wedge heel or paleosol UHC 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 burial. The age difference between DCT-RC3 and RC4 suggests the rate of scarp formation at Deep Canyon was 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. Based on this, we believe the MRE on the Wellsville fault likely occurred between 4,400 to 4,800 years ago.

Units 1 through 3 in the Deep Canyon trench are alluvial-fan sediments comprised of 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 which yielded an age of 21,500 ± 160 yr B.P. Although this age is too old to calibrate directly, the method we use elsewhere 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 15,100 years ago (13,000 yr B.P.) after dessication of pluvial lakes in the region and retreat of glaciers and soil ice (Kleber, 1994; Donald R. Currey, verbal communication, 1998). Based on this, we believe the PE likely occurred sometime between 15,100 and 25,000 years ago. This suggests a minimum of 10,300 and a maximum of 20,600 years passed between the PE and MRE on the Wellsville fault.

Displacement and Slip Rate

No correlative stratigraphy is in the Deep Canyon trench to indicate displacement from the PE on the Wellsville fault. However, unit 5 is traceable across the fault and can indicate displacement from the MRE (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 displacement from multiple surface-faulting earthquakes. A compound scarp often contains multiple breaks in slope, each of which originated in separate rupture events; 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 trench site shows three gradient changes that we believe represent three past surface-faulting earthquakes (figure 12). Average 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.

Assuming two surface-faulting earthquakes on the Wellsville fault in the past 15,100 to 25,000 years and a total displacement of 4.4 meters (14.4 ft), the slip rate for the Wellsville fault would be 0.18-0.29 millimeters/year (0.007-0.011 in/yr). This rate is near 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 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 displacement. Based on this displacement and the estimated age for the faulted alluvial-fan deposits, the maximum long-term slip rate for the Wellsville fault since middle Pleistocene time is 0.13 millimeters/year (0.005 in/yr).

Fault Segmentation and Comparison

Paleoseismic data obtained from our investigations suggest that the Clarkston, Junction Hills, and Wellsville faults rupture independently and can be considered separate segments of the West Cache fault zone. Timing for the MRE on all three faults differs, which suggests that each fault generated a separate earthquake. However, because of the limited age span of our paleoseismic data, we are uncertain if the faults always rupture independently (such as in the MRE). Slip rates also differ between the faults, with the Clarkston fault having the highest rate and the Junction Hills fault the lowest.

The Short Divide fault marks the boundary between the Clarkston and Junction Hills faults, and Solomon (1997) believes the Clarkston fault is a seismically independent structural segment of the West Cache fault zone 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 (1997) 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 and slip rates for the Wellsville fault and the central segment of the East Cache fault zone. The MRE and PE on both faults have similar ages, and their slip rates since late Pleistocene time are also similar. The earthquake timing similarity suggests a large earthquake on one of the faults may have triggered a

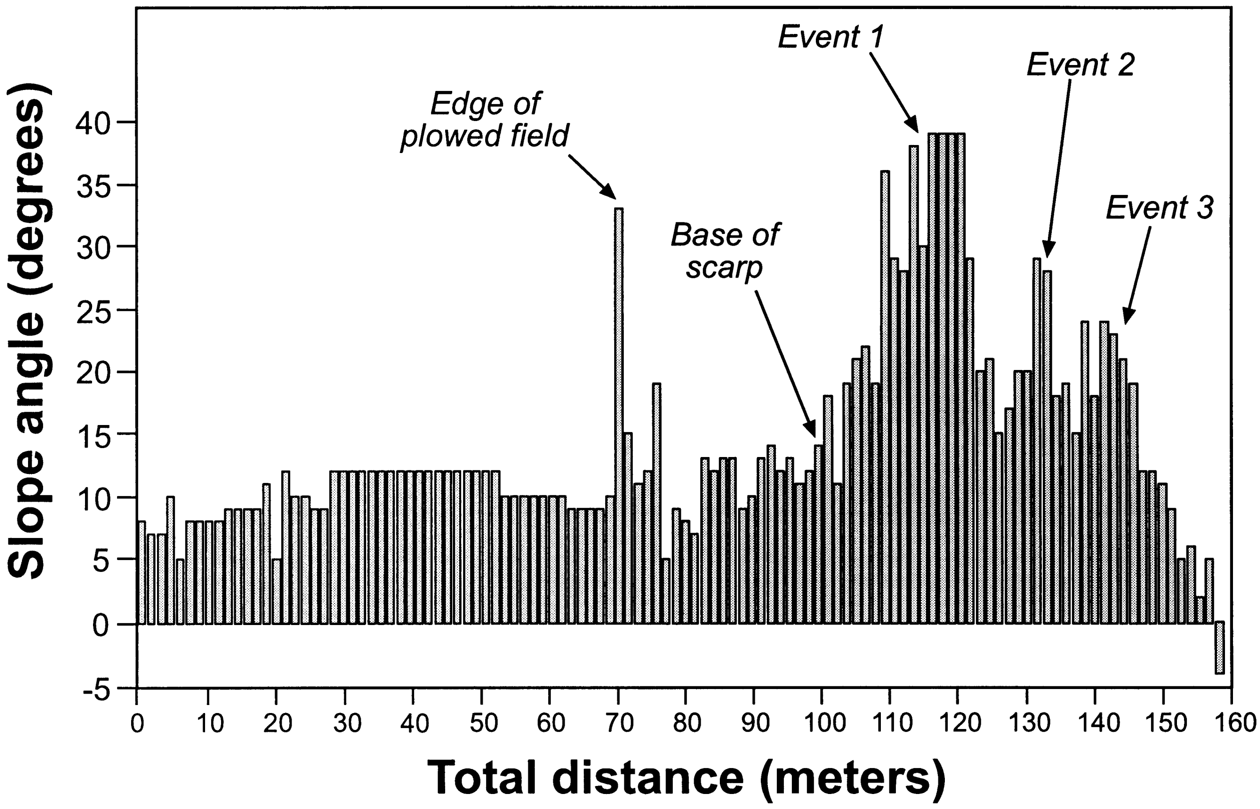


Figure 12. Histogram of slope angle versus total distance for scarp profile 1, Deep Canyon, Wellsville fault. The scarp shows three gradient changes (spikes) possibly representing three surface-faulting earthquakes.

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 such correlations are evident between the East Cache fault zone and the Clarkston and Junction Hills faults.

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)	0.54 millimeters/year (late Pleistocene)
Junction Hills fault	8,250-8,650 years ago	Pre-Bonneville (>16,800 years ago)	0.13 millimeters/year (late Pleistocene)
Wellsville fault	4,400-4,800 years ago	15,100-25,000 years ago	0.18-0.29 millimeters/year (late Pleistocene)
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	15,100-18,000 years ago	0.28 millimeters/year (late Pleistocene)
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 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.

Earthquake Magnitude

Various empirical relations have been developed 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). Moment magnitude (M_w) is generally considered to be a better estimate of earthquake magnitude than surface-wave magnitude (M_s) (Hanks and Kanamori, 1979; Machette, 1986). Based on the various rupture parameters, table 3 shows moment magnitudes for surface-faulting earthquakes on the Clarkston fault are M_w 6.9-7.1; surface-faulting earthquakes on the Junction Hills and Wellsville faults are M_w 6.8-7.1 and M_w 6.6-6.9, respectively.

Table 3 also shows 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,

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)*	*Maximum slip rate (S, in millimeters/year)*
Clarkston fault	37	3.7	1.00×10^{-4}	0.54
Junction Hills fault	33	2.9	8.79×10^{-5}	0.13
Wellsville fault	20	2.2	1.1×10^{-4}	0.13
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		7.0		
Junction Hills fault		7.1		
Wellsville fault		6.8		
Based on displacement (D)				
Clarkston fault	7.1		7.4	
Junction Hills fault	7.0		7.3	
Wellsville fault	6.9		7.2	
Based on rupture length (L_S) and displacement (D)				
Clarkston fault				7.1
Junction Hills fault				7.0
Wellsville fault				6.9

[1] *Regression for all types of slip; $M_W = 5.08 + 1.16\log L_S$; $M_W = 6.69 + 0.74\log D$.*
[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] *$M_S = 6.1 + 0.47\log(D \times L_S)$*

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) around 10^{-4} or less may have a longer rupture length than is evident, and thus earthquake magnitudes may be underestimated

(Zollweg, 1998). All the faults in the West Cache fault zone have aspect ratios near 10^{-4} (table 2). Observations of historical surface-faulting earthquakes also show a discrepancy between predicted and observed values of M_w based on rupture length, and Anderson and others (1996) indicate inclusion of 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. Our estimates from displacement and rupture length-slip rate are similar, and indicate moment magnitude for surface-faulting earthquakes on the Clarkston and Junction Hills faults is M_w 7.0-7.1, and M_w 6.8-6.9 for the Wellsville fault.

SUMMARY

The West Cache fault zone extends 80 kilometers (50 mi) from northern Utah into southern Idaho, and consists of three normal faults: the Clarkston, Junction Hills, and Wellsville faults. The faults dip eastward beneath Cache Valley, and form the boundary between the valley to the east and the mountains to the west. Cache Valley is near the center of the Intermountain seismic belt, a north-south trending zone of historical seismicity that extends from northern Arizona to central Montana, and three major fault zones are in and adjacent to the valley that pose a significant seismic risk to citizens living nearby: the Wasatch, East Cache, and West Cache fault zones. All of these faults displace the surface and show evidence of large earthquakes in recent geologic time. Trenching to identify the size and timing of prehistoric earthquakes has been done for the Wasatch and East Cache fault zones, but no such studies have been previously conducted for the West Cache fault zone.

Cache Valley is an intermontane graben formed by movement on two high-angle normal faults, the East Cache and West Cache fault zones. The East Cache fault zone dips westward beneath the valley and forms the boundary between the eastern edge of the valley and the uplifted Bear River Range. The West Cache fault zone dips eastward beneath the valley and bounds the uplifted Malad Range and Wellsville Mountains. The Quaternary geology of Cache Valley is dominated by deposits of Pleistocene Lake Bonneville, which occupied the valley between about 25,000 to 15,000 years ago. Shorelines formed by the lake provide useful datums for evaluating Holocene and late Pleistocene structure and stratigraphy.

To determine the paleoseismic history of the West Cache fault zone, the Utah Geological Survey 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 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. Evidence for a PE was exposed in the Deep Canyon trench on the Wellsville fault, but timing for this event is uncertain and between 15,100 to 25,000 years ago. Indirect evidence for a PE on the Junction Hills fault was exposed in the Roundy Farm stream cut; although we could not determine timing for this event, younger undisplaced Lake Bonneville deposits in the exposure suggest this event occurred prior to the transgression of the lake across the site 22,500 years ago. No evidence for a PE was exposed in the Winter Canyon trench on the Clarkston fault, but a difference in shoreline elevations between the Junction Hills and Clarkston faults suggests two or three events occurred on the Clarkston fault since the Lake Bonneville highstand.

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 displacement from the MRE and a maximum slip rate of 0.54 millimeters/year (0.021 in/yr) since late Pleistocene time. For the Junction Hills fault, the data show 2.9 meters (9.5 ft) of displacement from the MRE and a maximum slip rate during late Pleistocene time of 0.13 millimeters/year (0.005 in/yr). For the Wellsville fault, the data show 1.9 meters (6.2 ft) of displacement from the MRE, and 6.6 meters (21.7 ft) from probably the last three surface-faulting earthquakes; slip rate for the Wellsville fault since late Pleistocene time is 0.18-0.29 millimeters/year (0.007-0.11 in/yr). The data and paleoseismic history suggest that the faults in the West Cache fault zone behave independently. Earthquake timing and slip rates are similar for the Wellsville fault and central segment of the East Cache fault zone and suggest a possible correlation between these faults, but no 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 7.0-7.1 for the Clarkston and Junction Hills faults, and M_w 6.8-6.9 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.

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 MATERIAL AND 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 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 portion 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 portion 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 ostracods and few animal burrows, paleosol S1 formed on top of unit, upper portion 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 MATERIAL AND 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 portion 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 MATERIAL AND 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 in footwall.*

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 subangular 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; organic rich, few roots.*

UNIT 7 **COLLUVIAL WEDGE** - *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.*