Paleoseismology of Utah, Volume 12

NEOTECTONICS OF BEAR LAKE VALLEY, UTAH AND IDAHO; A PRELIMINARY ASSESSMENT

by

James P. McCalpin

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

Cover photo: Bear Lake looking northeast from the Bear River Overlook on U.S. Highway 89: photograph by Mel Lewis

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Paleoseismology of Utah, Volume 12

FOREWORD

This Utah Geological Survey Miscellaneous Publication, Neotectonics of Bear Lake Valley, Utah and Idaho; A Preliminary Assessment, is the twelfth report in the Paleoseismology of Utah series. This series makes the results of paleoseismic investigations in Utah available to geoscientists, engineers, planners, public officials, and the general public. These studies provide critical information of paleoearthquake parameters such as timing, recurrence, displacement, slip rate, and fault geometry, which can be used to characterize potential seismic sources and evaluate the long-term seismic hazard presented by Utah's Quaternary faults.

This report presents the results of a preliminary evaluation of the East Bear Lake (EBF) and West Bear Lake (WBF) fault zones, which bound the east and west sides, respectively, of the Bear Lake Valley. The Bear Lake Valley straddles the Utah/Idaho border northeast of Logan, Utah. The results of this study show that both the EBF and the WBF have experienced surface-faulting earthquakes in the recent geologic past and therefore represent an ongoing seismic hazard to northeastern Utah and southeastern Idaho. Fault-trace mapping conducted as part of this study indicates that both faults are likely segmented, although only one potential segment on each of the faults was trenched as part of this study. The author concludes that additional detailed paleoseismic investigations are warranted to evaluate the full extent of the hazard represented by these faults. In that sense, the EBF and WBF are indicative of the many other Quaternary faults in Utah for which only limited or no paleoseismic data are available, and for which the hazard is likewise largely unknown. It is hoped that this preliminary investigation will serve as a catalyst for further study of the WBF and EBF faults and kindle an interest in investigating Utah's other "paleoseismically unknown" Quaternary faults.

Dr. James P. McCalpin, GEO-HAZ Consulting, Inc., conducted the Bear Lake Valley study with funding received through the U.S. Geological Survey National Earthquake Hazard Reduction Program. The Utah Geological Survey appreciated the opportunity to work with Dr. McCalpin to make the results of this important paleoseismic investigation more readily available to the user community.

William R. Lund, Editor
Paleoseismology of Utah Series

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

ABSTRACT

Bear Lake Valley is an east-tilted half graben bounded by the master East Bear Lake normal fault zone (EBF) on the east and the hinge-type West Bear Lake fault zone (WBF) on the west. Each fault zone is composed of three geometric sections that range from 20 to > 32 kilometers long. Fault scarps displace Quaternary deposits in all six fault sections, and reach maximum heights of > 30 meters on the southern section of the EBF, although heights of 2 to 6 meters are the most common. In 1989 I excavated two trenches across scarps 8 and 13 meters high at North Eden Creek, Utah on the southern section of the EBF, and observed evidence for 5 to 7 paleoearthquakes in the past ca. 39 ka, which together were accompanied by ≥ 23.3 meters of vertical displacement. The most recent event occurred about 2.1 ka and was accompanied by 4.6 meters of vertical slip (throw). The long-term slip rate on the EBF at this site since about 39 ka is ≥ 0.58 mm/yr, but slip rates in individual seismic cycles range from < 0.26 mm/yr to 1.6 mm/yr. Based on the > 32 kilometer length of the southern section and ca. 3.8 to 6.1 meters displacements per event, past earthquakes had magnitudes from M ~ 6.8 to 7.2.

I also excavated two trenches across 1.5- and 6-meter-high scarps on the WBF at Bloomington, Idaho and dated the most recent displacement event (1.75 m slip) at 6.7 to 7.4 ka. The long-term slip rate since about 13.1 ka there is roughly 0.5 mm/yr, but carries a large uncertainty. Based on the 20-kilometer length of the section and 1.75 meters of displacement per event, maximum magnitude ranges from M 6.7 to 6.8.

This study is preliminary in nature and only results in reliable paleoseismic characterization of two of the six fault sections in Bear Lake Valley. Future studies should be performed on the other four sections. Bear Lake Valley may be at relatively high risk for liquefaction failures in future earthquakes, due to the widespread occurrence of young, sandy deposits in areas where ground water is less than 10 meters deep.

INTRODUCTION

Scope of Work

This study describes the distribution and character of Quaternary fault scarps on the margins of the Bear Lake Valley of northeastern Utah and southeastern Idaho (figure 1). I mapped fault scarps between Laketown, Utah and Georgetown, Idaho, mainly from black-and-white aerial photographs (scale 1:20,000; Mission CNS dated 21 July 1949 and 13 August 1949). After I completed the scarp mapping in 1988-89, I excavated four trenches across fault scarps in July and October 1989, all in the southern part of the valley. These trenches were the first (and to date, only) paleoseismic trenches excavated in Bear Lake Valley, and provide preliminary data on the timing and size of Holocene and late Pleistocene earthquakes. However, the trenches provide paleoseismic information on only two of the six fault sections identified in this study, so future paleoseismic work is warranted on the remaining four sections. Based on the scarp mapping and trenching, I make conclusions about the rate and character of large prehistoric earthquakes in the valley, and what they imply for future seismic hazards.

Location and Physiography

Bear Lake Valley lies in the Middle Rocky Mountains physiographic province (Fenneman, 1931), straddling the far eastern part of the Utah-Idaho border (figure 1). The valley is 100 kilometers long, 10 to 15 kilometers wide, and lies between the Bear River Range on the west, the Preuss Range on the northeast, and the Bear Lake Plateau on the southeast (figure 2). Physiographically, the valley can be subdivided into three parts. The southern part trends north, is 30 kilometers long, 15 kilometers wide, and contains Bear Lake (elevation 1806 m). This part of the valley, which extends from Laketown, Utah to St. Charles, Idaho, is characterized by

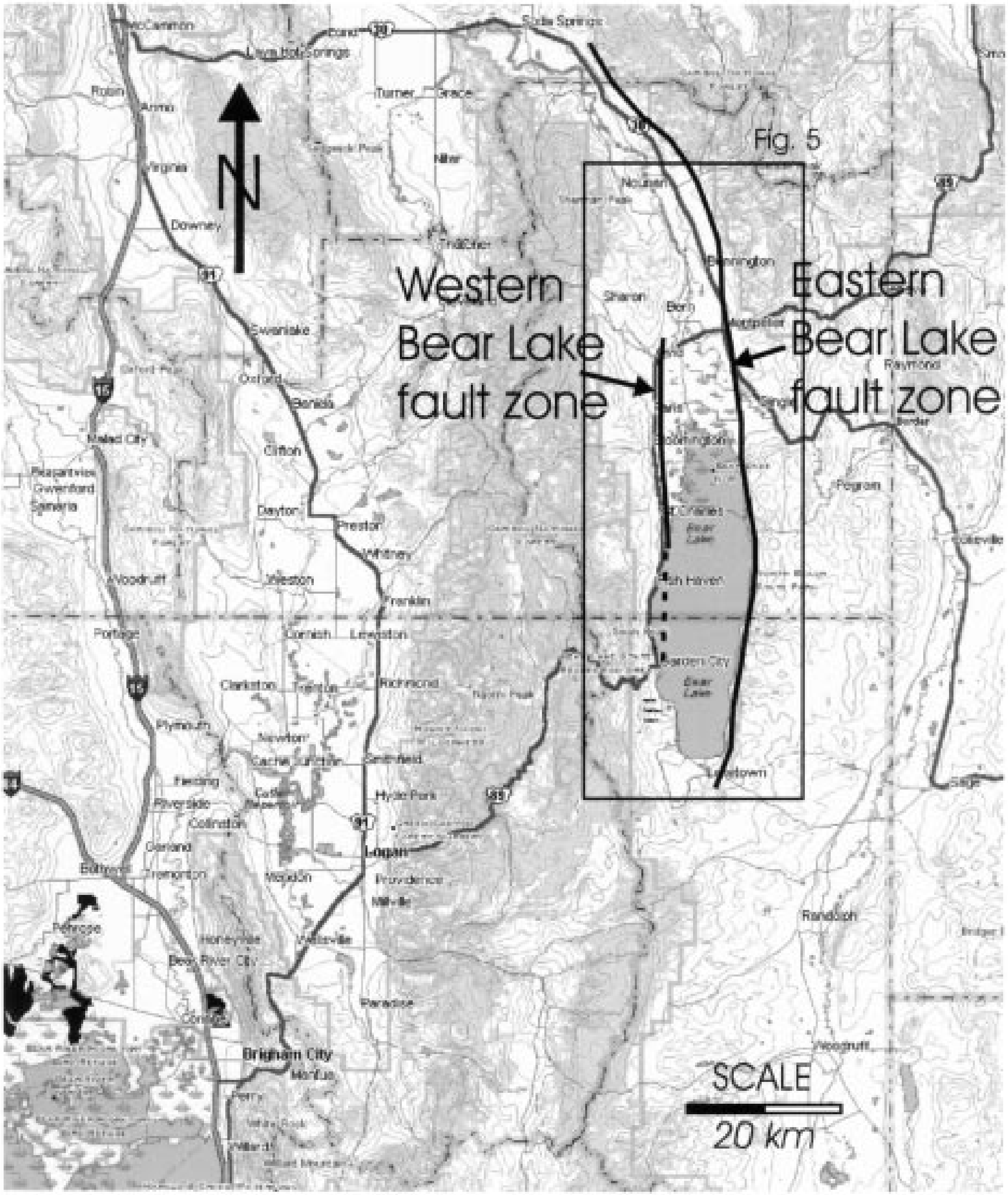

Figure 1. *Regional setting and major fault zones in Bear Lake Valley. Study area in rectangle.*

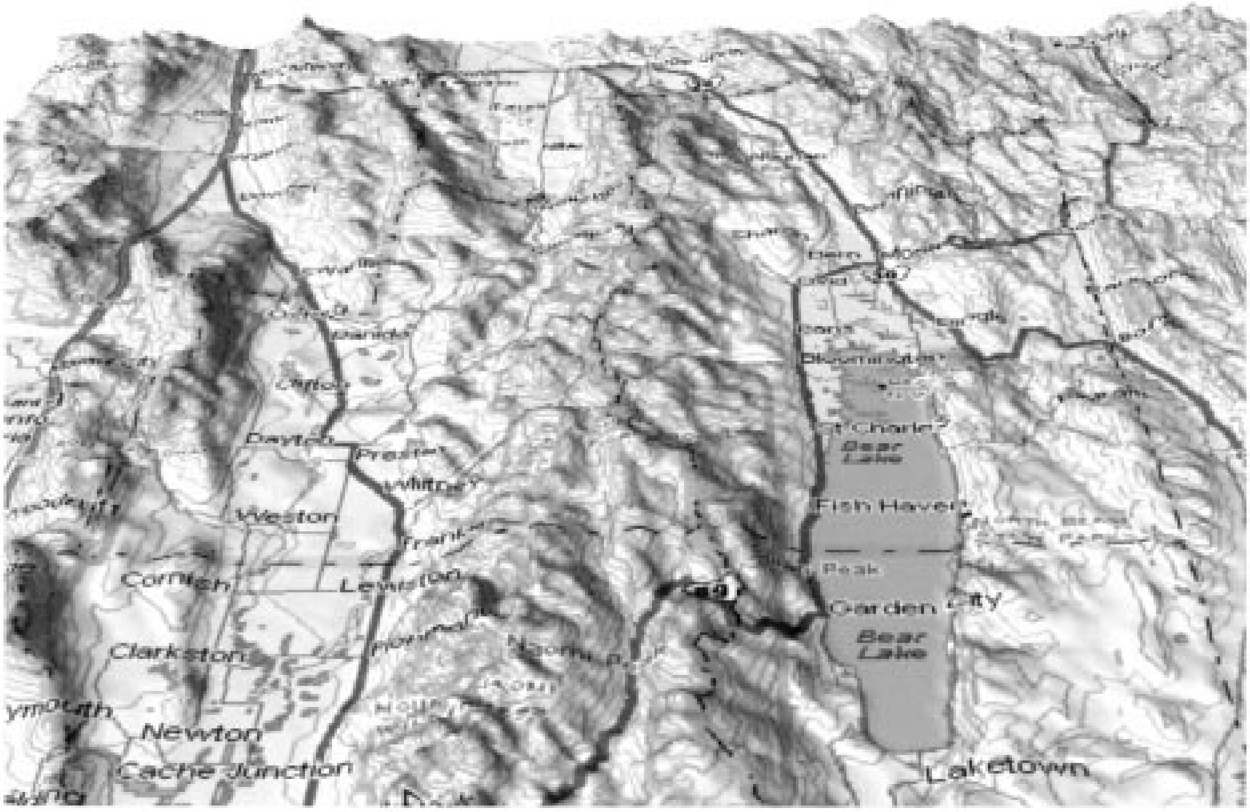

Figure 2. *Shaded relief map of the Bear Lake Valley and vicinity. North is at top. Scale varies in this perspective view, but Bear Lake (lower right) is 30 km long and as much as 12 km wide. Bear Lake Valley extends north from Bear Lake toward Soda Springs, Idaho (top center). The Utah-Idaho border passes from left to right through Bear Lake. The prominent mountain range at center, west of Bear Lake, is the Bear River Range, bisected by US Highway 89 (bottom center). West of the Bear River Range is the large intermontane depression of Cache Valley, a Neogene graben.*

Figure 3. *Photograph of Bear Lake and the range-front escarpment created by the East Bear Lake fault zone. The level surface atop the escarpment is the Bear Lake Plateau. View is to the south from near Indian Creek at the northeast corner of Bear Lake.*

Figure 4. *Photograph of Bear Lake from the Bear River Range west of Garden City, looking northeast.*

straight, fault-controlled valley margins (figures 3, 4), with the Bear River Range to the west (elevations up to 3043 m) and the Bear Lake Plateau to the east (elevations up to 2306 m).

The central part of the valley also trends north and is 15 kilometers wide, stretching north from St. Charles to Montpelier, Idaho. To the west, peaks in the Bear River Range rise to 2918 meters (Paris Peak), while to the east the Bear Lake Plateau rises to an elevation of 2323 meters at Merkely Mountain, and then descends to the incised valley of the Bear River. The valley floor is dominated by Dingle Swamp and Mud Lake, which lie directly north of Bear Lake, and farther north by the low alluvial fan of the Bear River, which enters the valley on its eastern margin about 7 kilometers south of Montpelier, Idaho.

The northern part of the valley trends north-northwest, is narrower than the southern and central parts, and lacks straight valley margins. The Bear River flows northwestward down the valley axis, flanked by the Preuss Range on the east (maximum elevation 3005 m at Meade Peak east of Georgetown, Idaho), and on the west by the Bear River Range (maximum elevation 2931 m at Sherman Peak west of Georgetown). The Bear River reverses its course at Soda Springs, Idaho, 20 kilometers north of Georgetown, and thence flows southward into Cache Valley, Utah and ultimately into Great Salt Lake.

Previous Work

Mansfield (1927) first described the geology of Bear Lake Valley in conjunction with a regional assessment of phosphate resources. He first reported raised shorelines in Bear Lake Valley, measured their height, and correlated them informally with the late Pleistocene shorelines of Lakes Bonneville (Utah) and Lahontan (Nevada). Williams and others (1961, 1962) were the first to study the Quaternary geology of the valley in detail, and they identified three raised shorelines (Lifton, + 6 ft [2 m]; Garden City, + 15 ft [4.5 m]; and Willis Ranch, + 25 ft [7.5 m]) around the lake. [Note that International System (metric) units of measure are used in this report without reporting the corresponding English System equivalents except in those cases where data reported from other sources were first published in the English System. In those cases, the English System values are reported first followed by International System equivalents.] Several Master's theses at Utah State University describe the surficial (Quaternary) geology in the southern valley (Robertson, 1975), northern valley (Robertson, 1978), and at North Eden Creek on Bear Lake (McClurg, 1970), as well as the fault scarps cutting Quaternary deposits. Kaliser (1972) summarized much of this work in his *Environmental Geology of the Bear Lake Area*. Skeen (1976) measured seismic reflection profiles in Bear Lake.

After a hiatus of two decades, work was begun again after the Beaver Mountain earthquake of 1988, directly west of Bear Lake (Pechmann and others, 1992). McCalpin (1993) mapped fault scarps in Quaternary deposits (figure 5) in 1989 and excavated paleoseismic trenches at two sites, described later in this paper. Evans (1991) described the structural setting of seismicity in northern Utah and investigated the 1884 Bear Lake earthquake (Evans et al., 2003). The U.S. Geological Survey (USGS) Bear Lake Project began in 1999 targeted at drilling into Bear Lake sediments to reconstruct paleoclimate trends. For example, Colman (2001) collected 200 kilometers of high-resolution seismic-reflection profiles in Bear Lake in order to explore the sedimentary framework of the lake's paleoclimate record as derived from cores and drill holes. In addition to a series of short cores, including piston cores as much as 5 meters long, the USGS drilled two deep holes at a site on one of the seismic-reflection lines. These continuously cored drill holes, 100 and 200 meters deep, respectively, were part of the testing operations for the Global Lake Drilling - 800 m (GLAD800) drilling system.

Regional Geology and Tectonics

Bear Lake Valley is in the foreland fold and thrust belt (Overthrust Belt) of the Sevier orogeny of late Cretaceous to Eocene age (Armstrong, 1968; Oriel and Platt, 1980). In late Tertiary time the Overthrust Belt was subjected to east-west extension, causing inversion of reverse faults to normal faults, the formation of new normal faults above thrust ramps, and the development of Neogene basins (Dixon, 1982; Blackstone and DeBruin, 1987). West (1992) proposed a geometric model to describe the evolution of normal faults

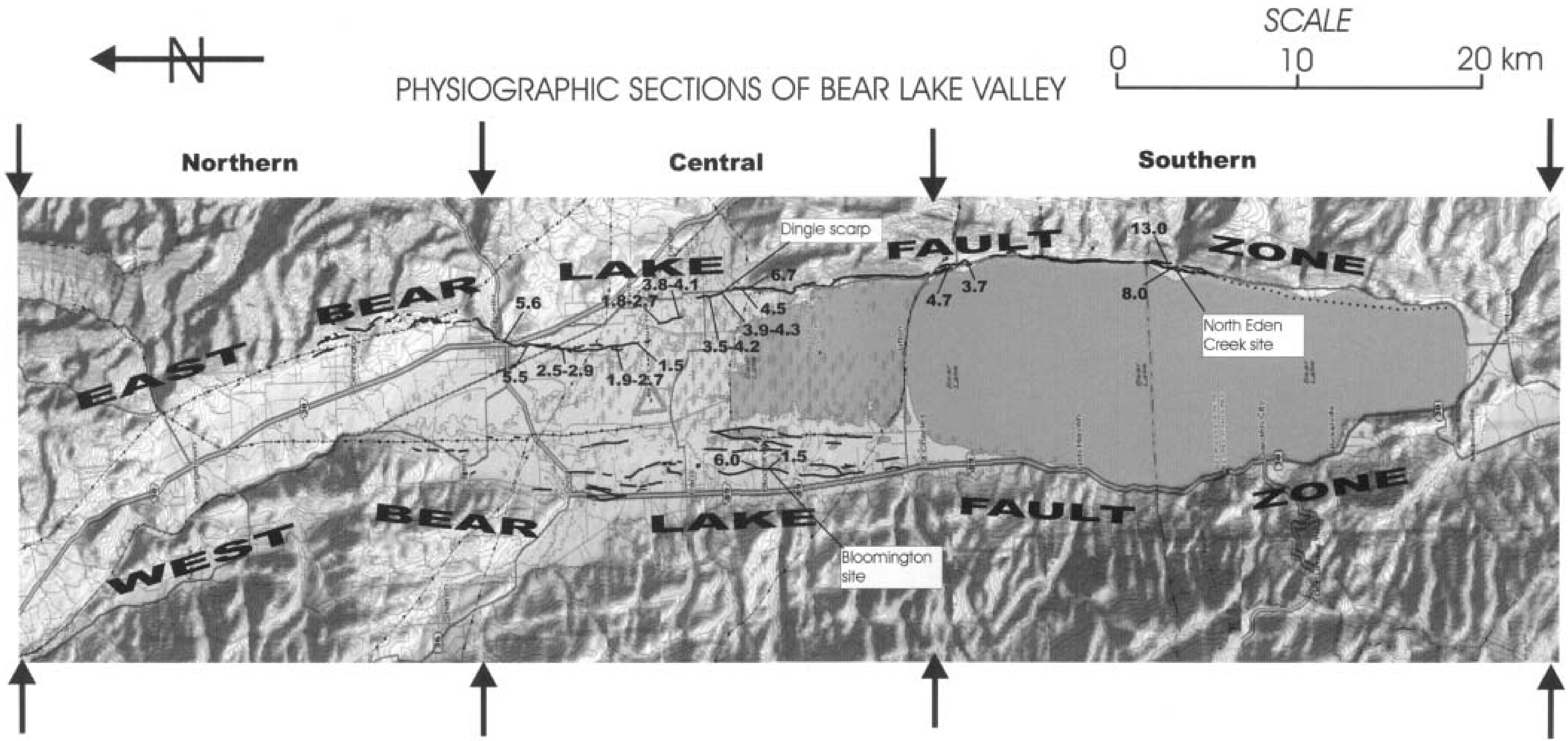

Figure 5. Physiographic sections of Bear Lake Valley, Utah and Idaho. Sections of the East and West Bear Lake fault zones correspond to the named physiographic sections. Fault scarps in Quaternary deposits are marked by thick black lines, with fault scarp heights in meters. These scarps are generalized from unpublished 1:24,000-scale mapping by McCalpin. Labels show the sites of the two trenching studies described herein, at North Eden Creek on the southern section of the East Bear Lake fault zone, and at Bloomington (Idaho) on the central section of the West Bear Lake fault zone. Good sites for future paleoseismic studies exist on other sections, such as on the Dingle Scarp (central section of the East Bear Lake fault zone) and in the eastern parts of Montpelier, Idaho. Conversely, fault scarps in Quaternary deposits are less well preserved in the northern section of the East Bear Lake fault zone, and are scarce in the northern section of the West Bear Lake fault zone. Dotted and dashed lines are power transmission lines.

during continued Neogene extension. This model explains the development of Cache Valley, Bear Lake Valley, Star Valley, and other valleys between the Wasatch fault and the Yellowstone Plateau.

The dominant normal fault in the area is the East Bear Lake fault (EBF), a listric normal fault that soles into the Meade thrust (figure 6). Kendrick (1994) and Coogan and Royse (1990) interpret the EBF to cut out the Meade thrust, leaving a tip of the thrust in the footwall of the normal fault. This geometry is similar to that documented by West (1992), which he ascribes to the intermediate amount of extension in the region. The EBF has 3.8 to 3.9 kilometers of slip as measured on the cutoffs on the Meade thrust. The EBF has a large radius of curvature, dipping 70° at the surface, and gradually reaching a dip of 20° at a depth of 6 kilometers below sea level (figure 6). Coogan and Royse (1990) show the fault to dip 65° at the surface, and at depth of 5.8 kilometers below sea level, the fault makes a sharp bend and becomes flat. In contrast, Evans (1991; and figure 6) shows the fault becoming listric at a depth of only 4 kilometers below the surface, or 2.2 kilometers below sea level.

Neither Kendrick (1994) nor Coogan and Royse (1990) show details of deformation or sedimentary structures in the hanging wall of the EBF. Evans (1991) used proprietary seismic data acquired along the north shore of Bear Lake to examine details of the structure of the hanging wall. Here, he interpreted numerous small-displacement faults to cut reflectors that represent the Paleozoic and Proterozoic rocks in the hanging wall of the EBF. These small displacement faults (throws > 40 m) may represent extensional strain in the hanging wall of the normal fault, and Evans (1991) suggested that one of these faults could have been responsible for the 1988 M 4.8 Bear Lake earthquake. Pechmann and others (1992) show that one of the nodal planes for this earthquake was a steeply dipping fault, consistent with this interpretation.

The overall basin geometry, at least in the southern two-thirds of Bear Lake Valley, is that of an east-tilted half graben. Neogene basin-fill sediments show increasing dips with depth. The western basin margin appears to be a hinge zone, broken by a swarm of north-trending normal faults downthrown both to the east and west. This swarm is informally referred to herein as the West Bear Lake fault zone (WBF), and is probably the result of east-west extension of the upper crust in the hinge zone. Seismic profiles are ambiguous as to whether these normal faults penetrate to any great depth, and they may in fact be rootless faults that accommodate stretching in the upper part of the crust above some neutral stress line. If the faults are rootless, they are probably aseismic and move only as passive structures during deformation events on the master fault. However, this aspect of the local neotectonics is beyond the scope of the present investigation, which exclusively studied tectonic landforms and shallow exposures.

In addition to the eastern master fault and the hinge-zone fault swarm, several normal faults appear on seismic profiles across Bear Lake (Skeen, 1976; Colman, 2001). These internal basin faults are downthrown to both the east and west, and some on the eastern side of the lake displace the lake bottom, indicating very recent movement.

Bear Lake Valley is in the Intermountain seismic belt. The largest historic earthquake in the area was the Bear Lake earthquake of 10 November 1884 (Arabasz and McKee, 1979; Evans et al., 2003). This earthquake had a felt area of 15,000 square kilometers, with the epicenter estimated about 16 kilometers southeast of St. Charles, Idaho (42°N. latitude, 111°16′W. longitude). In the epicentral area the maximum modified Mercalli intensity was VIII, and together with the large felt area, this intensity was used to estimate a moment magnitude of 6.3. The epicenter was in the Bear River Range west of the WBF, but locational accuracy is poor.

A second earthquake occurred in the same general area in November 1988 about 5 kilometers due west of Bear Lake near Beaver Mountain ski area. This earthquake had a moment magnitude of 4.8, and its focal mechanism indicated probable down-to-the-east slip on an east-dipping normal fault (Pechmann and others, 1992).

Acknowledgments

I wish to thank several scientists of the U.S. Geological Survey including Tony Crone, who loaned me the aerial photographs of the study area, and Bob Bucknam, Mike

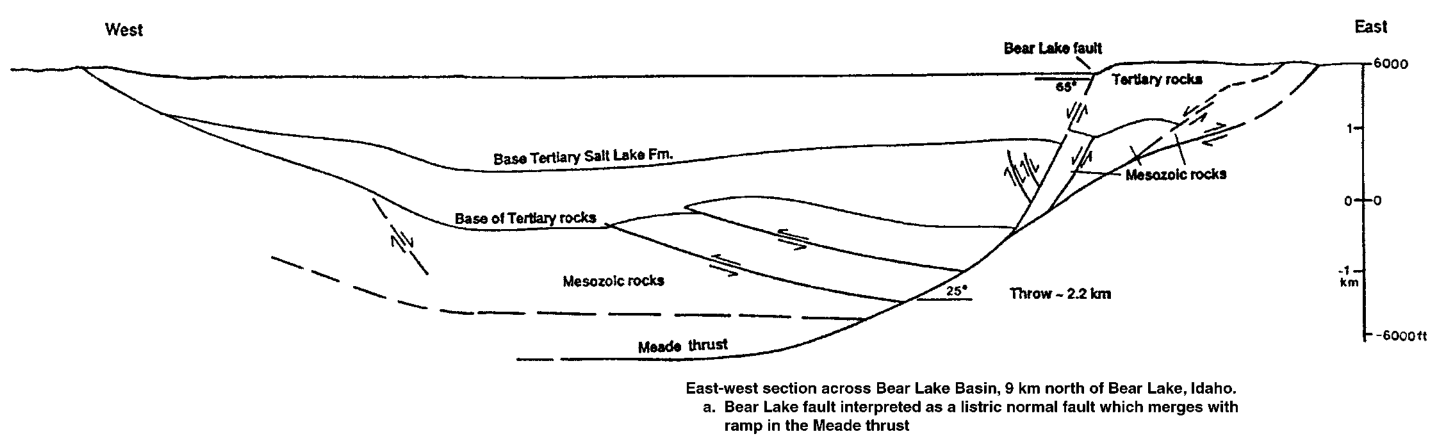

Figure 6. Schematic east-west cross section of Bear Lake Valley at the northern margin of Bear Lake. This diagram is an interpretation of proprietary industry seismic reflection data by J.P. Evans, Utah State University, Logan, Utah (Evans, 1991). Bear Lake (not shown) lies just south of the line of cross section. The master normal fault labeled "Bear Lake fault" is the same as the East Bear Lake fault zone (EBF) of this report. According to Evans' interpretation, the EBF merges with the Meade thrust at a depth of about 2.5 km, and the fault becomes listric at a depth of roughly 4 km.

Machette, and Kathy Haller, who reviewed the trenches on the EBF. The author, Liren Zhang [State Seismological Bureau, Beijing, China], L.C. Allen Jones, Dean Henderson, and other students from Utah State University logged the EBF trenches. Landowners Steven Nebecker and Chase Peterson granted permission for the EBF trenches. Bloomington landowner Roy Bunderson, who also assisted with logistics, permitted the WBF trenches. The author, Vladimir Khromovskikh [Institute of the Earth's Crust, Irkutsk, Russia], L.C. Allen Jones, and Greg Warren logged the WBF trenches. Steve Forman [University of Illinois at Chicago] performed the thermoluminescence dating, and Beta Analytic [Miami, Florida] performed the radiocarbon dating. Organic matter was concentrated from bulk soil samples by Rolf Kihl [Institute of Arctic and Alpine Research, Boulder, Colorado]. Marith Reheis [U.S. Geological Survey] provided details on geologic mapping in the Bear Lake Valley from the ongoing USGS Bear Lake Project. Benjamin Laabs and Darrell Kaufman [both Northern Arizona University, Flagstaff, Arizona] provided data on the Quaternary stratigraphic framework and geochronology of Bear Lake from studies of the 1990s. Bill Lund [Utah Geological Survey] provided several critical reviews of this manuscript, parts of which were adapted from an earlier publication by McCalpin and others (1993).

QUATERNARY TECTONICS

Because the Bear Lake Valley is an active Neogene graben, its ongoing subsidence has been a major control on the pattern of Quaternary deposition and erosion, combined with the effects of Quaternary climate change. In the sections below I summarize current knowledge on Quaternary stratigraphy and the segmentation of graben-bounding faults.

Quaternary Stratigraphic Framework

At the time of the paleoseismic trenching described herein (1989), detailed studies of Quaternary geology had been limited to the southern part of the Bear Lake Valley, including Bear Lake and the Dingle Swamp. Williams and others (1961, 1962) documented the existence of an enlarged, Pleistocene Bear Lake, marked by shorelines at 5948 feet (1782.5 m, Willis Ranch shoreline), 5938 feet (1809.9 m, Garden City shoreline), and 5929 feet (1807.2 m, Lifton shoreline), compared to the modern lake level of 5923 feet (1805.4 m). Later work by Robertson (1978) correlated the Willis Ranch shoreline to the Liberty episode of Pleistocene lake deposition at and below 5945 ± 10 feet (1812.1 ± 3 m), and further identified this shoreline with the lake highstand coeval with the latest Wisconsin (Pinedale) glaciation. Robertson (1978) identified an even older episode of lacustrine deposition reaching up to 5990 feet (1825.8 m) elevation, named the Ovid episode. Radiocarbon ages on shells indicated the Ovid episode occurred ca. 27 uncal ka (i.e., 27,000 ^{14}C years Before Present). [Note: Throughout this paper numerical ages are cited either as uncalibrated ^{14}C years Before Present (^{14}C yr BP, or uncal ka), calendar-corrected years Before Present (cal yr BP or cal ka, from Stuiver and Reimer, 1993), or simply years Before Present (or ka) for ^{14}C ages older than 40 ka or for luminescence age estimates. Uncertainties cited are 1 sigma.]

More recent work by Laabs (2001), Laabs and others (2001, 2002), and Laabs and Kaufman (2003) shows that the elevation of Bear Lake fluctuated up to 25 meters higher than present between ~ 400 and 120 ka. Laabs identified raised shoreline deposits 8, 11, and 25 meters above modern Bear Lake that represent highstands of the lake at ca. 15, 40, and 130 ka, respectively. The following summary is taken from Laabs and others (2002). As the level of the lake rose, it presumably captured the Bear River (which currently bypasses the lake to the north) and transgressed to an outlet at the north end of Bear Lake Valley. The elevation of Bear Lake was then controlled by the outlet elevation, which is currently 12 meters below modern lake level. The outlet elevation must have been at least 37 meters higher in the past to allow highstands of Bear Lake. However, no evidence has been found for a temporary obstruction, such as a landslide, that could have raised the outlet high enough to impound a lake 25 meters above modern lake level. Movement on valley-bounding normal faults has undoubtedly changed the geometry of Bear Lake Valley and affected the elevation of its outlet; therefore, tectonic activity influenced the elevation of Bear Lake.

Local faulting in Bear Lake Valley probably caused differential lowering of the valley floor to the southeast, which is currently the deepest depocenter in the valley and contains the deepest part of Bear Lake (figure 7). This pattern of normal faulting may have ultimately caused lake-level change

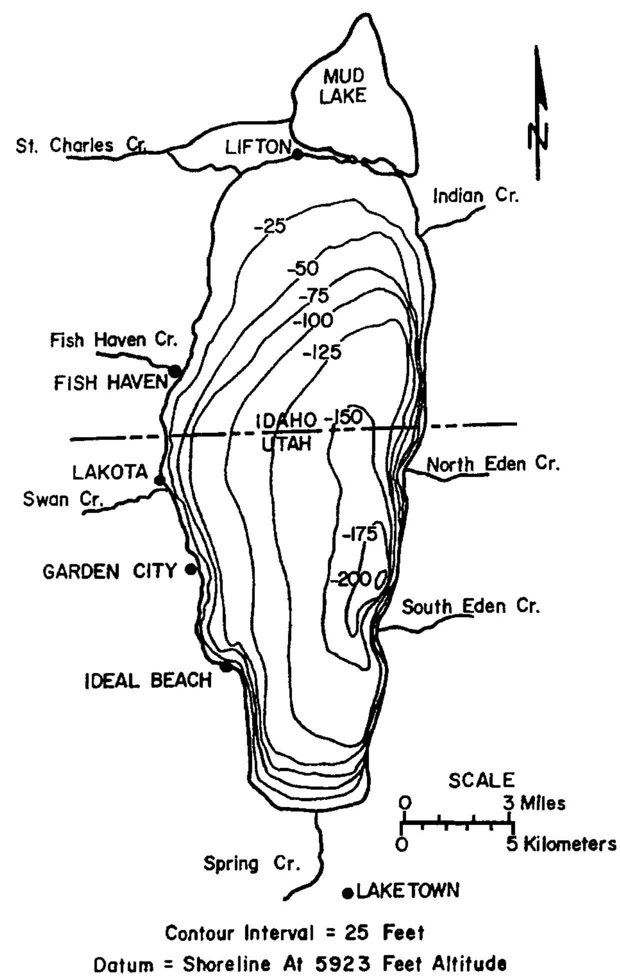

Figure 7. *Bathymetry of Bear Lake. From Skeen (1976).*

by either: (1) uplifting the Bear Lake Valley outlet relative to the southern valley, and/or (2) reversing or reducing the gradient of Bear River, causing it to flow southward into Bear Lake or aggrade in northern Bear Lake Valley and raise the elevation of the outlet. The first of these two mechanisms may have led to transgressions of Bear Lake up to 25 meters between ~ 400 and 120 ka, and the second, combined with climate change, may have led to more minor transgressions since ~ 120 ka that interrupted an overall 25 meter drop in lake level. After rising to the Bear Lake Valley outlet, downcutting by an out-flowing Bear River caused the lake level to drop and the north shoreline of Bear Lake to retreat southward.

Recent work has also shed light on the interplay between sedimentation and tectonics in Bear Lake. According to Colman (2001) the seismic stratigraphy below the lake indicates the lake basin is a simple half graben, with a steep normal-fault margin on the east and a ramp margin on the west (figure 8). Seismic reflections diverge toward the master fault, bounding eastward-thickening sediment wedges. The seismic stratigraphy imaged secondary normal faults west of the master fault beneath the lake, and many of these faults show progressively increasing throw with depth and age. Several faults cut the youngest sediments in the lake as well as the modern lake floor. Although pinch-outs of sedimentary units are common in relatively shallow water, no major erosional or depositional features suggestive of shoreline processes are evident on seismic profiles in water deeper than about 5 meters. The relative simplicity of the sedimentary sequence is broken in the northern part of the basin by what appears to be a large (2.5 by 9.5 km) bedrock landslide block, which overlies stratified lake sediment.

Preliminary identification of volcanic ashes, gross correlation of climate proxies, and preliminary U-series data all suggest that the base of a 100-meter-deep drill hole drilled by the USGS is about 250,000 years old, and that sedimentation has been relatively uniform at an average rate of about 0.5 meters per thousand years. These data will theoretically allow isochronous seismic-reflection horizons, tied to the drill hole, to be traced throughout the basin.

In the central part of the valley the Bear River has deposited a low-gradient alluvial fan. My reconnaissance observations show that this fan contains geomorphic surfaces of at least three ages, only the youngest of which (late Holocene) is not displaced by the EBF. Mapping by Reheis (in preparation) identifies the two older surfaces as Holocene and Pleistocene, respectively.

It is unclear to what extent Pleistocene lakes extended into the northern Bear Lake Valley, north of Montpelier. Based simply on shoreline elevations, all shorelines higher than 1807.2 meters should have extended into northern Bear Lake Valley. Presently there is no topographic barrier that would have prevented this extension. However, such shorelines are rarely observed in the northern valley, raising the possibility that the prehistoric shorelines measured near Bear Lake by previous workers may have been locally uplifted above their original elevations.

Neotectonic Framework and Fault Segmentation

Based on photogeologic mapping of fault scarps, I divide the EBF and WBF into three geometric sections each, which correspond to the three parts of the Bear Lake Valley defined previously (figure 5). Whether these geometric sections define earthquake rupture segments cannot be determined from the present paleoseismic study because I only trenched the central section of the WBF and the southern section of the EBF (two of six fault sections).

I divided the EBF into southern, central, and northern sections. The southern section extends 32 kilometers from Laketown, Utah to Bear Lake Hot Springs at the northeastern

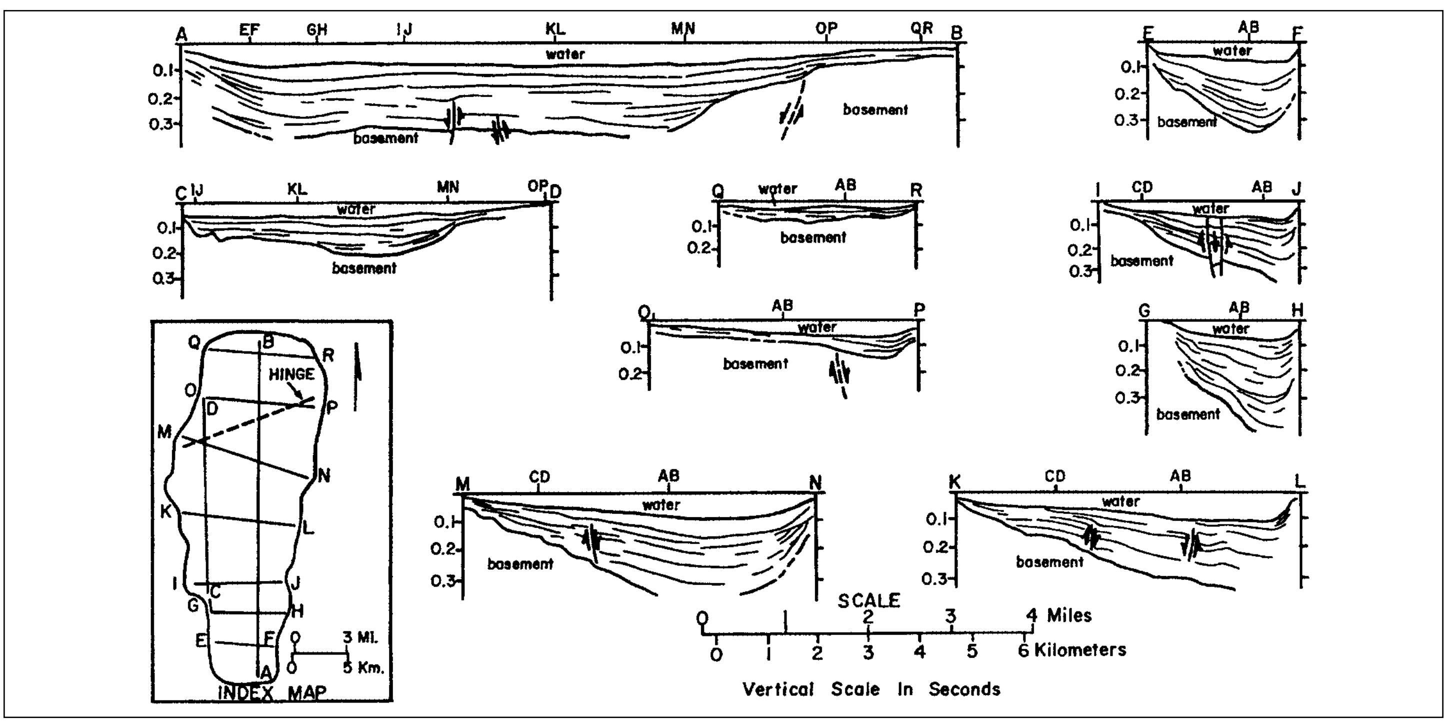

Figure 8. Seismic-reflection profiles from Bear Lake. From Skeen (1976).

Table 1. *Phases of Bear Lake during the past 1 million years (adapted from Laabs and Kaufman, 2003).*

Phase	Age (cal ka)[1]	Shoreline Elevation (feet asl)
Modern controlled level	historical[1]	5923 (artificial)
Garden City/ Lifton[2]	<9	<5938
Willis Ranch[2]	~9	~5948
Cisco[3]	9 to ~12	??
Raspberry Square[3]	15 to ~16	~5950
Jensen Spring[3]	39 to ~47	~5960
Bear Hollow[3]	100 (best-developed shoreline) to ~1000 (multiple highstands)	~6005 (130 ka ? shoreline)

[1] Thousands of calibrated years, [2] Named by Williams and others (1961, 1962), [3] Named by Laabs (2001)

corner of Bear Lake. Along most of the southern section the range-front escarpment is very straight and appears to have well-developed faceted spurs (figures 3, 4). However, these "facets" are actually dip slopes on the resistant Nugget Sandstone (Jurassic), so are not true erosional facets as described by Wallace (1978). Discontinuous fault scarps up to 13 meters high at the base of the range front displace colluvium and alluvium. Scarps are best developed where the fault crosses the mouths of major drainages such as North Eden Creek (combined scarp heights of 22 m), and Indian Creek (scarp heights of 3.7 to 4.7 m; figure 5). South of North Eden Creek I did not observe any obvious fault scarps, but Marith Reheis (USGS-Denver, personal communication, 2002) states scarps are present in Quaternary deposits "in the Holocene fan-delta of South Eden Creek, in late Quaternary? fan deposits near the southeast corner of the lake, and south of the mouth of Pine Canyon." South of South Eden Canyon, Kaliser (1972) documented at least one fault trace in the littoral zone of Bear Lake (see low-water photographs in Kaliser, 1972).

The southern boundary of the southern section of the EBF is not well defined. Although the topographic depression ends directly south of Laketown, Dover (1985) mapped multiple down-to-the-west normal faults continuing several kilometers south of Laketown. Hence, the 32-kilometer length measured for this section may be a minimum value. I define the northern boundary of the southern section herein as the 1 kilometer left stepover in the EBF between the mouth of Indian Creek and Bear Lake Hot Springs.

The central section of the EBF extends 26 kilometers from Bear Lake Hot Springs (figure 9) to Montpelier, Idaho (figure 10). The southern 10 kilometers of this section is marked by the steep, linear range-front escarpment of the Bear River Plateau (figure 11) which rises up to 2323 meters at Merkely Mountain, but the escarpment rapidly dies out northward to where the Bear River enters Bear Lake Valley from the east. Fault scarps in the southern 10 kilometers displace small, steep alluvial fans of unknown age, and I measured no scarp heights there in this study. A low, north-trending fault scarp (named the Dingle scarp by Robertson, 1978; see figure 5) that displaces the broad alluvial fan of the Bear River marks the remainder of the central section. Fault scarp heights are largest at the margins of the Bear River fan (6.7 m south of Dingle, 5.5 m south of Montpelier), but decrease steadily toward the Bear River (figure 5). This decrease may be caused by two factors: (1) scarps displacing successively younger geomorphic surfaces toward the Bear River, and thus representing a smaller number of displacement events, or (2) a scarp of uniform 5.5- to 6.7- meter displacement (and number of events) being progressively buried on the downthrown block by deposition from the Bear River. My reconnaissance observations support the first explanation, but mapping the several geomorphic surfaces within the Bear River fan was beyond the scope of this study.

I arbitrarily defined the northern boundary of this section at Montpelier. Within the eastern limits of the town a prominent 5.6-meter-high scarp trends north-south just east of 3rd Street, and goes through numerous suburban back yards. This same scarp crosses U.S. Highway 89 at the mouth of Montpelier Canyon, where it appears to be about 3 meters high. Young-looking 5- to 6-meter-high fault scarps continue a few kilometers north of Montpelier on a north-northeast trend, but then swing to a north-northwest trend and become older looking as the eastern valley margin changes to a north-northwest trend.

The northern section of the EBF extends at least 20 kilometers from Montpelier to Georgetown. Northwest of Georgetown a series of low hills that separate Georgetown from Nounan Valley interrupts the Bear Lake Valley, and these hills represent the northern end of Bear Lake Valley as discussed in this report. Discontinuous, eroded fault scarps that lie at the boundary between the Preuss Range and dissected, early to middle (?) Pleistocene pediments cut on Tertiary (?) valley fill characterize the northern section of the EBF. Pediments and Tertiary valley fill are not present at the surface south of Montpelier, and suggest that the northern part of Bear Lake Valley has not subsided as much as the central and southern parts.

Figure 9. *Photograph of faulted pediment (?) surfaces on the East Bear Lake fault zone, directly east of Bear Lake Hot Springs at the northeast corner of Bear Lake. The low-gradient geomorphic surfaces are truncated by a fault scarp (in shadow) about 30 m high. The age of the pediments is unknown, but Marith Reheis (USGS, Denver, personal communication, 2002) estimates a mid-Pleistocene age for them. The road in the foreground is at the eastern end of Bear Lake State Park; Bear Lake is visible in the lower right corner.*

Figure 10. *Oblique aerial photograph looking south down Bear Lake Valley from over Montpelier, Idaho (lower right corner). This photograph shows the entire central section of the East Bear Lake fault zone, which extends from Montpelier to the northeast corner of Bear Lake. Montpelier Canyon is at bottom left and center. Bear Lake is in the far distance at upper center. The Bear River enters the valley at upper left center and flows to the right, eventually merging with the Bear Lake Canal (linear ditch that extends from Bear Lake to center right margin of photo). Photograph by Jim McCalpin.*

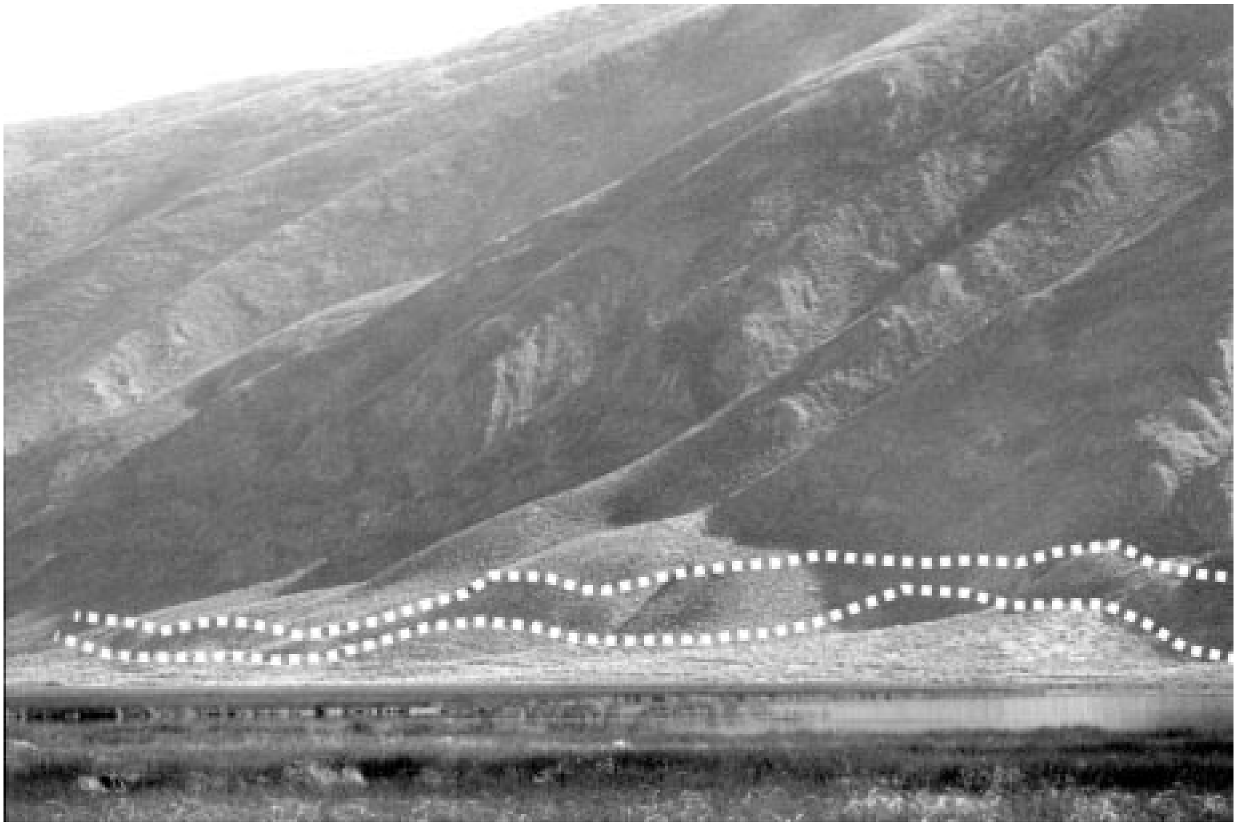

Figure 11. *Range-front scarps of the central section of the East Bear Lake fault zone, about 1 km north of Bear Lake Hot Springs at the base of Merkely Mountain. Mud Lake is in the foreground. The fault scarps displace sagebrush-covered Quaternary deposits of several ages at the base of the range, and appear as oversteepened slopes that are shadowed in this photograph. View to the northeast.*

I subdivided the WBF into three sections that correspond in latitude to the sections of the EBF (figure 5), but less is known about them. The southern section of the WBF hugs the western shore of Bear Lake and is only visible as normal faults exposed in rare cuts, such as the roadcut on U.S. Highway 30 east of Pickleville, Utah. The linear western shore of Bear Lake south of Pickleville is probably controlled by a fault, although the seismic profile of Skeen (1976) does not show a fault projecting northward at that location. Additional fieldwork is required to locate strands of the WBF in the southern section, especially submerged fault traces.

The central section, which stretches about 23 kilometers from St. Charles, Idaho to Ovid, Idaho, contains the best-developed fault scarps on the WBF. The 3-kilometer-wide zone of low horsts and graben coincides with meandering, abandoned drainage (outlet) channels from Bear Lake. The largest scarp, termed the Bloomington scarp by Robertson (1978), faces east and is probably responsible for downdropping the western side of Bear Lake Valley such that all outlet channels are on this side of the valley.

I infer the northern section of the WBF to bound the western side of Bear Lake Valley north of Ovid, essentially coincident with the Bear River. Oriel and Platt (1980) show this fault section to consist of several Neogene fault strands that displace Tertiary valley fill. I only mapped fault scarps in Quaternary deposits near Bern, Idaho in the southernmost part of the section. I spent little time examining aerial photographs of this area for this study, and I did not field check the area.

QUATERNARY FAULTING ON THE EASTERN BEAR LAKE FAULT ZONE

The main new results presented in this paper are fault scarp heights measured on the southern and central sections of the EBF, and data from two paleoseismic trenches excavated in 1989 across fault scarps on the southern section. At the time of the trenching, the only available data on Quaternary shorelines and deposits was that published in the 1970s, which did not account for uplift of shorelines along the EBF. Accordingly, I was unable to relate the stratigraphy in the trenches to a basin-wide Quaternary framework. That drawback is partly rectified in this paper, based on the new models of Laabs (2001).

Trenches in the Southern Section of the EBF

In June of 1989 I excavated two backhoe trenches across fault scarps at the mouth of North Eden Creek (figure 5). Fault scarps here trend north-south and displace the subaerial part of a large fan-delta deposited by North Eden Creek into Bear Lake.

Geomorphology of the Trench Site

North Eden Creek is a major west-trending stream that drains a portion of the Bear River Plateau, and has built a prominent fan-delta into Bear Lake just south of the Idaho-

Utah border. The currently emergent part of the fan-delta is 2.9 kilometers wide (north-south dimension) and it protrudes 0.9 kilometers into Bear Lake. The surface of the late Holocene fan-delta slopes gently (0.7°) toward the lake.

The EBF crosses the North Eden Canyon fan-delta as two parallel fault scarps that displace the eastern side of the fan-delta (figure 12). Together these scarps have uplifted the eastern part of the fan-delta surface 22 meters, roughly 8 meters on the western fault scarp and 14 meters on the eastern fault scarp (figure 13). The modern canyon floor in North Eden Creek (Unit Qd_2 in figure 12) is graded to the top of the western, 8-meter-high fault scarp (figure 13), whereas a poorly preserved upper terrace extends upstream from the top of the eastern, 14-meter-high scarp. The active channel of North Eden Creek has incised a narrow slot into the western fault scarp, to reach grade with the downthrown part of the fan-delta 8 meters below.

The western, 8-meter-high fault scarp is continuous across the entire fan-delta (except where eroded by the modern wash), whereas the eastern 14-meter-high fault scarp has been removed by erosion in the northern third of the 350-meter-wide modern canyon floor, but is expressed as a 1-meter-high scarp in Qd_2 in the southern two-thirds of the fan-delta (figure 12, inset). This geometry indicates that 13 meters of the 14 meter displacement on the eastern scarp occurred after deposition of Qd_1 but before deposition of Qd_2, after which the creek incised 13 meters, formed the modern canyon floor (Qd_2), and left the upper terrace level (Qd_1). Subsequent to formation of the modern canyon floor, there has been an additional 8 meters of vertical slip on the western fault trace and 1 meter of slip on the eastern fault. The latest movement on the western scarp is sufficiently recent that North Eden Creek has so far only incised a 10-meter-wide channel through the scarp.

Two large flood-scoured pits formed in the footwall of the western scarp in 1983 when a reservoir 1 kilometer upstream failed and flood waters poured over the western scarp (Michael Nebecker, personal communication, 1989). These 5- to 8-meter-deep exposures reveal the character of the fan-delta gravels (map unit Qd_2) and its overlying finer cover sediments in the intermediate fault block between the western and eastern fault scarps (figure 14). The southern pit also exposes the eastern fault trace in its walls (figure 12, inset). Most of the pit walls expose well-sorted, well-stratified, red cobble and pebble, fan-delta gravels, mainly composed of Jurassic Nugget Sandstone. Overlying these fan-delta gravels is a 15-centimeter-thick, mottled red and brown silt deposit that contains pockets of charcoal and gastropods (figure 14). I interpret this deposit as a marsh or swamp deposit, laid down when lake level was close to this elevation, and the locus of fan-delta gravel deposition had shifted away from this area.

Overlying the marsh deposit is 55 centimeters of massive brown silt, the upper 20 centimeters of which is a buried

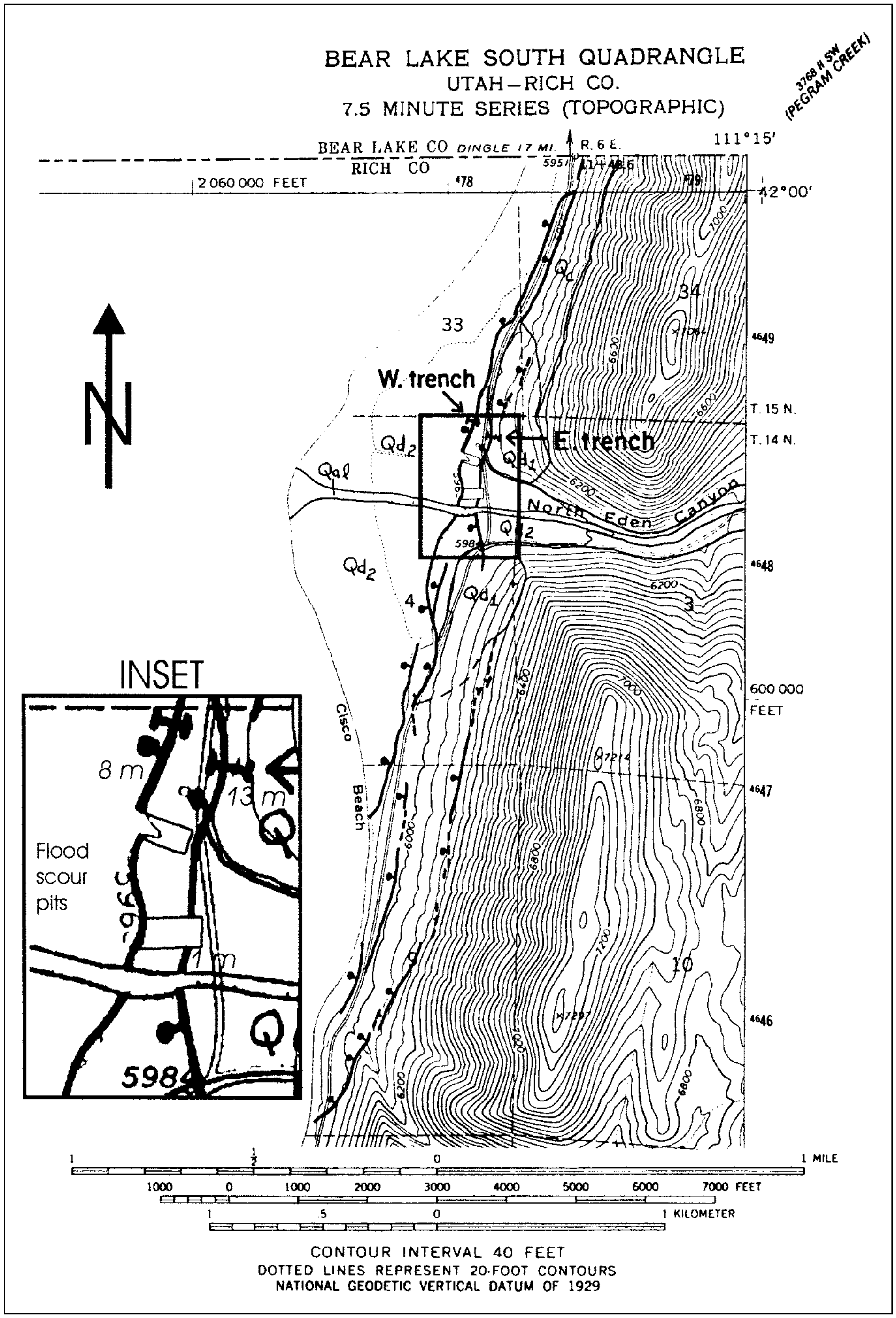

Figure 12. Map of fault scarps and Quaternary deposits on the fan-delta of North Eden Creek. Qd_1, older fan-delta deposit (middle Pleistocene?); Qd_2, younger fan-delta deposit (late Pleistocene); Qal, Holocene alluvium. Inset map shows two flood-scour pits that expose Qd_2 and overlying marsh sediments and loess (see figure 14); scarp heights are in meters.

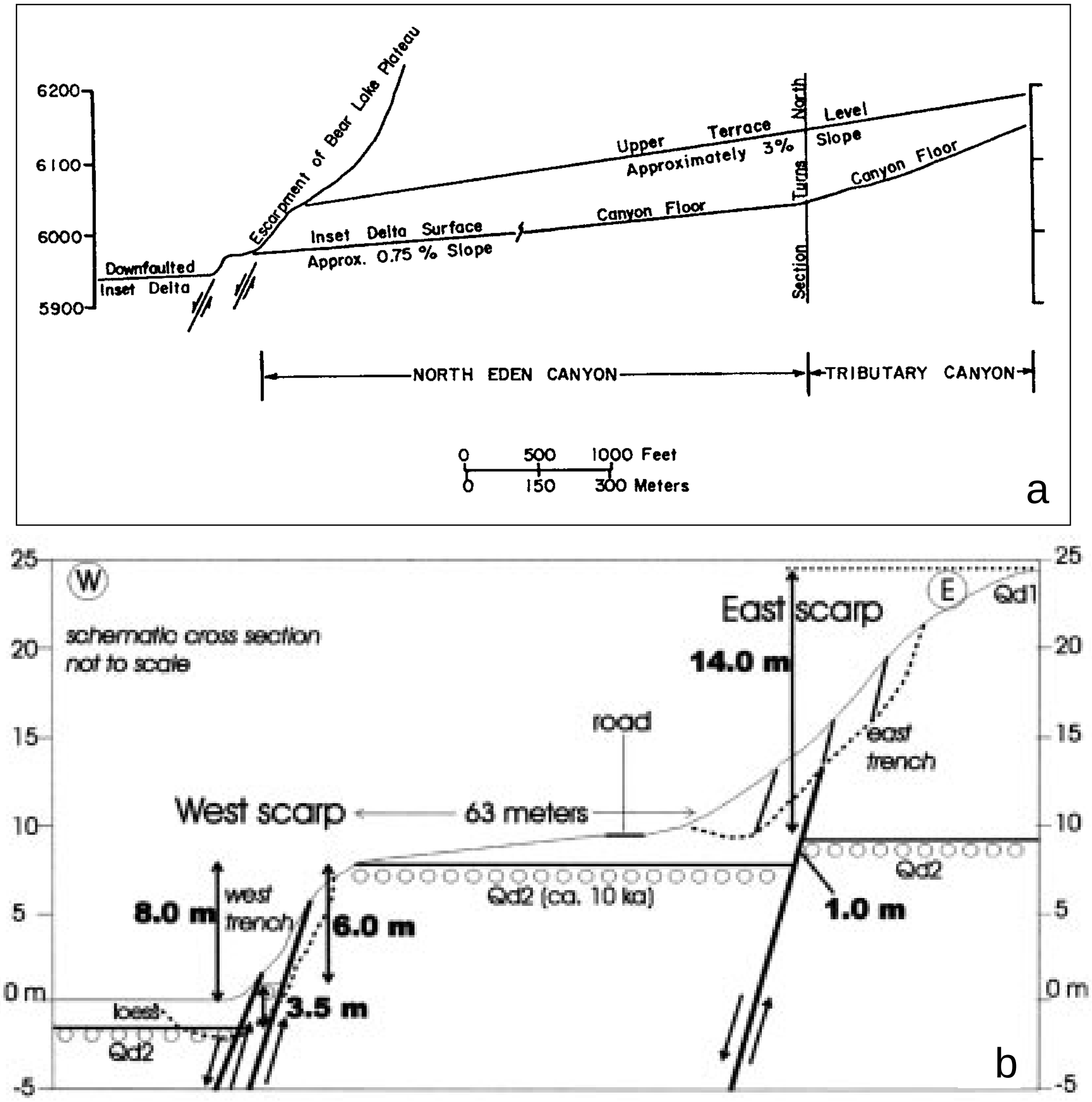

Figure 13. *Schematic cross sections at the North Eden Creek trench site. (a) Longitudinal topographic profiles of the older-fan delta (unit Qd_1, "upper terrace") and younger fan-delta (unit Qd_2, "inset delta") surfaces at North Eden Creek; from McClurg (1970). The minor amount of modern stream incision between the two faults is not shown. (b) Enlarged cross section of the two fault scarps, showing the net 10.5 m of vertical displacement of the Qd_2 gravels. Qd_1 gravels are displaced an additional >13 m vertically (not shown) by older faulting events on the eastern and western fault zones in the east trench.*

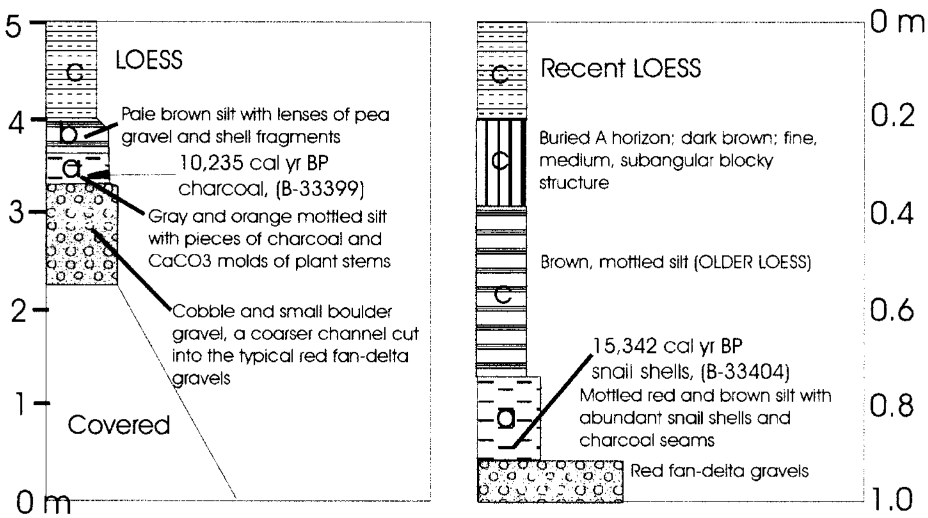

Figure 14. *Stratigraphic section exposed in flood scour pits in the footwall of the western fault scarp. These pits expose the deposits that underlie the modern "canyon floor" labeled in figure 13.*

soil A horizon. Based on the uniform fine grain size and lack of sedimentary structures, I interpret this silt as a loess deposit, similar to loess deposits exposed in the eastern and western trenches described later in this report. Overlying the buried soil A horizon is an additional 20 centimeters of loose, massive, brown silt that also appears to be loess. This uppermost loess has no soil development and may be a historical deposit, related to clearing and plowing the fan-delta surface farther west (upwind) in the late 1800s.

These exposures record a falling lake level, grading upward from fan-delta, to marsh, to loess depositional environments. Radiocarbon samples of charcoal in the marsh deposit yield an age of 9100 ± 90 ^{14}C yr BP (10,235 ± 310 cal yr BP), whereas adjacent gastropods yield an older age of 12,700 ± 130 ^{14}C yr BP (15,342 ± 1,082 cal yr BP). This age discrepancy can be explained in three possible ways: (1) the hard-water effect makes the snails appear too old , (2) the snails are reworked from an older deposit, or (3) the charcoal is intrusive and is too young. Laabs (2001) preferred explanation 1, due to the hard-water effect from springs in North Eden Creek. The charcoal appeared to be detrital, not intrusive, so the marsh deposit here is more likely 10 ka than 15 ka.

Western Trench

I excavated the western trench across the western fault scarp north of North Eden Creek, where the scarp is 6.5 to 7 meters high (figure 15). The trench was 33 meters long, 1 meter wide, and from 2.5 to 4.5 meters deep (figure 16). I divided the deposits exposed in the trench into six major and 24 minor units, including two buried soils (appendix 1).

Stratigraphy: The oldest deposits are present on the fault footwall and at the bottom of the trench in the hanging wall (figure 17, Units 1a-1i). These deposits are composed of horizontally stratified, slightly lenticular, alternating beds of silty sand to cobble gravel (appendix 1). Most beds are very well sorted and stratified, and are interpreted as fan-delta deposits. At the western end of the trench, Unit 1 interfingers with a series of well-sorted silts (Units 2a, 2b), sands (Unit 2d), and fine gravels (Unit 2c). I interpret these deposits as beach (gravels and sands) and lagoon (silts) sediments. Overlying Unit 2 is a lens of mud (Unit 3), on which a buried soil (soil 1) is developed (A and B horizons). The mud evidently filled a depression left after the beach was abandoned at this site, after which soil 1 formed under subaerial conditions.

To the east, buried soil 1 grades into a transitional Unit (4a) that separates the fan-delta gravels from overlying loess. The loess (Unit 4) is a uniform 1.1 to 1.3 meters thick on the hanging wall, but thins in the fault zone due to erosion. Overlying Unit 4 is a series of four poorly sorted stony silts (Units 5a-5d) that are restricted in lateral extent, and appear to be derived from erosion of underlying Units and redeposition as scarp-derived colluvium. Units 5b and 5d are atop the main normal fault and look like proximal colluvial wedges derived from Units 1 and 5. Unit 5a is colluvium disturbed by shearing of a younger event, and may be partly composed of fissure fill. Unit 5c, in contrast, has a much higher silt content in the matrix and is inferred to be wash-facies colluvium mainly derived from erosion of Unit 4 exposed in the footwall free face.

West of the toe of the scarp, the surface soil is developed on Unit 4c. However, at the toe of the scarp the organic material that defines the surface soil is split by Unit 6b, with the thicker section of organics underlying Unit 6b in Unit 5cAB, and the thinner section of organics overlying Unit 6b in Unit 6bA. From this relationship, it appears that most of the surface soil developed over a long period of time that predates the deposition on Unit 6b, but that a small part of surface soil (Unit 6bA) formed after the deposition of Unit 6b.

The youngest unit in the trench overlies the fault and is comprised of a debris-facies colluvial wedge on the scarp face (Unit 6a) and clast-free, wash-facies silt at the base of the scarp (Unit 6b). A very weak soil (A horizon only) is developed atop Unit 6b at the toe of the scarp, as previously described. The trench log shows that Unit 6b pinches out about 8 m west of the scarp toe, and thus apparently interfingers with the surface soil developed on Unit 4 (Unit 4cA). In actuality, the upper part of Unit 4cA west of the pinchout is probably developed on a parent material contemporaneous with Unit 6, but the younger deposit (probably an eolian admixture) is obscured by the high content of organic material in the surface soil A horizon and could not be mapped as a separate unit.

Structure: The deformation zone in this trench is composed of nine faults in a fault zone 7 meters wide (figure 17). The cumulative throw on these faults is 8.7 meters, a value greater than the scarp height of 6.5 to 7 meters. This difference is explained because the hanging wall is buried by up to 1.5 meters of loess that is not present on the footwall, at least not near the scarp crest. The main normal fault is composed of strands F1 and F2 (figures 18, 19), which together account for 5.0 of the 8.3 meters of total throw (table 4). Faults F2 and F6 bound a perched structural block of fractured Unit 1 gravels, with the top of Unit 1 dropping down 1.5 meters to the west across F6, which is partly a tension fissure. Presumably, faults F3 through F6 all merge with the main normal fault about 3 meters below the floor of the trench.

The contact between Unit 1 and Unit 5 that dips 60° and projects upward from F1 and F2 is interpreted as a buried fault free face. Faults F1 and F2 evidently steepen to near-vertical about 2.5 meters below the ground surface, and then post-faulting erosion has laid back the scarp to a lower angle, after which it was buried by colluvium (Unit 6). Faults F1 and F2 displace Unit 5 but not Unit 6, implying that Unit 5 is colluvium shed after the penultimate faulting event (PE) and Unit 6 is colluvium shed after the most recent faulting event (MRE).

Geochronology: The lower part of the A horizon of buried soil 1 (Unit 3Ab1) yielded a ^{14}C age of 9150 ± 110 ^{14}C yr BP (10,400 ± 130 cal yr BP), indicating that the beach here (Unit 2) was abandoned before 10.4 cal ka, and Unit 4 loess was deposited after 10.4 cal ka (accounting for several hundred additional years in the upper half of buried soil 1). The top of Unit 4 yielded a thermoluminescence (TL) age estimate of 2.5 ± 0.5 ka, indicating that the 1.1 to 1.3 meters of loess was deposited over a period of ca. 8 ky (2.5 ka to 10.4 cal ka). The base of the MRE colluvial wedge (Unit 6) contained dispersed organic material (perhaps reworked from a soil exposed on the MRE free face) that dated at 2130 ± 80 ^{14}C yr BP (2119 ± 220 cal yr BP). Finally, the soil buried by Unit 6b (wash-facies colluvium) at the scarp toe dated at 580 ± 70 ^{14}C yr BP (586 ± 80 cal yr BP).

Interpretation: The trench exposes evidence for two faulting events, based on the existence of two colluvial wedges

Table 2. *Radiocarbon ages from North Eden Creek.*

Trench	Lab. No.	Material	Lab. Age (^{14}C yr BP) 1-sigma error	Calibrated Age (cal. yr BP) 1-sigma error	Significance
eastern	B-33403	Organic silt	12,780 ± 140	15,150 ± 760	Predates PE on E scarp
western	B-33400	Buried A horizon	9150 ± 110	10,400 ± 130	Predates PE on W scarp
western	B-33401	Colluvial wedge, weakly organic	2130 ± 80	2119 ± 220	Closely dates MRE on scarp W
western	B-33402	Buried A horizon	580 ± 70	586 ± 80	Postdates MRE on W scarp
Gravel pit	B-33399	Charcoal-rich silt	9100 ± 90	10,235 ± 310	Predates PE on W scarp
Gravel pit	B-33404	Snail shells	12,700 ± 130	15,342 ± 1082	Predates PE on W scarp

Table 3. *Thermoluminescence ages from the North Eden Creek site.*

Trench	Lab. No.	Stratigraphic Unit	Equivalent Dose[1] (Gy)	TL Age[2] (ka)
western	OTL-452	Loessy colluvium	8.2 ± 1.0	2.5 ± 0.5
eastern	OTL-514	colluvium	144.2 ± 2.6	39 ± 3
eastern	OTL-513	colluvium	112.0 ± 26.3	31 ± 6
eastern	OTL-512	Loessy colluvium	35.9 ± 2.8	10 ± 1.0
eastern	OTL-511	Loessy colluvium	29.4 ± 2.1	9.0 ± 1.0
eastern	OTL-453	Loessy colluvium	19.3 ± 1.8	5.0 ± 0.5

[1] All TL measurements were made with a 5-58 filter (blue wavelengths) and HA-3 filters in front of the photomultiplier tube. Samples were preheated to 124 degrees Celsius for 2 days prior to analysis. The total bleach method was used for all samples, based on 16 hours of natural sunlight exposure in Columbus, Ohio. Equivalent dose was calculated for the temperature range 250-400 degrees Celsius, except for samples OTL-452 (240-390 degrees Celsius) and OTL-513 (250-350 degrees Celsius).

[2] All errors are at one sigma and calculated by averaging the errors across the temperature range.

and on crosscutting relations. The older event (Event Y) shed colluvium Unit 5, subunits of which both fill a fissure in Unit 4c (5a) and overlie Unit 4c (5c), so that this event must postdate Unit 4, the top of which is TL-dated at 2.5 ± 0.5 ka. The younger event (Event Z) was immediately followed by deposition of Unit 6a, the base of which yields an age of 2119 ± 220 cal yr BP.

Taken at face value, these ages appear to constrain both Events Y and Z to the period after 2.5 ± 0.5 ka but before 2119 ± 220 cal yr BP. For example, there is no soil developed on Unit 5 beneath Unit 6, suggesting that the time between Events Y and Z was insufficient for soil formation. In contrast, there is no stratigraphic evidence (such as colluvial wedges or fissure fills) for any displacement events between 10.4 cal ka (when Unit 4 began to be deposited) and 2.5 ka. The Unit 4 loess maintains a constant thickness and uniform grain size right up to the fault zone, which suggests that no topographic scarp existed here at the time of its deposition.

Of the net 8.7 meters of fault throw, it is difficult to estimate how much occurred in Event Y versus Event Z. Across fault F6 the top of Unit 1i is displaced 1.2 meters, whereas the Unit 4c/5c contact is displaced only 0.6 meters. The 0.6 meter displacement of Unit 5c must have occurred during Event Z, which implies that the displacements during Events Y and Z were an identical 0.6 meters. A different argument can be used on the main normal fault (F1/F2), where the net throw is 5.0 meters and the post-Event Z colluvium (Unit 6) reaches a maximum thickness of 1.3 meters. If we assume that the maximum thickness of colluvium is half the height of the free face, then the Event Z free face on F1/F2 would have been about 2.6 meters high. This value is about half of the net throw of 5.0 meters, again suggesting that the Event

__Figure 15.__ Photograph of the backhoe excavating the trench on the western fault scarp at North Eden Creek. View is to the north, with Bear Lake visible in the middle distance, and Merkely Mountain in the right distance.

__Figure 16.__ Photograph of the western trench at North Eden Creek, looking east. The eastern fault scarp is barely visible beyond the top of the trench.

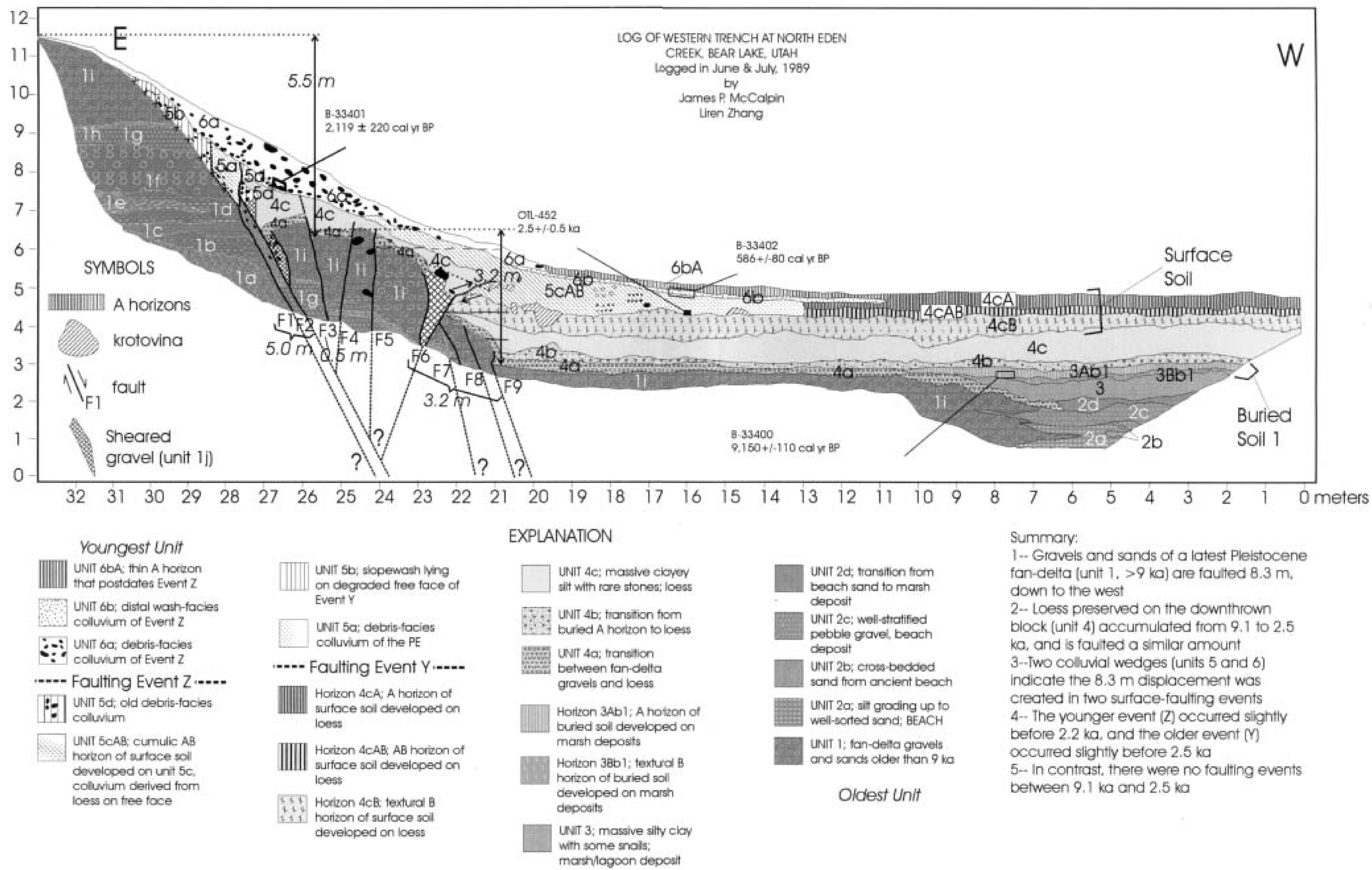

Figure 17. *Log of the western trench at North Eden Creek. Expanded unit descriptions are contained in appendix 1.*

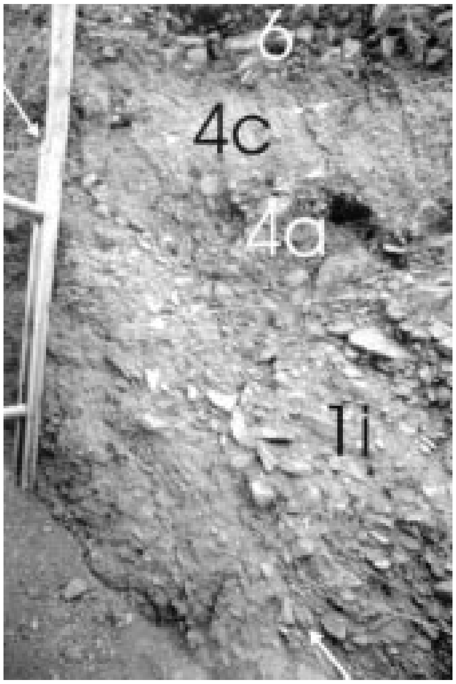

Figure 18. Photograph of fault zone F1 (between white arrows) in the western trench at North Eden Creek. Trench units on the hanging wall are numbered.

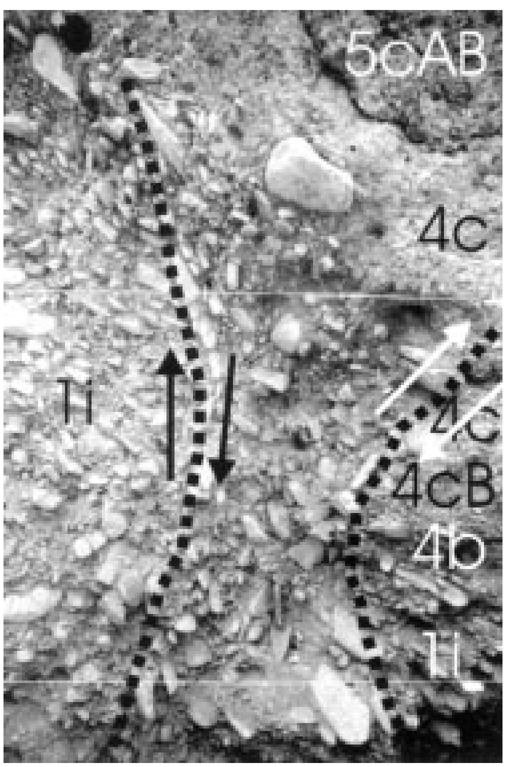

Figure 19. Close-up photograph of fault zone F6 (between dotted lines) in the western trench at North Eden Creek. Numbers of trench units correlate with those on figure 17.

Table 4. Estimated displacements during the latest two paleoearthquakes on fault strands exposed in the western trench at North Eden Creek.

Fault Strand	Displacement during the MRE (m)	Displacement during the PE (m)	Total Displacement (m)
1+2	2.5	2.5	5.0
3	0.5	0	0.5
4 +5	0	0	0-- cancels
6	1.0	1.0	2.0
7	~0.2	~0.2	~0.4
8	0?	0?	0?
9	~0.4	~0.4	~0.8
Totals	4.6	4.1	8.7

Y and Event Z displacements were similar. Based on these observations, I estimate the displacement on each fault strand (or zone) in Events Z and Y (table 4).

The chronology of faulting can be represented on a slip history diagram (figure 20). In this diagram the TL age estimate of 2.5 ka is considered as erroneous, and the age of the PE (Event Y) is taken to be 5 ka, which is the age of the youngest paleoearthquakes dated in the eastern trench. By making this assumption (discussed at length later), slip rates are estimated as 1.6 mm/yr for the closed Event Z seismic cycle, < 0.76 mm/yr for the open Event Y seismic cycle, and < 1.0 mm/yr for the combined (also open) cycles.

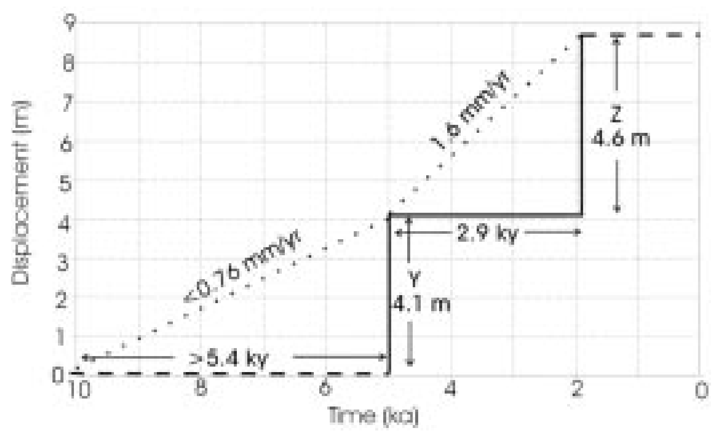

Figure 20. Slip history diagram for the western trench at North Eden Canyon. Vertical heavy lines indicate displacements in Event Z (4.6 m at 2.1 ka) and Event Y (4.1 m at 5 ka). Slip rates (heavy dotted lines) range from 1.6 mm/yr (Event Z cycle, closed cycle) to less than 0.76 mm/yr (Event Y cycle, minimum value for this open seismic cycle).

Eastern Trench

I excavated the eastern trench across the eastern fault scarp directly east of and upslope of the western trench, where the eastern scarp is about 13 meters high and the scarp toe lies very close to a road (figure 21). The trench was 32 meters long, 1 meter wide, and from 2.3 to 5.0 meters deep (figure 22). Due to the proximity of the road to the scarp toe, I was not able to excavate as far into the hanging wall sediments as I had hoped.

Figure 21. *Photograph of the eastern fault scarp (between small arrows) and trench (between large arrows) at North Eden Creek, looking southeast.*

Figure 22. *Photograph of the head of the eastern trench at North Eden Creek, looking west. Gravels visible at the head of the trench are fan-delta gravels older than 39 ka, which now lie at an elevation of about 1829 m (6000 feet), or about 23.5 m (77 feet) above the modern level of Bear Lake.*

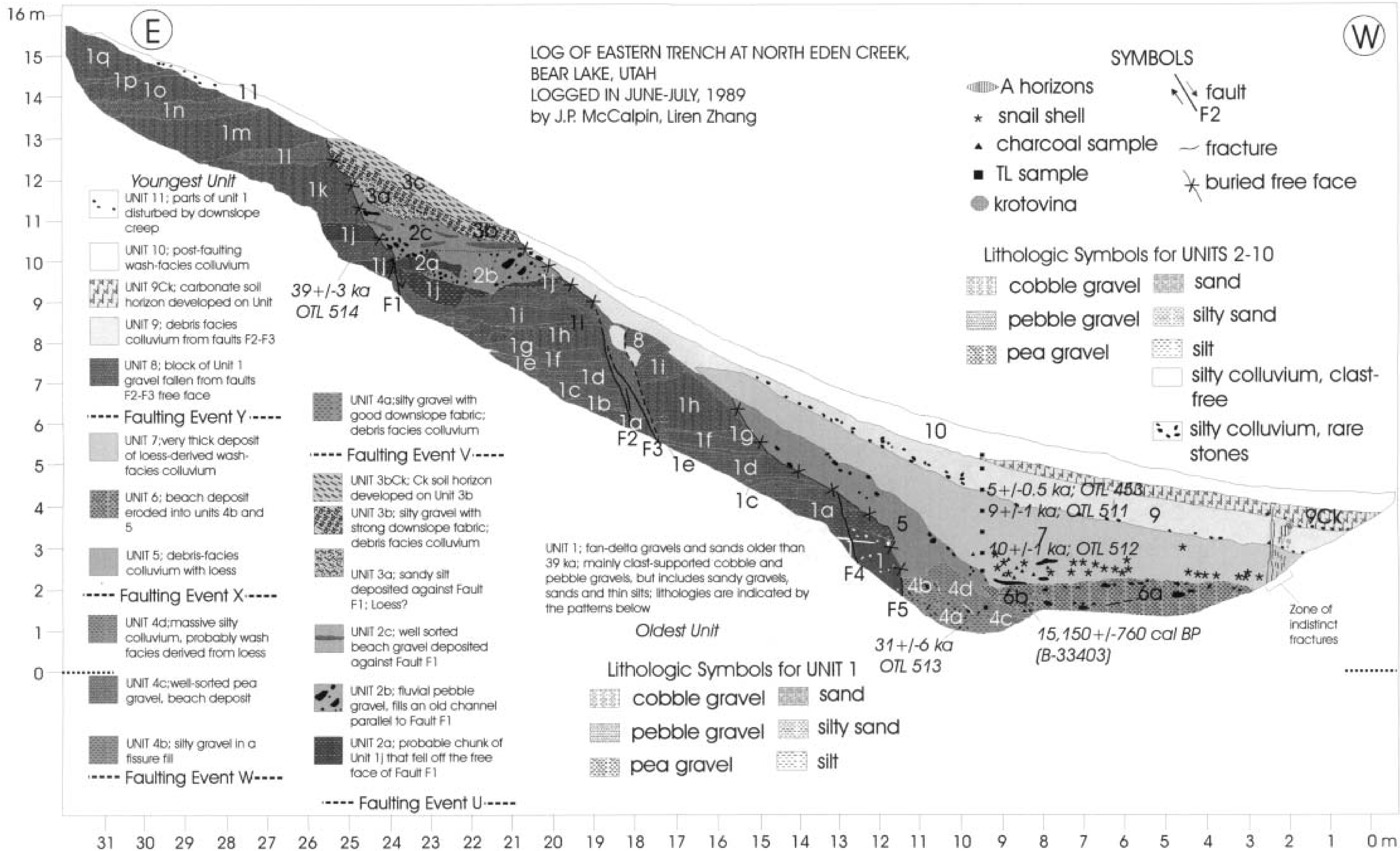

Figure 23. *Log of the eastern trench at North Eden Creek. Expanded unit descriptions are contained in appendix 2. OTL labels indicate TL samples processed at Ohio State University.*

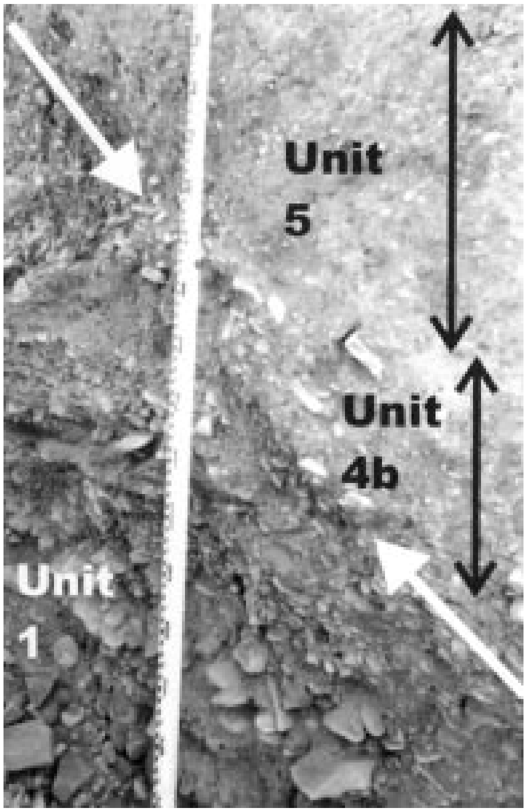

Figure 24. *Photograph of the eroded and buried fault free face upslope from the western fault zone in the eastern trench at North Eden Creek. The buried free face (between arrows) is a depositional contact between units 4a and 7 (colluviums) and unit 1 (faulted fan-delta gravels older than 39 ka). Stadia rod is numbered every 10 centimeters.*

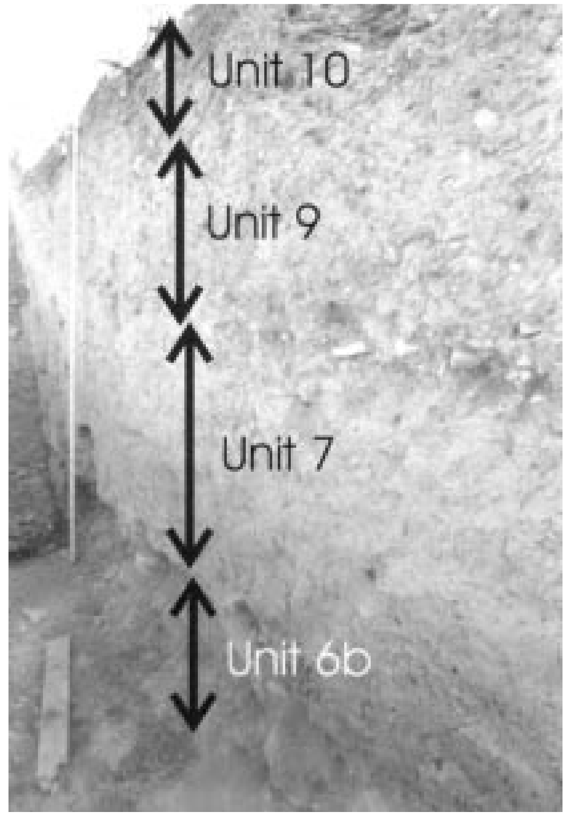

Figure 25. *Photograph of the eastern trench at North Eden Creek, looking east from the toe of the trench. The trench wall here exposes a nearly 2 m thickness of unit 7 (loess-rich colluvium), overlain by unit 9 (scarp-derived colluvium) marked by a basal stone line. The white stadia rod at left is 4.5 m long.*

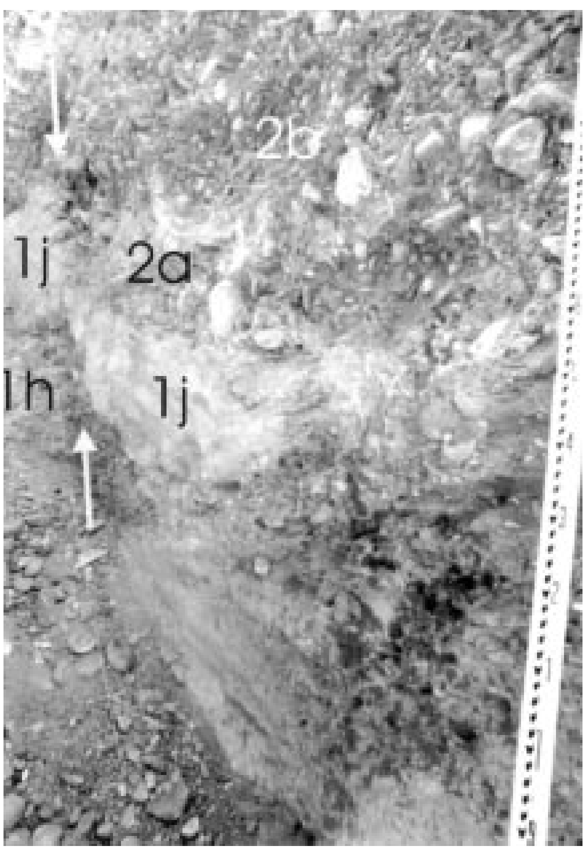

Figure 26. *Photograph of the eastern fault zone in the eastern trench at North Eden Creek. The main fault trace is shown by the white arrows at left, and displaces unit 1j down to the right (west) 1.9 to 2.1 m. Stadia rod at right is numbered every 10 centimeters.*

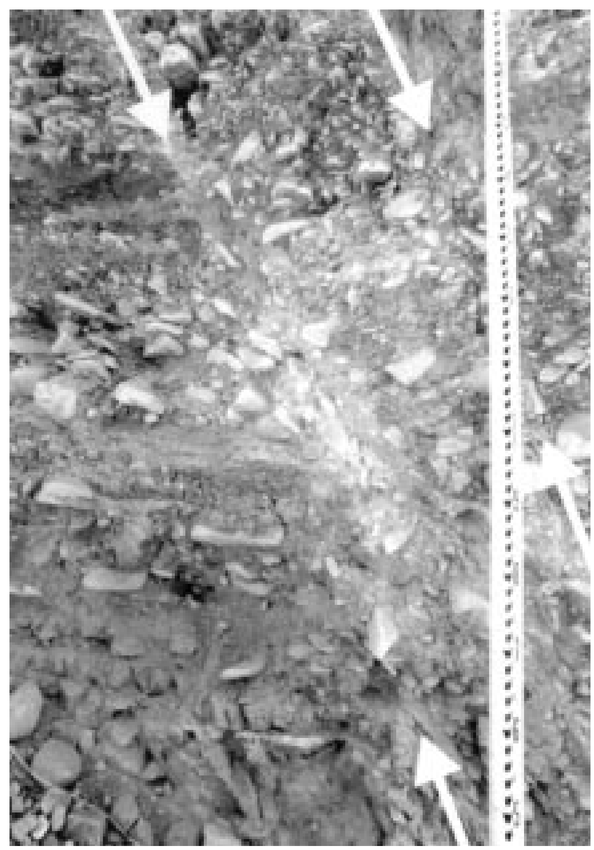

Figure 27. *Photograph of the central fault zone in the eastern trench at North Eden Creek. The two main fault traces are between the white arrows. Note the zones of aligned clasts rotated to parallelism with the faults by dip-slip shear motion. Stadia rod at right is numbered every 10 centimeters.*

Stratigraphy: I divided deposits in the trench into 11 major units and 32 minor units. Unit 1 (subdivided into 18 minor units labeled 1, and 1a through 1q) is composed of a series of alternating beds of well-sorted, well-stratified cobble to pebble gravel, sand, and rarely, silt (figure 23). As in the western trench, I interpret this unit as fan-delta deposits (unit Qd_1 on figure 12), transported from east to west.

Unit 2 is a series of lens-shaped fluvial gravels, sands, and silts that appear to represent fluvial transport in a channel parallel to the fault scarp (figure 23). In addition, individual beds appear to be affected by soft-sediment deformation and input of a colluvial component from the east (site of fault F1). Unit 2 is overlain by a wedge-shaped deposit of silty to stony colluvium (Unit 3), which is now "perched" anomalously three-quarters of the way up the scarp face. I interpret the couplet of Units 2 and 3 to represent the fluvial and later colluvial infill of an active delta channel that was formed after faulting (Event U) on Fault F1.

Unit 4 is a complex unit that includes scarp-derived colluvium from at least two faulting events, but age relationships are obscure. The oldest part of Unit 4 (Unit 4a) is debris-facies colluvium shed from Fault F5. Unit 4b forms a fissure fill of similar composition that intrudes into Unit 4a, so was presumably formed during a later earthquake than was responsible for deposition of Unit 4a. Unit 4b also truncates the eastern edge of Unit 4d, described later. From these geometric relationships, and the fact that Fault F5 has a total throw of 11.3-11.5 m, Unit 4 presumably contains deposits of at least two paleoearthquakes, one of which (Event V) predates Unit 4a, and the other which postdates Unit 4a (Event W). I also included in Unit 4 two deposits that are clearly younger than Event W, the older of which (Unit 4c) is a beach gravel eroded into the top of the Unit 4a colluvial wedge. After this beach was abandoned, the scarp toe was buried by a silty slopewash deposit (Unit 4d). Because Units 4a and 4b are faulted against Unit 1, and Unit 4d is internally deformed, they were all deposited before the latest displacement event (Event X) on Fault F5.

Overlying Unit 4 is a thick deposit of silty colluvium (Unit 5), which lies unconformably on a large buried free face cut on Unit 1, above Fault F5. The location and shape of this deposit imply it is scarp-derived colluvium shed from a free face of Fault F5, and the fact that it is in depositional contact with Unit 1 implies it was deposited after the latest faulting event (Event X) on Fault F5.

At the toe of the trench, Unit 6 is composed of well-sorted, horizontally stratified gravels and sands, probably deposited at a beach. Traced westward, this deposit would correlate with Unit 1 at the head of the western trench. Unit 6 cuts laterally into Units 4d and 5, suggesting that the beach/shoreline was cutting into the toe slope of preexisting scarp-derived colluvium.

Overlying Units 5 and 6 is a very thick, silt-rich colluvial wedge (Unit 7; see figure 24). This wedge pinches out about halfway up the scarp, does not contain a basal concentration of stones, nor does it coarsen upslope toward a paleo-free face. Therefore, it is likely that this colluvium is not derived from a post-faulting free face in Unit 1 gravels, but instead represents loess that was blown onto and above the fault scarp, and redeposited at the scarp toe.

Unit 8 is a small block of gravel beneath the center of the scarp that probably fell intact into a fissure during the MRE (Event Y). Downslope from this mid-scarp fissure and fault, a long, thin colluvial unit (Unit 9) extends to the scarp toe. In contrast to Unit 7, this colluvium coarsens upslope to the suspected source free face at mid-scarp, and contains a basal concentration of clasts. Hence, I interpret Unit 9 as scarp-derived colluvium deposited after Event Y. At the toe of the scarp, the upper part of Unit 9 contains a weak carbonate-rich soil horizon (Unit 9Ck), probably formed by infiltration of runoff at the toe of the fault scarp.

Unit 10, a silty, stone-free colluvium, mantles the scarp face and toe. As with Unit 7, this colluvium is interpreted as retransported loess. Unit 11 is mapped only on the crest of the scarp and is actually a retransported component of Units 1m through 1q, which has crept slightly down the scarp face under the influence of gravity.

Structure: This trench exhibits three widely spaced fault zones of different ages (figure 23). The eastern fault zone (F1; see figure 25) is a poorly defined zone of minor fractures and warping with a net throw of 1.2 meters in Unit 1. The central fault zone (F2 and F3; see figure 26) is a well-defined zone of down-to-the-west normal faulting with shear rotation of gravel clasts; net throw is 1.9 to 2.1 meters. The western fault zone (F4 and F5; see figure 27) consists of two discrete faults, the eastern of which (F4) has very small displacement. Throw on strand F5 cannot be measured directly, because Unit 1 is not exposed on the hanging wall. However, projection of the top of Unit 1q westward, and measurement from that projection to the bottom of the trench, indicates that net throw on all three fault zones must be at least 14.6 meters. Because the eastern and central fault zones account for only 3.1 to 3.3 meters of net throw, fault strand F5 must account for the remainder, or at least 11.3 to 11.5 meters of throw.

At the extreme western end of the trench, a zone of indistinct fractures extends from the bottom of the trench (Unit 7) up through Unit 9, but cannot be traced through the soil horizon 9Ck. The fracture zone does not displace the Unit 7/9 contact vertically. It is not clear whether the fractures are tectonic, or whether they represent some localized differential compaction at the toe of the scarp. If the fractures are tectonic, they must have formed during an event younger than Event Y in this trench, because they extend through the colluvium shed after Event Y (Unit 9). That faulting event might have been the event recognized as Event Z in the western trench, which is dated about 2.1 ka. Table 5 summarizes the paleoearthquakes interpreted for this trench and the displacement on each fault strand during each paleoearthquakes.

Geochronology: The five TL and one ^{14}C age estimates from the eastern trench provide a consistent stratigraphic chronology, albeit older than the chronology in the western trench. Units 3a and 4d yielded TL age estimates of 39 ± 3 ka and 31 ± 6 ka, respectively. The entire Unit 1 (footwall) stratigraphic sequence in this trench is thus older than 39 ka. The top of Unit 6 yielded a ^{14}C age of 12,780 ± 140 yr BP (15,150 ± 760 cal yr BP), or about 16 ka younger than the age of Unit 4d, into which Unit 6 is cut. This age for Unit 6 is compatible with my correlation of Unit 6 in the eastern trench with Unit 1 in the western trench, based solely on elevation; Unit 1 there is significantly older than 10,400 ± 130 cal yr BP.

A vertical sequence of three TL samples from Units 7 and 9 yield stratigraphically consistent ages of 10 ± 1 ka

Table 5. *Estimated displacements during all paleoearthquakes exposed in the eastern trench (listed for faults F1-F5), total displacement in western trench, and combined "grand total" displacements for both fault scarps at North Eden Creek.*

Fault Strand	**Displacement (m)**						
	Event Z	**Event Y**	**Event X**	**Event W**	**Event V**	**Event U**	**Totals**
F1	0	0	0	0	0	1.2	1.2
F2+3	0	2.0	0	0	0	0	2.0
F4	?	?	?	?	?	?	0.1
F5	0	0	~3.8	~3.8	~3.8	0	>11.3
Total in E Trench	0	2.0	~3.8	~3.8	~3.8	1.2	>14.6
Total in W Trench	4.6	4.1	nd	nd	nd	nd	8.7
Grand Total	4.6	6.1	~3.8	~3.8	~3.8	1.2	>23.3

(bottom), 9.0 ± 1.0 ka (middle), and 5.0 ± 0.5 ka (top). These ages, combined with the 15.2 cal ka age of the subjacent beach, suggest that a long period of loess deposition dominated this landscape, beginning about 15.2 cal ka and lasting at least until 5 ka. That age overlaps with the long period of loess deposition (2.5 to 10.4 cal ka) inferred from the western trench.

Interpretation: The trench log and geomorphic observations indicate a long history of deposition, faulting, and colluviation at this site. First, Unit 1 was deposited as a series of beach and fan-delta gravels before 39 ka. While the site was still near lake level, the first faulting event (Event U) occurred on strand F1 (throw = 1.2 meters). Surface faulting of the soft, wet deltaic sediments opened up a north-trending structural trough into which the active stream channel was diverted, depositing Unit 2. This stream deposited the lenticular gravels of Unit 2 and cut the channel into which Unit 3 colluvium was later deposited. Because such a channel could only exist at the base of the fault scarp, its existence argues that no vertical movements had yet occurred on fault strands F2 through F5.

Sometime later (but before 31 ka) faulting began on the western fault zone (F4 and F5). The > 11.3 to 11.5 meters of throw must represent at least three ca. 4-meter faulting events, the oldest of which (Event V) created the free face from which Unit 4a was deposited, and the middle of which (Event W) created the fissure in Unit 4a that filled with Unit 4b. The youngest event (Event X) then faulted both Units 4a and 4b. Thus, the two earlier events on strand F5 (Events V, W) are younger than 39 ka but older than 31 ka, while the latest event (Event X) is younger than 31 ka but much older than 15.2 cal ka. An alternative scenario would only call for two paleoearthquakes between 15.2 and 31 ka (W and X), but that requires very large displacements (11.4 m in 2 events, or 5.7 m average per event).

Following these faulting events, the scarp free face above Fault F5 retreated upslope and Unit 4b colluvium was deposited against Unit 1 on the degraded free face. By this time (before 15.2 cal ka) the scarp had attained most of its present height (that is, 12.5 to 12.7 m of the present 14.6 m).

Following deposition of Unit 5, the lake level rose and an active shoreline began to erode the base of the scarp. This erosion removed much of the distal (western) part of Units 4 and 5 (note the oversteepened nature of the Unit 5/7 contact) and left a one-meter-thick lag gravel with interbedded beach sands and shell fragments (Unit 6). This beach deposit contains shells and charcoal dated at 15.2 cal ka here, and dated at 10.2-15.3 cal ka in a nearby gravel pit (described previously). After the beach was abandoned near 15.2 ka, the lower part of the scarp was buried by a thick wedge of silt (Unit 7).

After Unit 7 was deposited (from 5 to 10 ka), a final faulting event (Event Y) on the central fault zone (F2 and F3) created a 1.9- to 2.1-meter-high free face with a basal tension crack. This event also created the ca. one-meter-high degraded scarp that crosses the Qd_2 surface of North Eden Creek. A block of Unit 1 fell off the free face and into the crack (Unit 8), but the bulk of colluvium was shed down the steep scarp slope below the free face, creating the coarse basal part of Unit 9. This event occurred about 5 ka, based on the TL age of the basal scarp-derived colluvium. Subsequently a weak Ck soil horizon formed on the distal part of Unit 9. Finally, post-faulting colluvium covers the modern scarp face (Units 10, 11).

Discussion of Faulting on the Southern Section of the EBF

Structural relations in the two trenches indicate that six faulting events have occurred at this site in the past ca. 40 ka, of which the earliest four ruptured the eastern fault trace and the later two of which ruptured mainly the western fault trace. This sequence of events is compatible in general with the geomorphic evidence (described earlier) that the western fault scarp formed after movement had nearly ceased on the eastern fault scarp. The timing of events is summarized on a space-time diagram (figure 28). Based on a strict interpretation of the numerical ages, the youngest event from the eastern trench (ca. 5 ka) must be older than both the events in the western trench (both younger than 2.5 ka). However, this interpretation raises some puzzling questions: (1) how was the EBF fault able to accumulate enough strain for two large-displacement events in less than 2500 years, and maybe less than 2000 years, compared to a mean recurrence of ca. 7 ky?, and (2) why did neither of these large-displacement events cause any faulting on the eastern scarp? A simple explanation of this dilemma is that the earlier event on the western fault is older than 2.5 ka, and in fact is the same event as the youngest event on the eastern fault (ca. 5 ka). Such an expla-

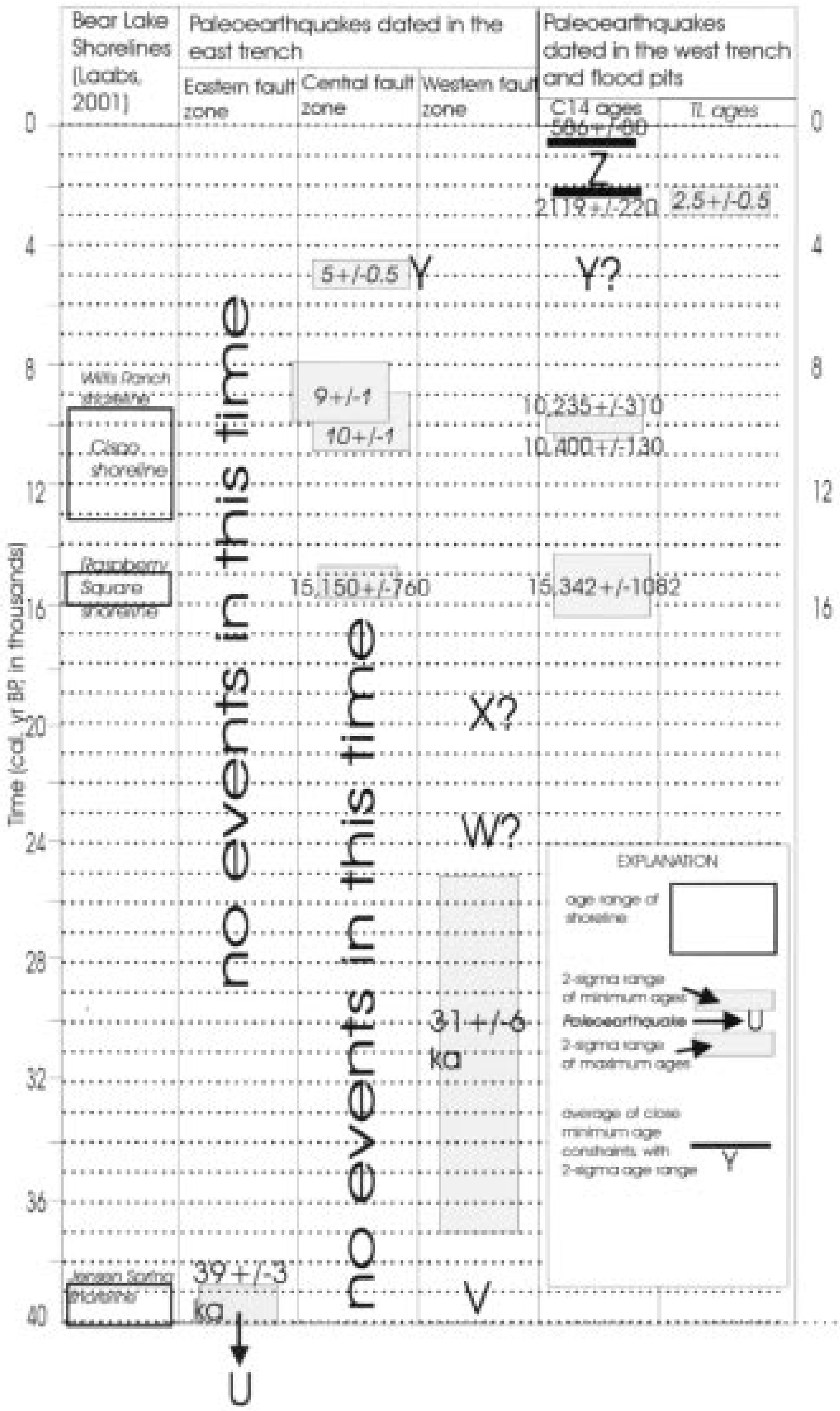

Figure 28. Correlation chart of depositional and faulting events exposed at North Eden Creek.

nation requires two events on the western fault in the past 5 ka, rather than in only the past 2.5 ka.

As appealing as this hypothesis is, it requires disregarding the TL age estimate of 2.5 ± 0.5 ka from the western trench (base of Unit 5c). One reason to question the accuracy of that TL age estimate is the stratigraphic context of the sample. The stratigraphic setting of the sample dated at 2.5 ± 0.5 ka in the western trench is very similar to that of the TL sample dated a 5 ± 0.5 ka in the eastern trench. Both samples come from the first silt-enriched scarp-derived colluvium, shed from erosion of a silt-mantled fault scarp fault free face, after a long period of loess accumulation that began ca. 10-15 ka. It is possible that the TL sample from the western trench was inadvertently collected from younger material disturbed by animal burrowing; however, such an explanation could be made for other TL samples as well.

Another geochronologic discrepancy is the age of beach abandonment compared among the eastern trench (15.2 cal ka), the western trench (10.4 cal ka), and the gravel pit (10.2 to 15.3 cal ka). Due to the age discrepancy between soil organics (10.2 cal ka) and shells (15.3 cal ka) from the same stratum in the gravel pit, it is unclear whether the gravel pit beds correlate with the 15.2 cal ka beach exposed in the eastern trench, or with the 10.4 cal ka beach exposed in the western trench. The simplest explanation for these diachronous dates is that the beach and fan-delta sediments in all three exposures are the same age (15.2 to 15.3 cal ka) and the younger ages of 10.2-10.4 cal ka on soil organics represent soil formation somewhat younger than the abandonment of the beach. This explanation does not explain why shells and soil organics from the same 30-centimeter-thick bed in the gravel pit yield such different ages (10.2 versus 15.3 cal ka), unless the shells were reworked from a nearby 15.3 cal ka beach deposit and redeposited in the marsh. A geologic section through all three exposures (figure 13b) indicates that the beach deposits in the eastern trench (15.2 cal ka) project to about the same elevation as the bottom of the marsh deposits in the gravel pit, suggesting a physical correlation. The corresponding marsh and beach deposits in the western trench would then be explained as the downfaulted equivalent of the deposits described above, downfaulted approximately 8 meters since 10.4 cal ka.

A second possibility is that the marsh and beach deposits in the western trench are younger than those exposed in the eastern trench and gravel pit. In this scenario, a beach lapped up against the base of the eastern fault scarp at 15.2 cal ka, and then faulting on the western fault raised that beach above water level. Subsequently a new beach formed at the base of the western scarp, and that younger beach was finally abandoned by lake recession ca. 10.4 cal ka. In this interpretation, unit 1 on the hangingwall of the western trench is a younger deposit than unit 1 on the footwall, as suggested by Reheis (personal communication, 2002).

My preferred interpretation is that there is a single, late Pleistocene beach here, occupied beginning about 15.2-15.3 cal ka and abandoned prior to 10.4 cal ka. Due to faulting, the beach deposits are now found at an elevation of about 1814.5 meters west of the western scarp and at an elevation of about 1823.9 meters east of the western scarp. The former elevation is similar to the elevation of 5945 ± 10 feet (1812.1 ± 3 m) cited by Robertson (1978) for his Liberty episode of Bear Lake, which he correlated with the Pinedale glaciation (ca. 15-30 ka). The latter elevation is similar to the elevation of 5990 ± 10 feet (1825.8 ± 3 m) cited by Robertson (1978) for the Ovid episode of Bear Lake, which he dated at 27.4 uncal ka. Clearly, the 15.2 cal ka beach deposit found in our eastern trench has been uplifted at least 8.7 meters relative to Bear Lake by faulting on the western fault scarp, so determining its age merely from elevation must take that faulting into account.

The preferred history of slip on both fault strands at North Eden Creek (figure 29) shows an irregular pattern. The latest closed seismic cycle (Event Z cycle) released 4.6 m of slip after an accumulation period of only 2.9 ky, yielding a high slip rate of 1.6 mm/yr. The prior (Event Y) seismic cycle, in contrast, released 6.1 m of slip after an accumula-

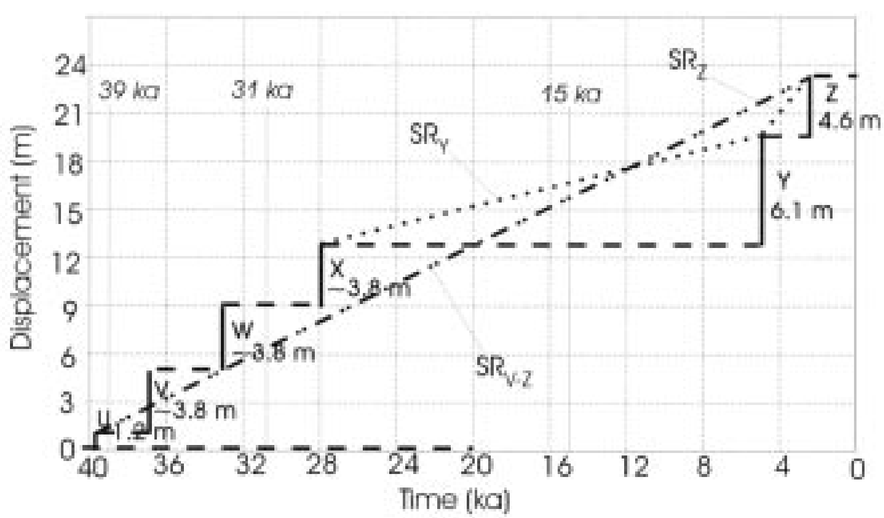

Figure 29. *Slip history diagram for both fault strands at North Eden Creek. Heavy vertical lines indicate paleoearthquake displacements, heavy dashed horizontal lines indicate time elapsed between paleoearthquakes. Exact displacement values for Events V, W, and X are unknown, but their sum is at least 11.4 m; their exact ages are also unknown, but are bracketed as shown by numerical ages of 39, 31, and 15 ka. Their time placement in this diagram is thus somewhat arbitrary. Closed-cycle slip rates can be computed for the Event Z cycle (SRZ, 1.6 mm/yr), Event Y cycle (SRY, ~0.26 mm/yr), and the average of time between Events V and Z (SRV-Z, >0.58 mm/yr).*

tion period of at least 10.2 ky (15.2 ka minus 5 ka), and probably nearer to 23 ky. The latter time span yields a slip rate of 0.26 mm/yr. The slip rates of seismic cycles V, W, and X cannot be computed individually; all we know is that > 11.4 m of strain began accumulating after 39 ka and was released between 31 ka and 15 ka. The long-term average slip rate spanning the past 5 closed seismic cycles (V through Z) is ≥ 0.58 mm/yr (≥ 22.1 m/38 ky).

QUATERNARY FAULTING ON THE WESTERN BEAR LAKE FAULT ZONE

The western Bear Lake fault zone (WBF) is defined broadly as a zone of down-to-the-east and down-to-the-west normal faults on the western margin of Bear Lake Valley. However, well-preserved Quaternary fault scarps exist only in the central section of the WBF, as a 20-kilometer-long, 3-kilometer-wide swarm of low fault scarps in swampy terrain between St. Charles and Ovid, Idaho (figure 5). I did not study the southern and northern sections of the WBF in detail, so this discussion will only describe the scarps in the central section.

Tectonic Geomorphology

The western margin of Bear Lake Valley between St. Charles and Ovid, Idaho is defined by a north-trending bedrock escarpment carved on Paleozoic sedimentary rocks, which is much more embayed than the straight range front of the eastern valley margin. The contact of Quaternary deposits with bedrock closely follows the 1829 meter contour line, about 400 to 800 meters west of U.S. Highway 89, and coincides with the high shoreline of the Ovid episode of Robertson, 1978 (elevation 5990 ft [1825.8 m], age 27.4 uncal ka). I did not observe any Quaternary fault scarps at the bedrock/Quaternary contact, so presumably the contact represents a depositional onlap rather than a fault contact.

The fault scarps of the WBF lie 0.15 to 1.5 kilometers east of U.S. Highway 89, slowly diverging from the highway northwards. The largest scarp in the WBF is on the western edge of the scarp swarm and was named the “Bloomington Scarp” by Robertson (1978). This east-facing scarp is up to 6 meters high and displaces the swampy valley floor between St. Charles and Paris, Idaho. The scarp cannot be traced across the mouths of Spring Creek, Bloomington Creek, or Paris Creek, leaving a gap 400 to 800 meters wide at each location. In these gaps, late Holocene stream activity has destroyed the scarp.

Trenches In the Central Section at Bloomington, Idaho

In October 1989 I excavated two small backhoe trenches across the Bloomington scarp.

Geomorphology of the Trench Site

Directly east of Bloomington, Idaho, the fault scarp trends slightly east of north and displaces geomorphic surfaces of two ages (figure 30). The higher faulted surface lies between elevations of 1829 meters on the west and 1814 meters on the east and is dissected by east-trending gullies 1.5 to 3 meters deep. According to Robertson (1978), this surface is an old lake floor and is mantled by the post-lacustrine Wardboro Loess (early Holocene?). Several small

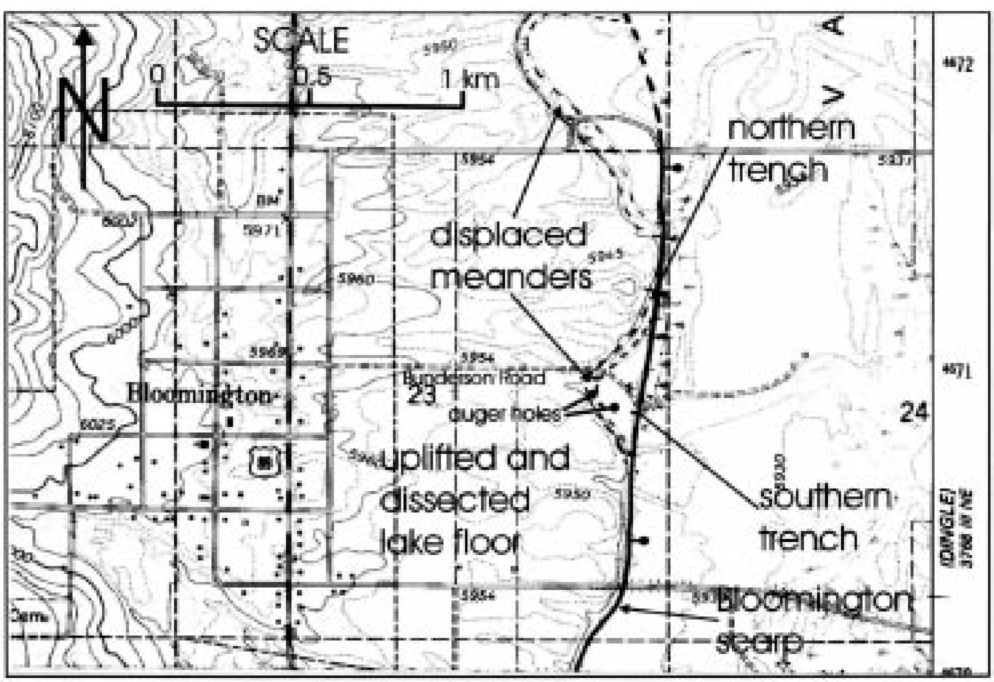

__Figure 30.__ Map of the Bloomington scarp and trench site. Base map from the Paris, Idaho 7.5’ quadrangle. Solid contours at 20-foot intervals, dotted contours at 5 foot intervals. The downthrown block of the Bloomington scarp (right one-third of figure) is occupied by a swamp with many meander bends and oxbow ponds. The upthrown block (center of figure) is a former lake floor, now dissected by east-trending gullies incised into the fault scarp. Parts of two meanders (labeled) were displaced by the MRE here and now lie on the upthrown side of the scarp. Terrain west of the 6000 foot contour is underlain by Paleozoic bedrock.

meandering streams flow northward along the Bloomington scarp, and in places have migrated laterally westward, eroding through the fault scarp. The streams and meanders form a younger, undissected valley bottom at about 1809 meters elevation. This younger valley bottom has subsequently been faulted on the Bloomington scarp, which led to stranding of the western parts of the meander bends on the upthrown side of the fault scarp. The scarp height on the older dissected surface is 6 to 8 meters and on the younger valley floor is 1.5 to 2.5 meters.

Prior to this study, Robertson (1978) constructed an east-west cross section from the town of Bloomington eastward across the Bloomington scarp, based on jet-rig drill holes (figure 31). His section shows that the Wardboro Loess beneath the higher geomorphic surface has been downfaulted about 6 meters. On the downthrown side, "undifferentiated" clayey sediments capped by peat bury the loess. I interpret these clayey sediments as post-faulting swamp deposits that accumulated after the downthrown side was depressed by faulting into the swamp.

I excavated two trenches and drilled two auger borings at this site. The northern trench cut into the scarp where it is 6 meters high in the older geomorphic surface, while the southern trench crossed the scarp on a younger floodplain where scarp height is only 1.5 meters (figure 30). I drilled the auger holes west of the southern trench, one in a meander channel truncated by faulting, and another in the younger floodplain that contains the meander.

Northern Trench

The northern trench was oriented east-west, and was 14.5 meters long, 1 meter wide (except where caved), and as much as 2 meters deep. On the downthrown block, trench depth was limited to about 1.5 meters by a high water table, and in fact the trench filled with water every night and had to be pumped out every morning (figure 32). Because this trench exposed only monoclinal folding and no well-preserved coseismic event horizons, the discussion below is brief and I include no detailed description of trench units in an appendix.

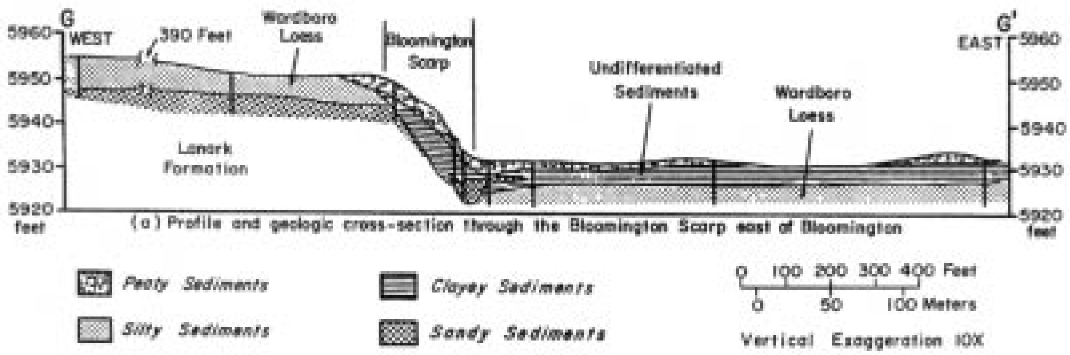

Figure 31. *Robertson's (1978) cross section through the Bloomington scarp, based on 9 drill holes (vertical lines). The western part of this drawn cross section contains a 390-foot-wide break on the upthrown block.*

Figure 32. *Photograph of the northern trench at Bloomington on the West Bear Lake fault zone. The widened part of the trench at the ladder is a section that caved in, when ground-water outflow from loose sands undermined the upper wall composed of cohesive silt and clay. This trench filled with water every 6 hours and had to be pumped out periodically in order to log the walls.*

Stratigraphy: The upthrown block (i.e., block west of the monocline) contained a transgressive-regressive sequence of lake deposits (figure 33), ranging from well-sorted beach sand (Unit 1a) to lagoonal (?) mud (Unit 1b), overlain by peaty mud (Unit 2a, marsh deposit) and loess (Unit 2b, the Wardboro Loess of Robertson [1975]; late Pleistocene). In contrast, the downthrown block contained a thinner bedded sequence of lenticular, interbedded clays, mud, peat, and buried soil A horizons (Units 3A through 8). Units 3A through 8 all pinch out on the fault scarp (onlap the monocline) and this geometry, together with their muddy and peaty textures, indicate they represent post-faulting deposits from the marsh that now occupies the downthrown block.

Structure: I observed no faults in this trench, but between 9 meters and 11 meters on the log (figure 33) Unit 1b (mottled lagoonal mud) abruptly steepens in dip and descends into the trench floor. Bedding planes in the mud steepen from an ambient 5 degrees to nearly 45 degrees at this point. Based on exposures in the southern trench, I believe that the Bloomington scarp at this location was created by monoclinal folding over a buried fault, in a manner similar to drape folding of bedrock over a steep fault.

Geochronology: I did not collect any samples for age analysis from this trench, despite the fact that units 2bA, 3A, 4A, 5A1, 5A2, 6A, 7A, and 8 all contained sufficient carbon for radiocarbon dating. My main reason for not dating samples from this trench was a lack of recognizable paleoseismic event horizons and resulting ambiguity in interpretation, as explained below. Therefore, the only age control is that for the Wardboro Loess on the upthrown block (Unit 2bA on figure 33).

Interpretation: I based the interpretation of this trench partly on the earlier drill hole transect of Robertson (1975; see figure 31) and partly on the trench log (figure 33). The geomorphic surface on the upthrown block is underlain by the Lanark Formation and Wardboro Loess, the latter of which is latest Pleistocene or earliest Holocene in age. According to figure 31, the Wardboro Loess has been displaced 6 meters vertically across the Bloomington scarp. It is unlikely that this 6-meter displacement was formed during a single surface-faulting earthquake, given the short (20 km) length of the central section of the WBF, and the discontinuous nature of fault scarps. However, due to the deformation style of monoclinal folding of plastic clayey sediments, no fault free faces formed during surface faulting and thus no colluvial wedges were deposited. Instead, nine lenticular stratigraphic units lap onto the scarp and none appear to contain scarp-derived material. Thus, I cannot associate the deposition of any of these mud units (Units 4, 5, 7) with tectonically induced deposition, or their associated soil A horizons (Units 3A, 4A, 5A1, 5A2, 6A, or 7A) with interseismic stability. The alternating deposition and soil formation that occurred on the downthrown block could have resulted from storm events, climatic changes, or drainage diversions unrelated to faulting. Slip rate estimates from the northern trench are crude. If the 6-meter scarp represents two Holocene faulting events (past 10 ky) of ca. 3 meters each, the longest possible span between them would be 10 ky, yielding a minimum closed-cycle slip rate of 0.3 mm/yr. Or, if two 3-meter events were equally spaced during the past 10 ky, say at ca. 9.9 and 5 ka, then a slip rate of 0.6 mm/yr would be indicated.

Southern Trench

I excavated the southern trench across the Bloomington scarp 1.2 kilometers east of the town of Bloomington, where the scarp transects a stream meander and is 1.5 meters high. The trench was about 5 meters south of a dirt road locally termed Bunderson Road. The trench was 10 meters long, 1 meter wide, and as much as 2 meters deep.

Stratigraphy: Deposits exposed on the upthrown block in this trench are beach sands (Units 1a-1e) and lagoonal (?) mud (Unit 2; see figure 34) that are similar to Units 1a and 1b in the lower part of the upthrown block in the northern trench. This situation was expected, because the alluvial surface comprising the upthrown block here is cut down 3 to 4 meters below the upthrown surface at the northern trench. Accordingly, stream meandering at this trench site had eroded away the upper part of the stratigraphic sequence seen in the footwall of the northern trench (mainly Unit 2bA, soil developed on the Wardboro Loess; figure 33), before this 1.5-meter-high scarp formed.

The upthrown block lacustrine deposits are overlain by a buried soil comprised of a textural B horizon (Unit 2B) and an A horizon (Unit 3A1). Between these two units in the far eastern part of the trench are two small clayey lenses (Units 3a, 3b) that were originally thought to represent deposits younger than Unit 2. However, I now consider them to more likely be discolored subunits of Unit 2. Unit 3A1 contains more silt than the underlying parent material of Unit 2 (sandy clay), and may contain some silt reworked from erosion of the Wardboro Loess. Both the A and B horizons are truncated by erosion beneath the scarp face, indicating that this soil formed before the scarp formed.

As in the northern trench, the downthrown block deposits (Units 4a, 4b) are lenticular and have no counterparts on the upthrown block. This geometry and their clayey texture suggest they are marsh deposits that postdate formation of the fault scarp. The entire scarp is mantled with a thick, cumulic soil A horizon (Unit A2) developed on a silty parent material of unknown origin (possibly a late Holocene loess). The upper part has been plowed (Ap horizon).

Structure: This trench displays both monoclinal folding in cohesive deposits (primarily Units 2a and 2b) and normal faulting. The main deformation zone lies in the center of the trench and displaces Units 1 and 2 by 1.75 meters down to the east (figure 34). However, normal faulting causes only about two-thirds of this net displacement; down-to-the-east monoclinal folding causes the other one-third (figure 35). Two types of liquefaction evidence are also present. First, sand from Unit 1 was injected upward along fault F1, to the level of Unit 2B. Second, Unit 3A1 on the downthrown block was cracked and segmented into discontinuous pods, probably by soft-sediment deformation during the earthquake.

Geochronology: I radiocarbon dated two samples from downthrown block strata (table 6). The older sample came from the deformed, pre-faulting soil horizon 3A1 and yielded an age estimate of 5900 ± 80 ^{14}C yr BP (6697 cal yr BP). The soil probably contained carbon with a mean residence age of several hundred years at the time of burial, so several hundred years would normally be subtracted from the 6.7 cal ka age when estimating the age of faulting. However, the soil may not have been buried by marsh mud immediately after faulting, if faulting did not depress the downthrown block

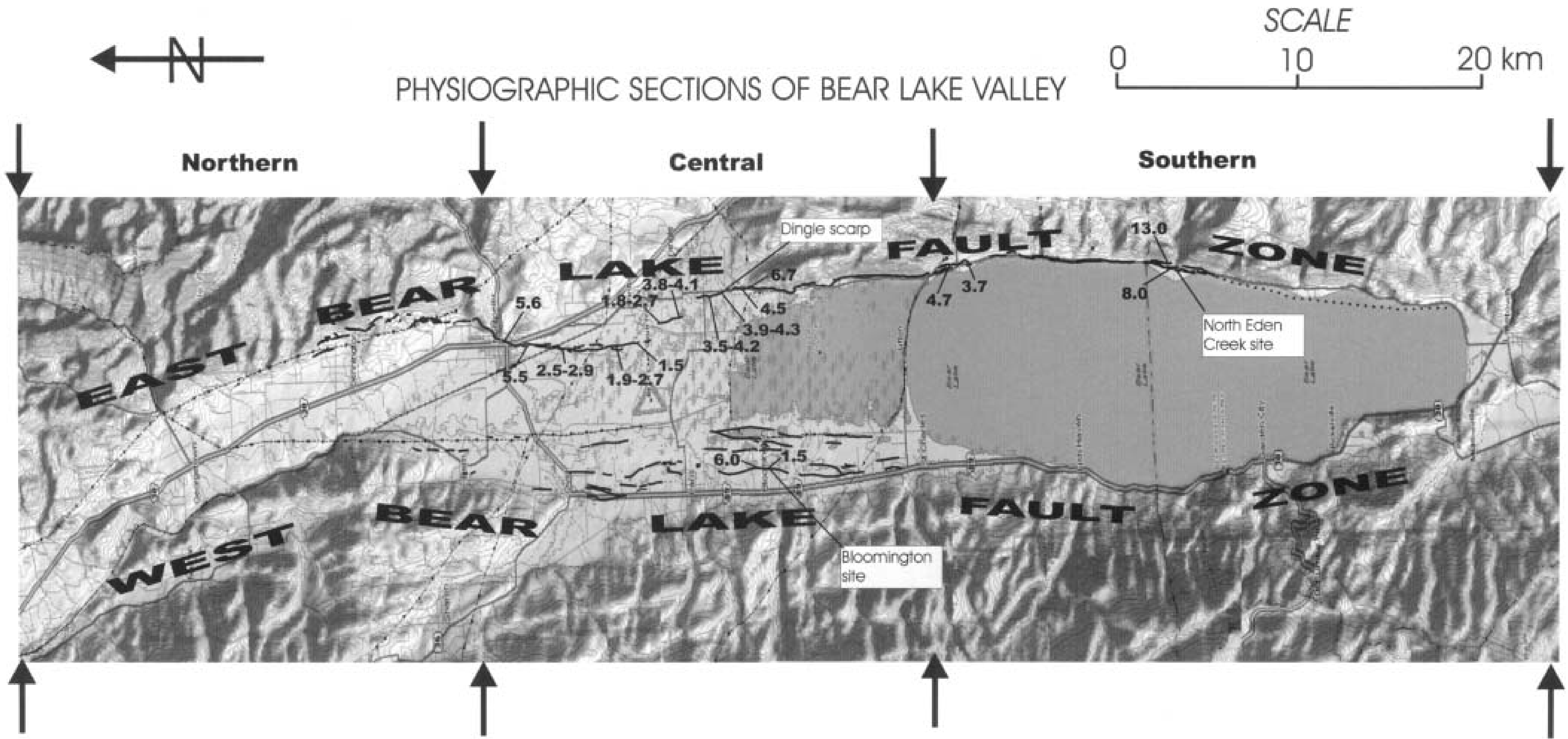

Figure 5. Physiographic sections of Bear Lake Valley, Utah and Idaho. Sections of the East and West Bear Lake fault zones correspond to the named physiographic sections. Fault scarps in Quaternary deposits are marked by thick black lines, with fault scarp heights in meters. These scarps are generalized from unpublished 1:24,000-scale mapping by McCalpin. Labels show the sites of the two trenching studies described herein, at North Eden Creek on the southern section of the East Bear Lake fault zone, and at Bloomington (Idaho) on the central section of the West Bear Lake fault zone. Good sites for future paleoseismic studies exist on other sections, such as on the Dingle Scarp (central section of the East Bear Lake fault zone) and in the eastern parts of Montpelier, Idaho. Conversely, fault scarps in Quaternary deposits are less well preserved in the northern section of the East Bear Lake fault zone, and are scarce in the northern section of the West Bear Lake fault zone. Dotted and dashed lines are power transmission lines.

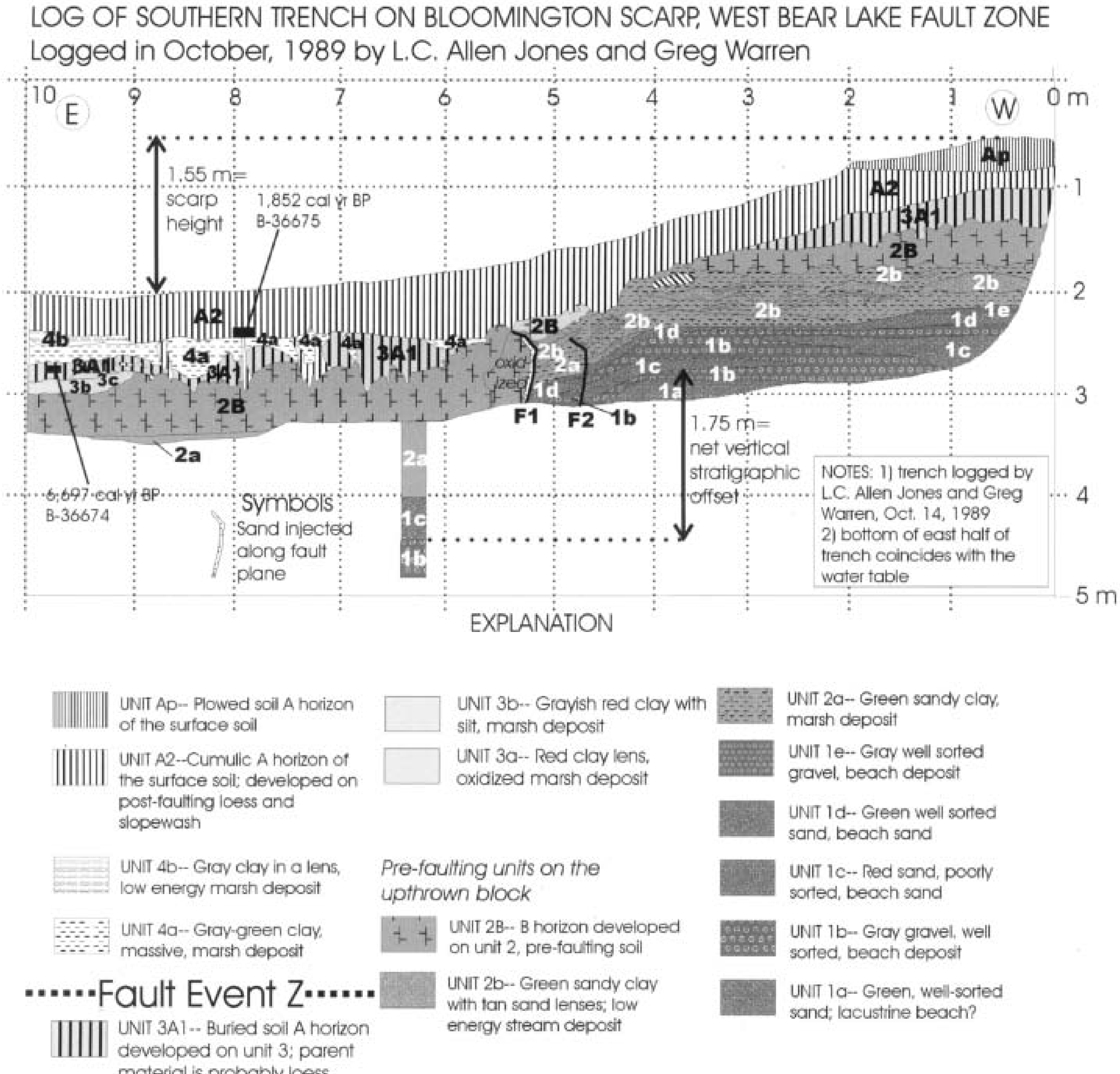

Figure 34. *Log of the southern trench across the Bloomington scarp, West Bear Lake fault zone.*

Figure 35. *Photograph of the south wall of the southern trench at the Bloomington site on the West Bear Lake fault zone. Numbers on the rod at right are decimeters, tick marks are centimeters. The upper part of the wall consists of cohesive silt and clay deposits that are monoclinally folded over the fault zone. The underlying sands and gravels are faulted down to the left (east) in the center of the photograph. The alcove at right was caused by a sapping failure in loose sand and gravel due to ground-water seepage.*

Table 6. *Radiocarbon ages from the Bloomington site on the West Bear Lake fault zone.*

Trench	Lab. No.[1]	Material	Lab. Age (^{14}C yr BP)	Calibrated Age (cal. yr BP)[2]	Significance
southern	B-36675	base of surface soil A horizon	1890±70	1852 (+139, -223)	postdates Event Z
southern	B-36674	buried peat	5900±80	6697 (+196, -197)	closely dates Event Z
auger hole	B-36677	organic mud	6530±90	7428 (+149, -160)	closely dates Event Z
auger hole	B-36676	buried peat	11,240±90	13,164 (+604, -250)	greatly predates Event Z

[1] Beta Analytic, Miami, FL. [2] Calibrated according to Stuiver and Reimer, 1993.

below the local water table. In that case, the soil may have continued to add atmospheric carbon for several hundred years until later burial by Unit 4a. These two sources of error add an uncertainty of several hundred years when relating the 6.7 cal ka age to the timing of the earthquake.

The second sample came from the base of Unit A2 and yielded an age of 1890 ± 70 ^{14}C yr BP (1852 cal yr BP). This sample postdates the MRE (Event Z) by the amount of time needed to deposit Units 4a, 4b, and the lower part of Unit A2, and thus provides a loose minimum age constraint on Event Z.

Interpretation: The 1.75 meters of vertical displacement measured in the southern trench are assumed to result from a single faulting event, which displaced the pre-faulting soil (Units 3A1 and 2B) into the marsh, followed by burial of those units by marsh mud. The stratigraphy of the trench does not require a second faulting event, with the possible exception of Units 3b and 3c. These oxidized clay lenses appear similar to marsh deposits, yet lie between Units 3A1 and 2B, thus splitting the soil that is a single soil on the upthrown block. A possible explanation for these units is a faulting event after the formation of Unit 2B and before the formation of Unit 3A1. However, in order for a soil B horizon to develop there must have been an overlying A horizon already in place, so it is unlikely that deposition could take place between those horizons, regardless of depositional environment. A more likely explanation is that Units 3b and 3c are actually parts of Unit 2B that have become discolored due to oxidation or reduction in marsh conditions (see appendix 3).

The 6-meter-high scarp at the northern trench site must therefore be the product of multiple displacement events, but the exact number cannot be interpreted from the northern trench due to lack of unambiguous paleoearthquake event horizons.

Auger Holes

As a check on the interpretation of the southern trench, I drilled two auger holes into the upthrown alluvial surface west of the southern trench (figure 30). The eastern hole was on the alluvial surface and was 4.8 meters deep; the western hole was in the abandoned meander channel and was 1.8 meters deep (figure 36). The eastern hole recorded a sequence of surface loess overlying stream gravels from the alluvial surface, which were in turn underlain by clayey and then sandy lake deposits. The upper clayey lake deposits were composed of red to brown to green clay, silty clay, and clayey sands, and resembled lacustrine Unit 1b in the northern trench and Units 2a and 2b in the southern trench. The greenish well-sorted sands at the bottom of the hole were very similar to Unit 1a in both the northern and southern trenches. I obtained an age estimate of 11,240 ± 90 ^{14}C yr BP (13,164 cal yr BP) on a thin peat between the clayey and sandy lake deposits. If my correlation is correct, this age can be assigned to the correlative units in the northern and southern trenches.

The auger hole in the abandoned meander recorded a simpler stratigraphic sequence, with a channel fill of black, peaty clay overlying sandy lacustrine deposits. Presumably the alluvial channel eroded away the upper, clayey part of the lacustrine sequence, and after abandonment was filled in with highly organic oxbow pond sediments. The base of the organic channel fill dated at 6530 ± 90 ^{14}C yr BP (7428 cal yr BP), which is a close minimum age for channel abandonment. Because the channel was abandoned when it was truncated and uplifted 1.5 meters by the MRE, this age is also a close minimum age constraint on the MRE.

Figure 37 shows the correlation of units between the southern trench and the two auger holes. The radiocarbon dates from the trench suggests the MRE occurred slightly before 6.7 cal ka, when the pre-faulting soil was depressed into the marsh and buried by marsh mud. By comparison, the auger hole indicates that the stream meander now on the upthrown block was abandoned slightly before 7.4 cal ka. This pair of age estimates indicates that the MRE on the Bloomington scarp probably occurred slightly before 6.7 to 7.4 cal ka, and was accompanied by 1.75 meters of vertical displacement.

Discussion of Faulting on the Central Section of the WBF

Structural relations in the southern trench indicate that two faulting events have occurred on the central section of the WBF in the past ca. 13 ka, the latter of which (Event Z) caused about 1.75 meters of vertical displacement slightly before 6.7-7.4 cal ka. The amount of displacement and timing of the earlier faulting event are more poorly constrained. If we assume that the vertical displacement of 1.75 meters was close to the average for the 6.7-7.4 ka event, then such a displacement correlates with historic, normal faulting earthquakes with rupture lengths of about 39 kilometers (Wells and Coppersmith, 1994). This estimated rupture length is 70% longer than the 23 kilometers length of the central section of the WBF. Offshore seismic surveys in progress by Steve Colman (personal communication, 2002) indicate that multiple small faults displace lake bottom sediments in the northwestern corner of Bear Lake. These faults may be the southern continuation of the central section of the WBF, in which case the actual length of the central section is somewhat greater than 23 kilometers. Alternatively, if we assume that the 1.75 meters was close to the maximum displacement in that event, then it would correlate with ruptures only 28 kilometers long, or only 20% longer than the central section. Thus, it is possible that Event Z represents an independent surface-rupturing earthquake on the central section of the WBF.

Dating control from the two trenches at North Eden Creek is insufficiently precise to correlate Event Z on the WBF (6.7 - 7.4 cal ka) to any particular paleoearthquake on the central segment of the EBF. For example, Event Y in the eastern trench at North Eden Creek occurred sometime after 9 ± 1ka and before 5 ± 0.5ka, and closer to the latter date (figure 29), based on TL age estimates. To prove whether this event had actually occurred during the period 6.7 - 7.4 ka would have required multiple closely spaced samples across the Unit 7/9 contact. However, the eastern trench was logged and then backfilled several months before the Bloomington trenches were dug, so at the time we did not know that such sampling would be critical. If the eastern trench at North Eden Creek could be re-sampled, then it might be advisable to collect a series of optically stimulated luminescence (OSL) samples from across the Unit 7/9 contact to more tightly constrain the age of Event Y.

Due to the loose dating constraints, I cannot confirm that the WBF acted as an independent seismic structure during its latest surface rupturing event, or whether it ruptured simultaneously with an even larger earthquake originating on the EBF. Such questions will have to be answered by further detailed studies.

IMPLICATIONS OF PALEOSEISMIC DATA TO SEISMIC HAZARDS ASSESSMENT IN THE BEAR LAKE VALLEY

Slip Rates, Maximum Magnitudes, and Recurrence of Large Earthquakes in the Bear Lake Valley

Fault scarp heights and displacements measured at the two trench sites provide data for preliminary slip-rate estimates for the EBF and WBF. At the North Eden site, all but 1.2 meters of the net > 23.3 meters of vertical displacement has occurred since 39 ka. Therefore, over at least the past 5 seismic cycles, > 22.1 meters of slip has been released in about 38 ky, for an average slip rate of > 0.58 mm/yr. This slip rate may overestimate the true tectonic slip rate if faulting events V-Z were accompanied by either undetected anti-

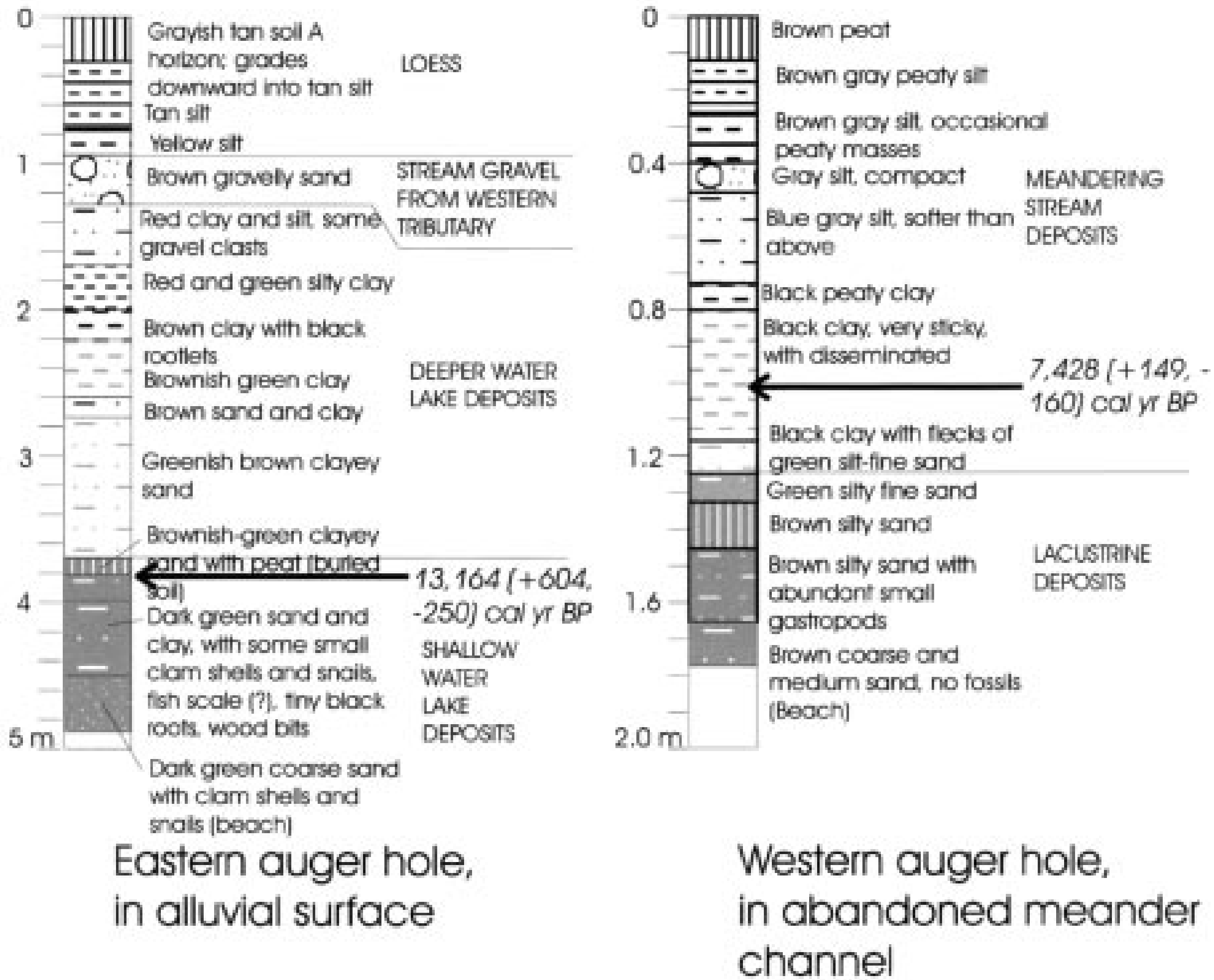

Figure 36. Logs of the two auger holes drilled into the upthrown block of the Bloomington scarp. The eastern auger hole is on the alluvial surface cut by a stream meander into the upthrown block, about 60 m west of the southern trench. The western auger hole is in the abandoned meandering stream channel, which filled with black, organic clay after it was abandoned following the most recent faulting event here, sometime shortly before 7.5 cal ka.

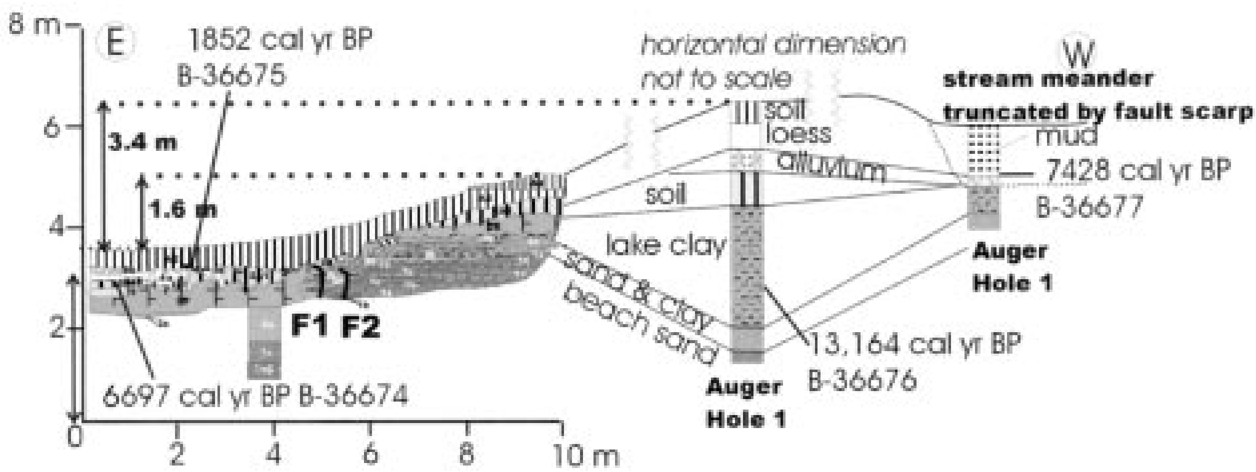

Figure 37. Schematic cross section showing correlation of units in the southern trenches and the two auger holes, Bloomington scarp.

thetic faulting beneath Bear Lake, or by unmeasured tectonic back-tilting (hanging wall rotation). The latter phenomena would increase stratigraphic displacements measured in the trenches over the true net vertical slip values. Based on the current horizontal dip of beach deposits in both trenches, there was negligible back-tilting during Events Z and Y, which together account for roughly half of the cumulative displacement here. However, I cannot preclude some back-tilting in Events U-X.

Over individual seismic cycles it is possible to calculate much higher slip rates, such as the 4.6 meters of displacement released by Event Z in the western trench, which accumulated in the period 5 ka to 2.1 ka. Slip of 4.6 meters in only 2.9 ka equates to an interval slip rate of 1.58 mm/yr, or nearly three times the (minimum) average over the past 39 ka (≥ 0.58 mm/yr). Such variations in slip rate through time have been documented previously in the Basin and Range and Rio Grande Rift physiographic provinces (McCalpin, 1995).

Slip rates for the WBF are best estimated by combining the data from the northern and southern trenches. The long-term slip rate calculated from a 6-meter scarp height on 13.1 ka lacustrine deposits is 0.46 mm/yr, but this value contains the incomplete seismic cycle between the MRE at 6.7 to 7.4 cal ka and the present, so is a minimum value. The 1.75 meters of slip released by the MRE at 6.7 to 7.4 cal ka began accumulating well after 13.1 ka, but we do not know exactly when, considering there were probably two additional paleoearthquakes between 13.1 cal ka and 6.7 to 7.4 cal ka. If there were two events and they were evenly spaced between 13.1 and 6.7 cal ka, the 1.75 meters of displacement could have accumulated over 2.1 to 3.2 ky (depending on the timing of the first event), which yields slip rates of 0.55-0.83 mm/yr. Given the uncertainties, all we can conclude is that the average slip rate for the Bloomington scarp is on the order of 0.5 mm/yr. However, this rate cannot be applied to the entire WBF because the WBF also contains down-to-the-west fault scarps east of the Bloomington scarp, and displacements on those scarps would have to be subtracted from the 6 meters before an overall slip rate can be calculated. Therefore, additional studies on the WBF will be necessary before an accurate slip rate can be obtained.

The lengths of the fault sections and displacements measured in trenches allow an estimation of the maximum magnitude of paleoearthquakes on the EBF and WBF (table 7). On the EBF, magnitudes estimated from displacements at North Eden Creek (M = 7.0-7.1) tend to be slightly higher than estimates based on section length (M > 6.8). This disparity could be caused by an underestimate of section length (and thus, surface rupture length), or from the assumption that the 2.0 to 5.0 meter displacement events at North Eden Creek were restricted to the southern section of the EBF; they may have extended into the central section. Another possibility is that past displacements of the North Eden Creek fan-delta contain both a fault displacement component and a landsliding component, the latter related to failure of the fan-delta mass into the lake.

Paleo-magnitude estimates for the WBF are similar, whether based on section length (M = 6.7) or displacement per event (M = 6.8), if one assumes that the 1.75 meters of displacement in the MRE was the maximum (rather than average) displacement during that event. This assumption cannot be strictly supported with only one displacement estimate along strike, but it informally "substitutes" for the fact that an unknown amount of displacement should be subtracted from the 1.75-meter MRE at Bloomington due to unmeasured antithetic displacements.

On the EBF recurrence is only tightly constrained for

Table 7. *Estimates of maximum earthquake magnitude for the EBF and WBF, based on geologic data.*

Fault zone	Section (km)	Section length displacement (m)	Per-Event from section length[1]	Maximum magnitude from displacement[2]	
EBF	southern	>32	3.8 average[3] 6.1 maximum[4]	>6.8	7.0 7.2
	central	26	unknown	6.7	N/A
	northern	>20	unknown	>6.6	N/A
WBF	southern		unknown-- fault zone is mainly submerged?		
	central	23 maximum[5]	1.75	6.7	6.8
	northern		unknown-- mapping is incomplete		

[1] From equation of Wells and Coppersmith (1994) relating magnitude and surface rupture length for normal faults
[2] From equation of Wells and Coppersmith (1994) relating magnitude and displacement for normal faults
[3] Average assumed from displacement of older events at North Eden Creek
[4] Maximum assumed from displacement of Event Y at North Eden Creek
[5] Displacement on the Bloomington scarp in the MRE is considered a maximum, because displacements on antithetic faults have not been subtracted.

one seismic cycle (Event Z) at ca. 2.9 ky. By comparison, the long-term average recurrence of the past 5 seismic cycles between ca. 40 ka and 2.1 ka is 7.6 ky. The Event Y seismic cycle was at least 10.5 ky long, and could have been as long as 26 ky. On the WBF age control for pre-MRE events is poor, so recurrence intervals could range from at least as long as the present elapsed time (6.7-7.4 ky) to as little as 2-3 ky as mentioned previously.

Hazards Due to Surface Fault Rupture

Future large (M > 6.5) earthquakes in Bear Lake Valley will be accompanied by surface fault rupture, as they have been in the past. The exact amount of displacement cannot be predicted, and could range from minor surface faulting of centimeters to displacements as large as 6 meters. However, potential surface ruptures should be mainly restricted to those zones that have experienced surface rupture in the past, that is, to the vicinity of the fault scarps mapped on figure 5. Due to the low population density in Bear Lake Valley and general lack of critical facilities, there are no current land-use restrictions requiring building setback distances from mapped fault scarps. In other areas of Utah such as Salt Lake County, building setbacks of 30-50 feet (9.1 to 15.2 m) are commonly required from fault traces with evidence of displacement in the past 11,000 years. As this report demonstrates, many strands of the EBF and WBF have experienced such recent movement.

Hazards Due to Liquefaction

Geologically recent, sandy sediments underlie large areas of Bear Lake Valley where the water table is less than 30 feet (9.1 m) below the surface. A high potential for liquefaction during earthquakes is typically associated with these geologic conditions. I observed several large craters along the EBF on the Bear River alluvial fan between Dingle and Montpelier, Idaho that may represent paleo-liquefaction events. Before constructing a critical facility, I recommend that a geotechnical study be performed to evaluate liquefaction potential, if the facility is in an area where ground water is less than 9.1 meters (30 ft) below the surface.

Hazards due to Ground Failure

Earthquake shaking commonly causes landslides and other types of ground failures. In my reconnaissance mapping I did not observe any obvious prehistorical landslides along the EBF or WBF, but more detailed geologic or geomorphologic mapping might reveal some. A likely failure type would be lateral spreads where ground-water tables are shallow, such as along the WBF, or along the beaches of Bear Lake. Colman (2001) reported a large submarine landslide of prehistorical age in northern Bear Lake, and similar landslides might take out part of a beach or shoreline area under certain conditions.

Recommendations for Future Research

This study represents only a preliminary investigation into the neotectonics and paleoseismology of faults in Bear Lake Valley. As indicated in table 7, there is reliable data for estimating maximum earthquake magnitude on only two of the six fault sections in the valley. Likewise, slip-rate estimates for the EBF and WBF are based on only a single trench site each, and for the WBF are subject to large uncertainties.

The most obvious future study would be trenching the central segment of the EBF, to date the latest several displacement events and to determine if they are continuations of events that ruptured the southern section at North Eden Creek. There are several promising trench sites in the section, ranging from multiple-event scarps up to 6 meters high to a probable single-event scarp near the Bear River only 1.5 meters high. Proving that the EBF has (or has not) experienced two-section ruptures would change estimates of future earthquake maximum magnitudes and recurrence intervals.

Additional studies could be made of the northern section of the EBF, where I did not even measure any scarp heights, and of the southern section of the WBF, which probably lies just offshore of Garden City and Pickleville, Utah. These resort communities have a growing population, especially in the summer. However, studying submerged fault traces would require specialized offshore paleoseismic techniques such as recently used to study the East Great Salt Lake fault near Salt Lake City (Dinter and Pechmann, 2000; Colman and others, 2002). Perhaps it would be better to start by mapping any on-land fault traces before going offshore.

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APPENDIX 1

UNIT DESCRIPTIONS, WESTERN TRENCH AT NORTH EDEN CREEK, BEAR LAKE, UTAH

UNIT la – pale brown (10YR6/3) to very pale brown (l0YR7/3) clayey silt with some sand and about 30 percent gravel clasts, very poorly stratified, clasts in random orientation; clasts subround, average diameter 2 centimeters, maximum diameter 12 centimeters; matrix very hard and compact; DEBRIS FLOW of MID-PLEISTOCENE AGE?

1b – light brown (7.5YR6/4) silt, with lenses of medium to coarse sand, moderately well stratified, lens-like beds of sand are 8 to 10 centimeters thick, parallel to unit boundaries; silt is very hard and compact, with rare vertical fractures; FLUVIAL SILT AND SAND

1c – strong brown (7.5YR5/6-matrix color) pebble gravel, clasts round to subround, average diameter 1.5 centimeters, maximum diameter 10 centimeters, moderately well stratified, stratification parallel to unit boundaries; matrix is coarse sand and small granules with some fine sand and silt, moderately friable; clasts not imbricated, most lie parallel to stratification; FLUVIAL GRAVEL

1d – reddish yellow (7.5YR6/6) silt, massive, very hard and compact, rare vertical fractures, breaks into blocks, fracture spacing decreases to 1 to 2 centimeters near fault; basal well-stratified, medium to coarse sand bed; no clasts below unit le, but small pebble lenses above le; upper contact with lf has about 30 centimeters of erosional relief on north trench wall, shows this contact is an unconformity of unknown duration: LOESS? MID-PLEISTOCENE?

le – light gray (2.5Y7/2) silty clay, extremely hard and compact, has about 5 percent floating pebbles, subround to round, average diameter 2 centimeters, maximum diameter 4 centimeters, with random orientations, massive, no stratification; contains small shell fragments; LAGOON MUD?

1f – reddish yellow (7.5YR6/6) pebble and cobble gravel, subangular to subround, average diameter 3 to 5 centimeters, maximum diameter 25 centimeters, moderately well stratified, clasts either horizontal or weakly imbricated to the east; matrix is friable, coarse sand and granules with some fine sand and silt; clasts are a bimodal mixture of smaller, round pebbles and larger, subangular cobbles, upper 10 to 15 centimeters is round pebbles only, openwork texture (beach gravel); DELTAIC GRAVEL

1g – reddish yellow (7.5YR6/6) pebble and cobble gravel, subangular to subround, average diameter 4 to 5 centimeters, maximum diameter 15 centimeters, poorly stratified, weak imbrication to the east, matrix is sparse but, contains more silt and fine sand than underlying unit, is not as friable as 1f; DEBRIS FLOW?

1h – reddish yellow (7.5YR7/6) silt, thin bed about 10 to 15 centimeters thick, massive, hard and compact, similar to unit 1d, $CaCO_3$ stringers along old rootlet pores; LOESS OR FLUVIAL SILT

1i – reddish yellow (7.5YR6/6) pebble and small cobble gravel; lower part is 1.4 meters thick, has dominantly large pebble and small cobbles, average diameter 5 to 8 centimeters, maximum diameter 15 centimeters, in a matrix of friable, coarse sand; also has lenses of clean, very coarse sand (beach?) with round granules and beds 10 to l5 centimeters thick of round to subround pebbles with no matrix in upper 50 centimeters (beach); upper part of unit is mainly large cobbles, average diameter 10 to 15 centimeters, maximum diameter 25 centimeters, in a slightly more friable matrix, $CaCO_3$ coats on stone bottoms and sides; $CaCO_3$ coats on unit below loess (between 7 and 21 meters on log) are thinner than elsewhere, probably due to redissolution; DELTAIC AND BEACH GRAVEL

1j – SHEARED ALLUVIUM; reddish yellow (7.5YR6/6) mixture of units 1a through 1i, sheared between strands of the main fault zone between 26 and 27.5 meters in the trench; consists of 2 subunits: (l) between the eastern (youngest) and central (intermediate age) faults, the unit contains intact fluvial strata in the lower 1 meter, upper 2 rmeters consists of gravel with a strong fabric paralleling the faults, matrix is relatively free of silt; (2) between the centra1 and western (oldest) faults, the gravels also have a shear fabric, but weaker than to the east, and contains slightly more silty matrix mixed with gravel (from loess?); the western subunit was produced by early (pre-loess) faulting, whereas the eastern subunit was sheared during the latest two faulting episodes; TECTONICALLY SHEARED GRAVEL IN MAIN FAULT ZONE

UNIT 2a – strong brown (7.5YR5/6) silt in lower two-thirds; upper one-third is medium to coarse sand, well stratified, beds roughly horizontal, upper sand contains small snail shells (high-spired) and charcoal; BEACH DEPOSITS

2b – same as 2a, except bedding dips about 35 degrees to the west, white colored sand (volcanic ash?) atop 2a goes into 2b.

2c – pink (7.5YR7/4) pebble gravel, moderately well stratified, clasts subround, average diameter 2 centimeters, maximum diameter 10 centimeters, horizontal fabric, in a matrix of granules and very coarse sand, moderately friable, well sorted; BEACH DEPOSITS

2d – pink to light brown (7.5YR6.5/4) sand, very hard and compact because of silt and clay matrix (infiltrated?) from overlying unit, poorly stratified, common clasts, subround, average diameter 1 to 2 centimeters, maximum diameter 8 centimeters; transitional unit; BEACH TO LAGOON/MARSH

UNIT 3 – light gray (10YR7/1) silty clay, massive, upper part has weak, coarse, subangular blocky structure, extremely hard and compact, has very rare low-spired snails; LAGOON/MARSH DEPOSIT

UNIT 3Bb1 – B HORIZON of Buried Soil 1 developed on Unit 3; brown to light brown (7.5YR5.5/4), same texture as overlying A horizon (see next) but slightly more clay, weaker soil structure, more reddish color; SOIL B HORIZON

UNIT 3Ab1 – A HORIZON of Buried Soil 1 developed on Unit 3; pinkish gray (7.5YR5.5/2) clayey silt, massive, moderate, coarse, subangular blocky structure, has about 5 percent floating pebbles, subround, average diameter l to 2 centimeters, and has abundant low-spired snails and rare small pieces of charcoal; SOIL A HORIZON

UNIT 4a – transition unit; between 11 and 21 meters, unit is a transition between underlying red deltaic gravels (1i) and overlying loess (4b), contains mainly silt with common pebbles and traces of organic matter; is correlative with the A horizon of Soil 1; between 6.5 and 11 meters on log, unit is a transition between underlying gravels of units 1i and 2c, and overlying gray clay (unit 3); here unit is a silty clay with common gravel clasts, very hard and compact, and is older than Soil 1; TRANSITION UNIT, VARIOUS AGES AND LITHOLOGIES

4b – pinkish gray (7.5YR6/2) clayey silt, rare pebbles floating in matrix, subround, average diameter 1 to 4 centimeters; massive, rare vertical fractures (much weaker structure than underlying A horizon); TRANSITION FROM A HORIZON TO LOESS

4c – pinkish gray to light brown (7.5YR6/3) clayey silt, massive, moderately compact, less than 1 percent pebbles floating in matrix, nearly stone free; LOESS

UNIT 4cB – B HORIZON of the Surface Soil developed on Unit 4c; light brown (7.5YR6/4) clayey silt, massive, nearly stone free; strong, fine, angular blocky structure, common rootlets from surface plants; gradational lower boundary; B HORIZON ON LOESS

UNIT 4cAB – AB HORIZON of the Surface Soil developed on Unit 4c; pinkish gray (7.5YR6/2) silt, massive, moderate, fine, subangular blocky structure, transitional colors between the adjacent units;
SOIL HORIZON DEVELOPED ON LOESS

UNIT 4cA – A HORIZON of the Surface Soil developed on Unit 4c; brown (7.5YR5/2) silt, fine laminar structure in bottom 5 centimeters, elsewhere strong, medium to large crumb structure, very friable and loose, contrasts with underlying horizons, possibly because its parent material is younger loess and slopewash than the parent material of the AB and B horizons; A HORIZON ON LOESS AND SLOPEWASH

UNIT 5a – brown (7.5YR5/4) silty gravel, very poorly sorted, contains subround clasts, average diameter 1 to 2 centimeters, maximum diameter 15 centimeters, in a hard matrix of sandy silt with granules; large clasts in lower 20 centimeters and upper 20 centimeters have a downslope fabric paralleling the lower contact; all of the center of the unit is small pebbles in an abundant sand/silt matrix; unconformably overlain by unit 6a; large stones in this unit east of the main fault seem to interfinger with the top of unit 4c; OLDER COLLUVIUM

5b – same colors as 5a, but coarse sand and small pebble gravel, clasts subround, average diameter 1 to 2 centimeters, maximum diameter 5 centimeters, moderately well sorted, well stratified, stratification dips about 30 degrees to the west, parallel to the bottom contact, friable matrix; SLOPEWASH ON OLD SCARP FACE, DEPOSITED BY RUNNING WATER

5c – grayish brown to brown (10YR5/2.5) pebbly sandy silt, massive and extensively burrowed, about 5 percent floating pebbles by volume, clasts subround, average diameter 1 to 3 centimeters, moderately friable; is entirely affected by surface soil formation (see next unit description); very coarse, moderate, subangular blocky structure; COLLUVIUM FROM A FREE FACE THAT EXPOSED LITTLE OR NO GRAVEL

UNIT 5cAB – AB HORIZON of the Surface Soil developed on Unit 5c; pinkish gray (7.5YR6/2) silt, massive, moderate, fine, subangular blocky structure, transitional colors between the adjacent units, developed on wash facies colluvium unit 5c; stone free west of 16 meters in the trench with increasing percent of small pebbles to the east, gradational contacts above and below; TRANSITIONAL SOIL HORIZON DEVELOPED ON OLDER COLLUVIUM AND SLOPEWASH

5d – light brown (7.5YR6/3) silty gravel, clasts subround to subangular, average diameter 5 centimeters, maximum diameter 20 centimeters, in an abundant matrix of silt; appears to be a mixture of colluvial cobbles and loess (unit 4c); was probably derived from the upper part of the free face of the earliest fault event on the main fault strand, which was subsequently eroded; in fault contact with unit 5a; OLDER PROXIMAL COLLUVIUM

UNIT 6a – brown (7.5YR5/2) cobble gravel with abundant organic-rich matrix, clasts subround to subangular, average diameter 15 centimeters, maximum diameter 35 centimeters, strong downslope fabric, in matrix of very friable, coarse sand and granules with abundant organic-rich silt mixed in, larger clasts are concentrated at the base of the unit and above main fault plane; PROXIMAL COLLUVIUM FROM LATEST FAULTING EVENT

6b – light yellow brown (10YR5.5/4) silt, medium, weak, laminar structure, breaks into angular clods, abundant rootlets; about 10 percent floating pebbles, subround, average diameter 1 to 10 centimeters; DISTAL SLOPEWASH, either from latest faulting event or from human disturbance of scarp.

UNIT 6bA – A HORIZON of the Surface Soil developed on Unit 6b-- light brownish gray to gray brown (10YR5.5/2) silt, fine, strong, laminar structure, fissile appearance, contains finely disseminated charcoal; SOIL A HORIZON WHICH POSTDATES THE LATEST FAULTING EVENT

APPENDIX 2

UNIT DESCRIPTIONS, EASTERN TRENCH AT NORTH EDEN CREEK, BEAR LAKE, UTAH (lowest numbers and/or letters indicate oldest deposits)

UNIT 1 – reddish gravels and minor sands of the upthrown block, probably of mid-Pleistocene age; MAINLY FLUVIAL GRAVEL, EXCEPT WHERE NOTED BELOW: basal (unlettered) subunit beneath subunit la is a yellowish red (5YR5/6) pebble and small cobble gravel, well stratified, with minor horizontal sand lenses; this subunit is truncated by faulting and in fault contact with unit 4a. In contrast, the remaining subunits of unit 1 (described below) are in depositional contact with most (if not all) of unit 4b.

1a – pink (5YR7/4) silt, plastic, slightly sticky, massive, pervasive closely spaced (2mm) fractures throughout the unit between 11.5 and 13 meters, apparent dip 40 degrees west, spacing increases to 2 to 3 centimeters by 14.5 meters, very hard and compact; OLD LOESS OR FLOODPLAIN/LAGOON SILT

1b – yellowish red (5YR5/6) large pebble and small cobble gravel, subround, average diameter 5 to 10 centimeters, sandy matrix

1c – reddish brown (5YR5/4) well-sorted, small pebble gravel, average diameter 1 centimeter

1d – yellowish red (5YR5/6) gravel and sand; lower half is similar to subunit 1b, only subangular clasts; upper half is similar to subunit 1c, average clast diameter 2 centimeters

1e – reddish yellow (5YR6/4) extremely well-sorted granule gravel, no matrix, average diameter 0.3 to 0.5 centimeters

1f – yellowish red (5YR5/6) moderately well-sorted, angular, small pebble gravel, average diameter 2 to 4 centimeters, lower part is well-sorted, granule gravel, rare clasts have partial $CaCO_3$ coats, especially at top of unit

1g – reddish yellow (5YR6/4) very well-sorted, small pebble gravel, like subunit 1c, but smaller (average diameter 0.5 to 1.0 cm) and more angular

1h – several different lithologies, ranging from 5YR6/6 to 5YR5/8: lower 20 centimeters, angular cobbles 10 to l5 centimeters in diameter and chunks of gray clay; the rest is moderately well-sorted, small pebble gravel, subround, in a well- sorted matrix of granules and coarse sand, $CaCO_3$ coats on stone bottoms

li – bright-red (2.5YR4/6), medium-coarse sand bed; then above subround, small pebble gravel in a bright-red sand and silt matrix

1j – reddish yellow (5YR6/6) silty fine to medium sand, cross-bedded, very well stratified, very well sorted, no clasts; upper 25 centimeters is sandy silt, massive, weakly stratified (disturbed by soil formation?); EOLIAN SAND AND SILT

1k – yellowish red (5YR5/6) pebble and cobble gravel, a mixture of subround, small pebbles 1 to 3 centimeters in diameter, in an openwork or very well-sorted, granule matrix, and larger subangular clasts up to 30 centimeters in diameter, which are imbricated to the right (west); in the top 20 centimeters of the unit clasts have $CaCO_3$ coats on bottoms

1l – yellowish red (5YR5/6) gravel, similar to subunit 1k, but more large angular clasts and a more silty matrix makes it more resistant to erosion; DEBRIS FLOW

1m – reddish brown (5YR5/4) large pebble and small cobble gravel, poorly stratified, clasts subangular and subround, in a matrix of sand and granules; $CaCO_3$ on all stones

1n – reddish brown (5YR5/4) gravel, similar to subunit 1m, but more red matrix, more resistant to erosion; DEBRIS FLOW

1o – yellowish red (5YR5/6) pebble and cobble gravel, similar to subunit 1k, a mixed unit

1p – reddish yellow (5YR6/4) openwork small pebble gravel, clasts subround, average diameter 1 to 3 centimeters, no matrix, very well sorted, $CaCO_3$ coats on bottoms and sides of clasts; BEACH GRAVEL

1q – reddish brown (5YR5/4) large pebble and small cobble gravel, similar to subunit 1m, but $CaCO_3$ coats on bottoms and sides of clasts, some $CaCO_3$ in matrix at top of unit; FLUVIAL GRAVEL

UNIT 2a – reddish yellow (7.5YR6/6) silty fine sand, massive, looks disturbed, no stratification visible, approximately 5 percent clasts, subround, 1 to 8 centimeters diameter, floating in the matrix with random orientation; POSSIBLY A CHUNK OF THE UPPER 25 CENTIMETERS OF UNIT 1j TO THE WEST

2b – reddish brown (5YR5/4) to light brown (7.5YR6/4) pebble and small cobble gravel, clasts subangular to subround, average diameter 3 to 4 centimeters; maximum diameter l5 centimeters, larger clasts concentrated at base of unit between 23 and 24.5 meters; looks like a channel fill oriented perpendicular to the trench, poor to moderate stratification, but individual beds pinch out in a few feet; contains some better sorted beds of small pebble gravel, average diameter 1 to 3 centimeters, in a granule matrix, most clasts have discontinuous $CaCO_3$ coats on bottoms only; also includes 20 to 30 centimeters in diameter chunks of brown silt and pink to gray clay, probably eroded from channel banks; FLUVIAL CHANNEL FILL

2c – light reddish brown (5YR6/5) small pebble gravel, clasts subrounded to subangular, average diameter 2 centimeters, maximum diameter 5 centimeters, in a friable matrix of granules and very coarse sand, well sorted, well stratified, forms a lens 10 centimeter thick, all clasts have thin $CaCO_3$ coating on bottoms; BEACH GRAVEL?

UNIT 3a – pink (7.5YR7/4) sandy silt, massive, very hard and compact, about 10 perecent clasts floating in matrix, subround to subangular, 2 to 15 centimeters in diameter, with a downslope fabric; many small pores with $CaCO_3$ stains around them--similar to unit 4a; LOESS?

3b – pink (7.5YR7/4) silty gravel, clasts subangular to subround, 1 to 10 centimeters diameter, with strong downslope fabric; basal 10 centimeters is a bed of reddish, well-sorted granule and small pebble gravel in a friable silty sand matrix; PROXIMAL COLLUVIUM

3bCk – very pale brown (10YR7/3) silt, with about 10 percent clasts by volume, subangular, 1 to 8 centimeters in diameter, with downslope fabric, medium, moderate, laminar structure grading into strong, medium, subangular blocky structure; thin, discontinuous $CaCO_3$ coats on peds and on bottom and sides of clasts, less than l millimeter thick (stage 2 carbonate development?); Ck HORIZON OF SURFACE SOIL DEVELOPED ON UNIT 3b

UNIT 4a – pink (7.5YR7/4) gravelly silt, plastic, non-sticky, compact when dry, breaks into angular clods, massive, contains floating pebbles, subround, maximum diameter 10 centimeters; clasts have a downslope fabric that becomes stronger toward Fault F5; unit is in fault contact with Unit 1 across Fault F5; DEBRIS-FACIES COLLUVIUM DEPOSITED AFTER EVENTS W and X

UNIT 4b – similar in composition to Unit 4a, but forms a downward-tapering wedge against Fault F5; OLD FISSURE FILL FROM EVENT W and X

4c – well-sorted pea gravel in a lens about 20 cm thick, which is eroded into the top of the Unit 4a colluvial wedge; probably a BEACH GRAVEL THAT POSTDATES EVENT X

UNIT 4d – pink (7.5YR7/4) silt, plastic, non-sticky, compact when dry, breaks into angular clods, massive, very rare floating pebbles; many small pores, 0.25-0.5 millimeters in diameter, usually rimmed with $CaCO_3$, gives unit a mottled appearance; OLD LOESS or LOESS-DERIVED WASH-FACIES COLLUVIUM THAT POSTDATES EVENT X

UNIT 5 – pale brown (7.5YR6/4), stony sandy silt, about 25 percent pebbles by volume, average diameter 5 centimeters, maximum diameter 15 centimeters, subangular to subround, weak $CaCO_3$ coats on stone bottoms and sides, but no stringers in matrix; moderate clast fabric parallel to upper and lower unit contacts, similar to unit 6 but more clasts; DEBRIS-FACIES COLLUVIUM DEPOSITED AFTER EVENT Y

UNIT 6 – mainly a yellowish red (5YR5/6) pebble and small cobble gravel (Unit 6a), clasts subround to subangular, average diameter 8 centimeters, maximum diameter 20 centimeters, moderately well sorted, in a matrix of coarse sand and granules; poorly stratified except for two lenses of well-sorted, small pebble and granule gravel (Unit 6b), which are subangular to angular, average diameter 0.5 centimeters, no matrix; all units are very friable due to very coarse and sparse matrix; unit is eroded into units 4a and 4b, unconformably overlain by unit 6; FINER LENSES LOOK LIKE BEACH GRAVEL, COARSER GRAVELS DELTAIC?

UNIT 7 – brownish yellow (10YR6/4), fine sandy silt, moderately plastic, non-sticky, very dusty when dry, moderately hard but surface remains friable when brushed, massive, rare clasts float in matrix, subround to subangular, average diameter l.5 centimeters, maximum diameter 5 centimeters, generally oriented long axis horizontal; in lower one-third contains discontinuous weak organic horizons (black to dark gray) 2 centimeters thick which overlie 3 centimeter-thick, strong brown (7.5YR5/6) oxidized horizons (indicates burning?); charcoal is common in soil A horizons, also a burnt snail shell; has fairly abundant low-spired gastropods (all marked on log); LOESSY SLOPEWASH AT BASE OF SCARP

UNIT 8 – light reddish brown (5YR6/5) intact block of upthrown block stratigraphy, fallen from a free face and back-rotated; middle bed of well-sorted, small pebbles with $CaCO_3$ coats is probably unit 2c, which indicates that the block fell off of the upper part of the free face (now eroded) which must have been around 19 meters on the log; TECTONICALLY ROTATED BLOCK DEPOSITED AFTER EVENT Z

UNIT 9Ck – that part on Unit 9 with thin $CaCO_3$ coats on all sides of clasts in stone line (stage 1+ carbonate development), $CaCO_3$ stringers abundant in matrix (stage 2+ carbonate development); similar structure to that of unit 3bCk (strong, medium, laminar to subangular blocky structure, discontinuous $CaCO_3$ coats on peds); soil becomes weaker and less distinct on the upslope part of the unit, probably due to flushing by infiltrated water; Ck HORIZON OF SURFACE SOIL DEVELOPED ON UNIT 9

UNIT 9 – pale brown (10YR6/3) silt, plastic, non-sticky, massive, darker colored and more dense (less friable) than underlying unit 6; base defined by a stone line, clasts subangular to subround, average diameter 4 centimeters, maximum diameter 15 centimeters, size increasing upslope; common clasts float in matrix, same sizes and shapes as in unit 6; downslope equivalent of Unit 8; SLOPEWASH/ COLLUVIUM, DEPOSITED AFTER EVENT Z

UNIT 10 – brown (10YR5/3), stony silty sand, slightly plastic, non-sticky, massive, common stones in matrix (15 to 20 percent by volume) with a weak fabric paralleling present ground surface; about half of pebbles (average diameter 4 cm, maximum diameter 10 cm) have weak $CaCO_3$ coats on bottoms, no $CaCO_3$ in matrix; sharp contact with underlying Ck horizon, but no obvious stone line or unconformity; NON-TECTONIC SLOPE COLLUVIUM

UNIT 11 – light reddish brown (5YR6/4) pebble and small cobble gravel, clasts subangular to subround, average diameter 4 centimeters, maximum diameter 20 centimeters, in a matrix of silty coarse sand and granules; basically a creeping layer of underlying stratigraphy mixed with a small amount of eolian silt; weak downslope fabric; ACTIVE COLLUVIUM

APPENDIX 3

UNIT DESCRIPTIONS, BLOOMINGTON SOUTH TRENCH, WESTERN BEAR LAKE FAULT ZONE

UNIT la – olive (5Y5/6) to olive gray (5Y5/2) sand, medium grained, well sorted, clean; bed thickness unknown, lower contact covered, upper contact is sharp; features black carbonized roots and other organics; BEACH SAND

1b – light gray (2.5Y6/2) to white (2.5Y8/0) gravel, clast size 0.25 to 2 centimeters, grading up to a heavier gravel clasts 5 to 3 centimeters, then back into lighter gravel, good sorting, angular to subangular; matrix, medium to coarse sand, moderately sorted; bed thickness 12 centimeters to 25 centimeters, massive; features, clam shell, piece of wood 0.5 centimeters by 1.5 centimeters; contacts are gradational; BEACH GRAVEL

1c – strong brown (7.5YR5/6), coarse sand, poorly sorted; bed thickness 15 to 25 centimeters; sedimentary structures, minor cross-bedding; features, faulted, a few clasts 0.2 centimeters; contacts, lower sharp, upper gradational; BEACH SAND, OXIDIZED

1d – olive gray (5Y5/2), medium sand, well sorted; bed thickness, 12 centimeters, grades downward into a gravel, upper contact sharp; BEACH SAND, REDUCED

1e – light gray (2.5Y6/2) to white (2.5Y8/0), well-sorted gravel; clasts, average 0.5 centimeters, maximum 3 centimeters, angular to subangular; matrix, well-sorted, medium sand; bedding thickness 6 centimeters; contacts sharp; BEACH GRAVEL

2a – sandy olive (5Y5/6) clay that grades into a olive gray (5Y5/2) silty clay at 5.5 meters from the west end of the trench, well sorted; bed thickness up to 1.5 meters; sedimentary structures, carbonized roots, clean, well-sorted sand lenses; redness in red-green clay comes from oxidation. Contacts are gradational; MARSH CLAY WITH MINOR INFLUX OF STREAM SAND

2b – sandy olive (5Y5/4) clay, over all color green with light tan sand lenses; sand appears randomly, without sedimentary structures, very poor bedding; beds consist of mostly random lenses; features, oxidation stains, carbonized roots appear mostly in the clay; contacts, lower grades into the green clay 2a, upper is very sharp; LOW ENERGY STREAM DEPOSIT IN A MARSH SETTING

2B – B SOIL HORIZON developed on Unit 2; strong brown (7.5YR5/6) clayey silt, well sorted, massive; bed thickness 10 to 25 centimeters; features, blobs of red clay, burrows filled with “A horizon soil”; weak, subangular blocky structure; contacts gradational and irregular; B SOIL HORIZON

3Al – BURIED A SOIL HORIZON; dark brown (10YR3/3) soil, rich in organics; bed thickness is discontinuous and ranges from 12 centimeters to 20 centimeters; lower contact is gradational, upper contact is sharp; PRE-FAULT SOIL A HORIZON, BURIED BY UNIT 4A AFTER FAULTING

3b – reddish brown (5YR5/4) clay, lens shaped; combined with displaced tan sand, medium coarse, poorly sorted with very coarse clasts; bed thickness 3 to 5 centimeters; features, displacement, dragged down by fault; OXIDIZED MARSH DEPOSIT, LENS

3c – olive gray (5Y5/2) clay with some reddish brown (5YR5/4) silty clay; bed thickness 6 centimeters; contacts, lower gradational, upper sharp. CLAY LAYER CAUGHT UP WITH THE SOIL HORIZONS, COVERED BY A PRE-FAULT B HORIZON

4a – olive gray (5Y5/2) clay, well sorted, massive; bed thickness varies from 10 centimeters to 25 centimeters; features- organics, carbonized roots; reduced; contacts- lower sharp, upper gradational; MARSH TYPE DEPOSIT THAT COVERED UP A SOIL A HORIZON

4b – small lenses of olive gray (5Y5/2) clay; no structures; some appear to be burrow filling, or low energy channel-fill, marsh type; reduced clay; REDUCED CHANNEL FILL, POST-FAULT MARSH DEPOSIT.

A2 – A HORIZON OF SURFACE SOIL; brown (10YR5/3) soil, rich in organics; bed thickness, averages 25 centimeters; features, columnar structures 9 to 15 centimeters apart; roots traveling through; lower contact is gradational when overlaying Al, sharp when overlaying 4a, upper contact is moderately sharp; parent material is obscured by high organic content, but is probably loess on the upper scarp face and retransported loess (wash-facies colluvium) on the lower scarp face and at toe; PRESENT DAY UNDISTURBED A SOIL HORIZON

Ap – PLOWED A HORIZON OF SURFACE SOIL; dark brown (10YR3/3) soil; denoted by the lack of columnar structure, approximately as thick as a plow; no structures, massive in appearance, disappears at the upper edge of the hill; PRESENT SOIL A HORIZON THAT IS USED FOR FARMING

APPENDIX 4

CALIBRATION OF RADIOCARBON AGES FROM THE BLOOMINGTON SITE ON THE WEST BEAR LAKE FAULT ZONE

UNIVERSITY OF WASHINGTON
QUATERNARY ISOTOPE LAB
RADIOCARBON CALIBRATION PROGRAM REV 4.3

based on Stuiver, M. and Reimer, P.J., 1993, Radiocarbon, 35, p. 215-230.
Listing file: c14res.doc
Export file: c14res.txt

SAMPLE B-36675
#Radiocarbon Age BP 1890 +/- 70

Calibrated age(s) cal AD 91, 98, 126 — Reference
cal BP 1859, 1852, 1824 — (Stuiver and others, 1998a)

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma**	cal	AD	31 - 39 (1919 - 1911)
			53 - 224 (1897 - 1726)
two Sigma**	cal	BC	41 - 8 (1990 - 1957)
			3 - cal AD 258 (1952 - 1692)
	cal	AD	282 - 289 (1668 - 1661)
			299 - 321 (1651 - 1629)

Summary of above:

maximum of cal age ranges (cal ages) minimum of cal age ranges:

1 sigma	cal	AD	31 (91, 98, 126) 224
	cal	BP	1919 (1859, 1852, 1824) 1726
2 sigma	cal	BC	41 (cal AD 91, 98, 126) cal AD 321
	cal	BP	1991 (1859, 1852, 1824) 1629

SAMPLE B-36674
#Radiocarbon Age BP 5900 +/- 80

Calibrated age(s) cal BC 4775, 4748, 4736 — Reference
cal BP 6724, 6697, 6685 — (Stuiver and others, 1998a)

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma**	cal	BC	4897 - 4893 (6846 - 6842)
			4847 - 4818 (6796 - 6767)
			4811 - 4706 (6760 - 6655)
			4703 - 4692 (6652 - 6641)
two Sigma**	cal	BC	4943 - 4550 (6892 - 6499)

Summary of above:

maximum of cal age ranges (cal ages) minimum of cal age ranges:

1 sigma	cal	BC	4897 (4775, 4748, 4736) 4692
	cal	BP	6847 (6724, 6697, 6685) 6642
2 sigma	cal	BC	4943 (4775, 4748, 4736) 4550
	cal	BP	6893 (6724, 6697, 6685) 6500

SAMPLE B-36677
#Radiocarbon Age BP 6530 +/- 90

Calibrated age(s) cal BC 5479 Reference
cal BP 7428 (Stuiver and others, 1998a)

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma** cal BC 5607 - 5590 (7556 - 7539)
5557 - 5466 (7506 - 7415)
5445 - 5419 (7394 - 7368)
5401 - 5381 (7350 - 7330)

two Sigma** cal BC 5627 - 5318 (7576 - 7267)

Summary of above:

maximum of cal age ranges (cal ages) minimum of cal age ranges:

1 sigma cal BC 5607 (5479) 5381
cal BP 7557 (7428) 733

2 sigma cal BC 5627 (5479) 5318
cal BP 7577 (7428) 7268

SAMPLE B-36676
#Radiocarbon Age BP 11240 +/- 90

Calibrated age(s) cal BC 11215 Reference
cal BP 13164 (Stuiver and others, 1998a)

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma** cal BC 11426 - 11299 (13375 - 13248)
11263 - 11186 (13212 - 13135)
11134 - 11089 (13083 - 13038)

two Sigma** cal BC 11818 - 11737 (13767 - 13686)
11516 - 11048 (13465 - 12997)
10978 - 10964 (12927 - 12913)

Summary of above:

maximum of cal age ranges (cal ages) minimum of cal age ranges:

1 sigma cal BC 11426 (11215) 11089
cal BP 13376 (13164) 13039

2 sigma cal BC 11818 (11215) 10964
cal BP 13768 (13164) 12914

 # References for calibration datasets:
Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plicht, J., and Spurk, M (1998a)
Radiocarbon 40:1041-1083.
Stuiver, M., Reimer, P.J., and Braziunas, T.F. (1998b)
Radiocarbon 40:1127-1151. (revised dataset); Stuiver, M. and Braziunas, T.F. (1993) The Holocene 3:289-305. (original dataset)

Comments:
* This standard deviation (error) includes a lab error multiplier.
** 1 sigma = square root of (sample std. dev.^2 + curve std. dev.^2)
** 2 sigma = 2 x square root of (sample std. dev.^2 + curve std. dev.^2) where ^2 = quantity squared.
[ ] = calibrated with an uncertain region or a linear extension to the calibration curve
0* represents a "negative" age BP
1955* denotes influence of nuclear testing C-14

NOTE: Cal ages and ranges are rounded to the nearest year which may be too precise in many instances. Users are advised to round results to the nearest 10 yr for samples with standard deviation in the radiocarbon age greater than 50 yr.